Study of the Reverse I-V in Component Subcells of III-V Multijunction Space Solar Cells

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Abstract

The reverse bias operation of triple-junction solar cells (GaInP/Ga(In)As/Ge), typically used for space photovoltaics, is poorly understood. In this work, we conduct reverse bias stress tests on both isotype subcells (GaInP, Ga(In)As and Ge) as well as in the complete triple-junction solar cell. After each reverse bias step, forward dark and lighted I-Vs are measured and modelled using Shockley and Spirito and Albergamo models to fit the characteristic parameters of each individual subcell and quantify the variations evolution caused by the stress. The changes in these parameters are thoroughly analyzed in order to comprehend the basic physical processes behind the degradation observed after the reverse bias is applied. Finally, we demonstrate that the individual parameters obtained from each subcell can be combined to simulate the final I-V curve of the complete triple junction and understand how it is affected when reverse bias is applied, linking the changes observed to a sudden degradation of the GaInP top subcell at low reverse voltages.

1. Introduction

For the last decades, multijunction solar cells based on III-V materials have been the most used technology for space applications, thanks to their power to weight and power to area ratios and their natural endurance to space environment stressors.^[1] These devices are manufactured monolithically and consist of series-connected subcells of different materials, using tunnel diodes as interconnects between subcells. The workhorse of this technology is the GaInP/Ga(In)As/Ge triple-junction solar cell,^[2] with AlGaInP/AlGaInAs/Ga(In)As/Ge four-junction upright metamorphic starting to reach the market and other designs based on inverted metamorphic growth (IMM) being used in limited applications.^[3,4]

One common problem faced by these devices is the degradation related to the operation under reverse bias. This type of damage could occur, for example, when a solar cell in the array gets partially or totally shaded. In this case, the shadowed device could be forced to operate under reverse bias, possibly near the breakdown region, multiplying its current exponentially.^[5] This may result in a catastrophic failure, even affecting the whole array in the worst case. In order to prevent this from occurring, bypass diodes are connected to every solar cell in the array.

Obviously, bypass diodes solve the practical problem, but our understanding of the basic failure mechanisms triggered by reverse bias is still incomplete and thus possible actions at the cell structure level to mitigate such damage remain considerably unexplored. In fact, there are very few studies on the analysis of reverse bias on multijunction solar cells and information about the precise effects that this type of stress has on each subcell is still scarce, being the exact causes for this degradation yet to be understood.^[5–8] Also, several operational situations of multijunction solar cells can force one or more of the subcells to operate in reverse. In addition, the subcell under reverse bias can change during the life of the cell in space. This can happen as well in the course of long duration tests, where the illumination conditions change due to the ageing of the light source.^[8] Hence, the main objective of this work will be to thoroughly analyze the changes in the characteristics of component subcells

exposed to different levels of reverse bias stress to, eventually, interpret the effects observed in complete multijunction solar cells, pinpointing which parameters suffer the most critical changes and also setting up hypotheses on the physical processes behind them.

2. Experimental

2.1. Samples

A series of 2x2 cm² multijunction solar cells of a state-of-the-art triple junction technology were used in this study. Specifically, the set included GaInP/Ga(In)As/Ge triple-junction solar cells and Ge, Ga(In)As and GaInP isotype (or component) cells, which are equivalent to the top, middle and bottom cells in the triple-junction stack.

As a starting point, I-V curves of these solar cells were measured in forward bias under dark and one-sun AM0 conditions using a Xe-lamp based AAA solar simulator and a four-quadrant Keithley 2600A source-monitor unit. This initial characterization will be termed as “*Non-stressed measurement*” throughout the manuscript. Then, the cells were measured under reverse bias reaching a given final voltage and immediately, new forward dark and one-sun lighted I-V curves were measured to assess the damage introduced, if any. This cycle (dark reverse + dark and lighted forward I-V) is repeated several times increasing the final reverse voltage at each step in a gradual approach to the estimated breakdown voltage of each isotype subcell. It should be noted that the cells are kept neither in reverse nor in forward bias for long times; just for the brief lapse needed to take the measurement.

2.2. Models used

The forward I-V of each subcell in the multijunction solar cell can be represented by Shockley’s equation with two exponentials:

$$I = I_L - I_{01} \left[\exp \left(\frac{q(V+IR_S)}{m_1 kT} \right) - 1 \right] - I_{02} \left[\exp \left(\frac{q(V+IR_S)}{m_2 kT} \right) - 1 \right] - \frac{V+IR_S}{R_{SH}} \quad (1)$$

where I_L is the subcell photogenerated current, I_{01} is the reverse saturation current considering the recombination in the bulk of the junction; I_{02} is the reverse saturation current considering the recombination at the perimeter and depletion region of the subcell; m_1 and m_2 are the ideality factors; R_S is the series resistance, R_{SH} is the shunt resistance; q is the electron charge; k is Boltzmann's constant; and T is the absolute temperature. The complete response of the multijunction device is obtained by the series connection of the subcells with the tunnel diodes being modelled by an additional contribution to the series resistance.^[2]

Likewise, to model the reverse behavior of the devices and given the moderate dopant concentrations used in the base of the three subcells, we assume that the breakdown region of the solar cell is dominated by avalanche multiplication and, to account for this effect, we have followed the model proposed by Spirito and Albergamo (also referred to as S-A model in this work).^[9] This approach considers that under reverse bias the primary currents of Equation (1) are multiplied by a certain multiplication factor $M(V)$:

$$I = \left\{ I_L - I_{01} \left[\exp \left(\frac{q(V+IR_S)}{m_1 kT} \right) - 1 \right] - I_{02} \left[\exp \left(\frac{q(V+IR_S)}{m_2 kT} \right) - 1 \right] \right\} M(V) - \frac{V+IR_S}{R_{SH}} \quad (2)$$

$$\text{with } M(V) = \frac{1}{1 - \left(\frac{|V|}{V_B} \right)^n}$$

where V_B is the breakdown voltage of each subcell, and n is a parameter –the so-called Miller factor– that can vary from $3 \leq n \leq 6$, depending on the semiconductor material forming the p-n junction.

3. Results and discussion

3.1. Isotype Ge bottom cell

Isotype germanium solar cells were characterized and then reverse biased at -2 V, -3 V and -4.5 V. These values represent around 50%, 75% and 105% of the calculated breakdown voltage for this subcell, which is -4.2 V. **Figure 1a** shows the forward dark I-V curve obtained in the non-stressed measurement (white circles) and after applying the maximum reverse bias

of -4.5 V (black squares). Both curves are almost identical in the measured range, suggesting that little to no damage has been induced in the device. The forward dark I-V curves after the smaller stresses (-2 V and -3 V) were also overlapping these two and thus have not been included to avoid a too busy chart. Figure 1a also shows the fitted forward dark I-V curves before (blue line) and after (red line) the stress was applied. Both fitted curves were modelled using the expression represented in Equation (1) and their most relevant parameters are given in **Table 1**. Only a slight variation of the reverse saturation current I_{02} can be observed; this confirms that virtually no damage is introduced in the device after the tests.

No change in the short circuit current of the cell was detected after any of the steps of the reverse bias experiments. The one-sun lighted I-V curve and the corresponding fit are shown as an inset in Figure 1a. As expected, the curve is well reproduced by the models using the parameters summarized in Table 1 and adding the photogenerated current (I_L).

Figure 1. (a) Forward dark I-V curves of the Ge component cell before any reverse bias (open circles) and after the maximum stress at -4.5 V (solid squares); the corresponding fits are included as solid lines. The inset represents the illumination I-V curve and its corresponding fit. (b) Reverse dark I-V curve of the Ge component cell and fit with the Spirito and Albergamo model.

Figure 1b shows the measured reverse dark I-V curve under the maximum stress of -4.5 V and the resulting fit obtained from Equation (2). The Y-axis is represented in a logarithmic scale

in order to magnify the differences between the modelled and the experimental I-V curves, which are very moderate indeed. The most relevant parameters for the Spirito-Albergamo model can be also seen as labels in Figure 1b.

Table 1. Fitting parameters for the forward dark and lighted I-Vs of the component subcells. The parameters that suffer some variation before and after the reverse bias stress are indicated in bold italic font.

	Ge Bottom cell		Ga(In)As middle cell		GaInP top cell	
	Non-stressed	After max. Reverse stress (-4.5V)	Non-stressed	After max. Reverse stress (-17V)	Non-stressed	After max. Reverse stress (-6V)
$R_s [\Omega]$	0.1	0.1	0.2	0.2	0.15	0.15
$R_{SH} [\Omega]$	238	238	$2.0 \cdot 10^7$	$2.0 \cdot 10^7$	$1.8 \cdot 10^5$	<i>$1.4 \cdot 10^5$</i>
$I_{01} [A]$	$6.0 \cdot 10^{-6}$	$6.0 \cdot 10^{-6}$	$5.0 \cdot 10^{-19}$	$5.0 \cdot 10^{-19}$	$5.5 \cdot 10^{-19}$	<i>$7.6 \cdot 10^{-19}$</i>
m_1	1.0	1.0	1.0	1.0	1.4	1.4
$I_{02} [A]$	$3.0 \cdot 10^{-5}$	<i>$3.5 \cdot 10^{-5}$</i>	$4.1 \cdot 10^{-11}$	<i>$4.8 \cdot 10^{-11}$</i>	$4.4 \cdot 10^{-12}$	<i>$7.7 \cdot 10^{-9}$</i>
m_2	2.0	2.0	2.0	2.0	2.65	<i>4.8</i>
$I_L [A]$	$1.4 \cdot 10^{-1}$	$1.4 \cdot 10^{-1}$	$7.1 \cdot 10^{-2}$	$7.1 \cdot 10^{-2}$	$6.7 \cdot 10^{-2}$	$6.7 \cdot 10^{-2}$

3.2. Isotype Ga(In)As middle cell

For the Ga(In)As isotype cell, **Figure 2a** shows the forward dark I-V curves measured in the *non-stressed measurement* (open circles) and after the application of the largest reverse bias of -17 V (solid squares), which corresponds to ~110% of the calculated $V_B = -15.6$ V for this subcell. Once again, the differences between the two curves are minimal, meaning that the device has suffered almost no damage during the test (and so again we do not include in the figure the curves after intermediate reverse bias stresses at -4 V, -8 V and -13 V, representing around 25%, 50% and 75% of our estimated V_B). In order to analyse the changes in the parameters of the device, Figure 2a also shows the fitted forward dark I-V curves before (blue line) and after (red line) the reverse bias was applied. The most relevant parameters of both fitted curves are again gathered in Table 1. As expected, only a very slight increase in the reverse saturation current I_{02} can be observed, as in the Ge subcell. Nevertheless, the change

is too small to be an unequivocal indication of any type of damage or premature deterioration of the device. The lighted I-V curve and the corresponding fit are shown as an inset in Figure 2a. As expected from the accurate modelling of the dark I-Vs, the curve is well reproduced by the models using the parameters in Table 1.

Figure 2b plots the reverse dark I-V curve of the device after the maximum stress of -17 V (solid squares), together with two simulation attempts using different shunt resistance values (green and magenta lines in Figure 2b). In this case, the Spirito-Albergamo model is not able to reproduce the behaviour of the measurements in the full voltage range (with $n = 3$ and $V_B = -15.6$ V). When a high R_{SH} —same as the one used for the forward dark I-V fit—is considered, a good fit is obtained for voltages between 0 V and -3 V, but the current is heavily underestimated for voltages below that point (green line in Figure 2b). On the other hand, if a smaller value for R_{SH} is considered, the fitted curve is almost identical to the measured curve for voltages below -13 V, but the current is heavily overestimated for the rest of the range (magenta line in Figure 2b).

This behaviour indicates an intensification of the leakage currents as the reverse voltage applied increases in magnitude. Mathematically, this can be modelled by a shunt resistance that decreases exponentially as the reverse bias increases, as can be deduced from the linear behaviour of the I-V curve when plotted in a logarithmic scale. Following this approach, if the shunt resistance is modelled with the expression in the label of Figure 2b, a reasonably good fit can be obtained in the full range measured (red line in Figure 2b). Possible physical causes behind such uncommon modelling of the shunt resistance will be discussed later in section 3.4. However, if we take into consideration that the forward dark I-V curves in Figure 2a do not show any sign of damage, the changes observed in leakage currents seem reversible and only affecting the reverse bias I-V. We hypothesise that this behaviour could be associated to the electrical properties of a small concentration of crystal defects present in the Ga(In)As material (as perhaps a minute concentration of dislocations). Once the reverse bias is high

enough, these defects could show a rapid increase in electrical conductivity that steadily lowers the shunt resistance and subsequently boosts the leakage currents. Once the reverse bias is decreased or the device reaches forward bias, the R_{SH} recovers its original value.

Figure 2. (a) Forward dark I-V curves of the Ga(In)As component cell before any reverse bias (open circles) and after the maximum stress at -17V (solid squares); the corresponding fits are included as solid lines. The inset represents the lighted I-V curve and its corresponding fit. (b) Reverse dark I-V curve of the same cell and three fit attempts with the S-A model: two fits (green and magenta lines) using different fixed values for R_{SH} and one fit (red line) using a voltage-dependent R_{SH} value of $R_{SH} = 5 \cdot 10^8 V^{-3.6} \Omega$.

The evolution described by Figure 2, summarizes the general performance under reverse bias of the cohort of devices measured. However, we found a specific specimen with a particular behaviour in reverse bias which is shown in **Figure 3** (solid red triangles), together with the typical behaviour of Figure 2b (solid black line). The first thing to note is that the shunt resistance of the anomalous device is much lower. Additionally, two specific features – marked with vertical arrows– stand out. At around -9.2 V, there is a sudden shift of the curve towards greater leakage currents, i.e. an abrupt decrease of the R_{SH} . Between -9.2 V and -10.6 V the curve stabilises but around -10.6 V another sudden increase in the current occurs, this time causing a catastrophic failure in the device, which becomes totally and permanently shunted. For the moment, we will just conclude that among the population of isotype middle

cells analysed a particular device showed an increased vulnerability vs. reverse bias damage. As this behaviour is also observed in isotype GaInP top cells, we will discuss it further in the following section.

Figure 3. Reverse bias dark I-V of a Ga(In)As component cell showing an abrupt damage event and catastrophic failure. The reverse bias dark I-V of the well-behaved cell from Figure 2b is also plotted as a solid line for comparison.

3.3. Isotype GaInP top cell

GaInP component subcells were subjected to several steps of reverse bias stress ending at -4 V, -5 V and -6 V, respectively. **Figure 4a** shows the forward dark I-V curves obtained for each step as well as for the original non-stressed device. It has to be noted that, although its calculated breakdown voltage is the largest among the three subcells of the triple junction stack -around -21.0 V-, the device shows a clear degradation after the initial stresses in reverse bias, as evidenced by the change in the shape of the different I-V curves in Figure 4a. For this reason, in order to avoid introducing further damage, the reverse bias experiments were interrupted after the -6 V step.

Figure 4. (a) Forward dark I-V curves of the GaInP component cell before any reverse bias (open circles) and after reverse bias stress at -4 V (squares), -5 V (stars) and -6 V (triangles); the corresponding fits are included as solid lines. The inset represents the lighted I-V curve and its corresponding fit. (b) Reverse dark I-V curves of the same cell.

The fits obtained for the four I-V curves are also shown in Figure 4a, while their relevant parameters are gathered in **Table 2**. In summary, after the first reverse bias step (reaching -4 V) no significant effect is observed in neither the forward dark I-V nor in the corresponding parameters of Table 2. However, after the -5 V and -6 V reverse bias steps, the degradation of the device manifests as an evident change in the forward dark I-V (curves in stars and triangles in Figure 4a) and a notable variation of their parameters in Table 2. This change is especially notorious in the saturation currents (I_{01} and I_{02}), especially in I_{02} as its value increases almost two orders of magnitude; whilst the associated parameter m_2 also shows an important degradation, as it almost doubles its original value. Moreover, it is also noteworthy that after the -5 V step a 25% decrease in the value of the shunt resistance (R_{SH}) can also be observed.

The lighted I-V curve and the corresponding fit are shown as an inset in Figure 4a. Again, as expected from the accurate modelling of the dark I-Vs, the curve is well reproduced by the models using the parameters in Table 2.

Table 2. GaInP component cell: Relevant parameters for the fitted I-V curves. The parameters that suffer some variation after each stress step are indicated in italic font

	Non-stressed	Stress at -4V	Stress at -5V	Stress at -6V
R_s [Ω]	0.15	0.15	0.15	0.15
R_{SH} [Ω]	$1.8 \cdot 10^5$	$1.8 \cdot 10^5$	<i>$1.4 \cdot 10^5$</i>	$1.4 \cdot 10^5$
I_{01} [A]	$5.5 \cdot 10^{-19}$	$5.5 \cdot 10^{-19}$	<i>$6.1 \cdot 10^{-19}$</i>	<i>$7.6 \cdot 10^{-19}$</i>
m_1	1.4	1.4	1.4	1.4
I_{02} [A]	$4.4 \cdot 10^{-12}$	$4.5 \cdot 10^{-12}$	<i>$1.9 \cdot 10^{-10}$</i>	<i>$7.7 \cdot 10^{-9}$</i>
m_2	2.65	2.65	<i>3.4</i>	<i>4.8</i>
I_L [A]	$6.7 \cdot 10^{-2}$	$6.7 \cdot 10^{-2}$	$6.7 \cdot 10^{-2}$	$6.7 \cdot 10^{-2}$

The dark I-V curves measured for the reverse voltages studied are represented in Figure 4b. Let us analyse the reverse bias experiment step by step, starting from the lowest voltage (-4 V). Similar to what happened with the middle cell, the S-A model fails to reproduce the behaviour of the curve. Again, as it happened with the middle cell, to model the reverse I-V an exponential reduction of R_{SH} vs. voltage needs to be considered and, once we finish the reverse bias experiment, the forward dark I-V seems almost unaltered (see curves in open circles and solid squares in Figure 4a). When we start the second reverse bias step –aiming at reaching -5 V– the curve evolves as expected (overlapping the -4 V curve) until a sudden change occurs at -4.1 V, marked with the first green arrow in Figure 4b. At this particular value, an abrupt shift in the leakage current has taken place. Afterwards, on the way to the final target of -5 V, a second jump occurs (second green arrow in Figure 4b) and then the curve seems stabilised again at much lower values of R_{SH} . This time, the subsequent forward I-V curve (star symbols in Figure 4a) does show a notable change at lower currents and the shunt resistance value needed to fit the curve has decreased 25%. Finally, at the third reverse bias step –aiming at reaching -6 V– the evolution starts at much lower values of R_{SH} and virtually converges to overlap with the final part of the -5 V curve until a new abrupt degradation event occurs at -5.1 V (marked with a magenta arrow in Figure 4b). Conversely

to what happened with the middle cell (where just one device showed these sudden damage events), all GaInP top cells measured suffered this abrupt degradation events when reverse biased beyond -4V. Given the fact that further reverse bias stress, caused a catastrophic failure in the middle cell of Figure 3, we decided to interrupt the reverse bias test at -6 V.

3.4. Discussion on the mechanisms behind the reverse I-V of top and middle subcells

Under the light of the experiments summarized in Figures 2 to 4, it seems clear that the reverse currents in Ga(In)As middle cells and GaInP top cells do not follow carrier multiplication as predicted by Spirito-Albergamo models but experience a larger than forecasted surge. In other words, the leakage paths responsible for the reverse conductance in both isotype solar cells increase their conductivity with applied reverse voltage, giving rise to a so-called a *soft-breakdown* process until the final breakdown voltage is reached. The origin of leakage currents in different types of p/n junction diodes is typically ascribed to conduction through defects in the crystal structure, specially to those that can punch through the junction, such as dislocations.^[10] Even though both Ga(In)As and GaInP subcells are grown lattice-matched to the substrate with a high degree of crystalline perfection, a minute amount of crystal defects –dislocations among them– is always expected to be present.

The electrical behavior of dislocations in different III-V materials has been studied using C-AFM measurements.^[11] It was shown that defective areas around dislocations show a higher conductivity and also show locally reduced breakdown voltages as compared to nearby material with greater crystalline perfection. Furthermore, such enhanced conductivity was demonstrated to change with applied bias and repeated measurements –for example after several forward and reverse I-V measurements–. Initially, defects show a minimum conductivity, which is then followed by a stable state with intermediate conductivity and, if higher voltages are applied for long enough, the current abruptly increases and a state of

minimum resistivity is reached. The origin of all these phenomena was related to the activation of defects in the semiconductor material which can be charged/discharged during the reverse voltage ramp, affecting the site conductivity.^[11]

We hypothesize that this explanation agrees well with the phenomenology observed in Figures 2 to 4. A voltage dependent conductivity –or, in other words, a voltage dependent effective shunt resistance– could explain the anomalous growth of leakage currents in figures 2.b and 4.b. So our hypothesis is that increasing reverse bias initially augments the conductivity of defect sites present in the crystal, dynamically creating low resistance paths, as it was observed for dislocations.^[11] Once reverse bias ceases, the structure returns to its original state and thus no change in the subsequent forward I-V would be observable (as in Figures 2.a and b and the red curves in Figures 4.a and 4.b). At this stage, we believe that defects are operating without a significant change in their structure. On the other hand, further stress in reverse bias would trigger a modification in the defect structure, which would in turn lead to its minimum conductance state, giving rise to the abrupt shift in the leakage current observed in some reverse I-Vs in Figures 3 and 4.b. At this point, the energy supplied has changed the defect structure –for example by point defect capture, dislocation structure modification or free charge trapping– and thus a change in its conductance and recombination properties remains and is measurable in subsequent forward or reverse I-Vs (as in Figure 4.b). Further reverse bias stress beyond this point inevitably leads to either a new abrupt damage event or to the catastrophic failure of the device.

In order to check the validity of this hypothesis we studied the evolution of reverse bias I-Vs of Ga(In)As and GaInP isotype cells over time. It was reported that the state of minimum conductivity of defect sites was reversible since, given long enough time, the defect tends to return to its thermodynamically stable structure.^[11] **Figure 5** represents several I-V curves under reverse bias taken on the same device after different waiting times at room temperature. Figures 5.a and b correspond to Ga(In)As Isotype cells whilst Figures 5.c and d are for isotype

GaInP cells. In the initial curve in Fig 5.b (open circles) an abrupt degradation event is observed close to -12V. In the second curve, taken immediately after (filled squares), the leakage current has increased accordingly. Finally, in the third curve taken after 2 hours (stars), the reverse I-V seems to have slightly recovered towards the original state. The corresponding forward dark I-V curves in Fig 5.a follow the same degradation and partial recovery trend. The same curves in Figs. 5c and d present a similar behaviour for isotype GaInP cells, being the degree of recovery quite small in this case.

Figure 5. (a) Forward dark I-V curves of the middle Ga(In)As isotype cell (b) Reverse dark I-V curves of the middle Ga(In)As isotype cell (c) Forward dark I-V curves of the top GaInP isotype cell (d) Reverse dark I-V curves of the top GaInP isotype cell. The inset represents the microplasma noise patterns measured at -3.5 V for the reverse current of the top GaInP isotype cell.

Another piece of evidence that supports this hypothesis comes from the observation of microplasma noise in III-V solar cells.^[12] In essence, this phenomenon occurs when under reverse bias the high electric field at structural defects (such as dislocations, stacking faults, or precipitates) or areas of mechanical damage creates localized high conductivity paths or hotspots. When such defect sites are reverse biased, they show complex current fluctuations, which in the simplest cases entail the random oscillation of the current between two levels.^[12] This phenomenon has clear connections with our explanation –leakage current flowing mainly through defect sites exhibiting fluctuating conductance– and so we decided to search for evidence of microplasma noise in our isotype solar cells. The results of these experiments are summarized in the inset of Figure 5d, where we present unequivocal microplasma noise patterns for the reverse current of the GaInP top cell. A detailed study on how this microplasma noise is related to the reverse bias I-V of the isotype cells and their evolution over time is beyond the scope of this work. However, we believe that its presence is consistent with the hypothesis presented.

Going back to Figures 2 and 4, we can say that the middle cell seems more resilient to reverse bias damage than the top cell. Within the limited experimental set that we could analyse, only two Ga(In)As devices experienced abrupt damage events and eventually catastrophic failure. On the contrary, for GaInP top cells, all the cells measured presented abrupt damage events that, in addition, took place at notably lower voltages. This seems to indicate that the crystal defects behind this behaviour are more abundant in GaInP than in Ga(In)As or that specific phenomena present in GaInP alloys (phase segregation, ordering, ...) have an impact on damage events under reverse bias.

3.5. Triple-junction solar cells

Figure 6a and **b** represent the dark and lighted I-V measurements of GaInP/Ga(In)As/Ge triple-junction solar cells at different stages in our experiments. In Figure 6a, the initial

forward dark I-V curve measured (open circles) together with its fit (solid blue line) are represented. Such fit was reached using for each subcell the parameters in Table 1, obtained for non-stressed isotype subcells and just making minor corrections on the top cell (increasing from $I_{02} = 4.4 \cdot 10^{-12}$ A to $I_{02} = 9.5 \cdot 10^{-12}$ A, as shown in the first column of **Table 3**), which produced a remarkably accurate result. Figure 6b shows the initial lighted I-V curve – measured under AM0 spectrum right after the dark I-V was taken, sweeping from V_{OC} to I_{SC} – with again its corresponding fit using the same parameters of Table 1 and Table 3 and taking into consideration the photocurrent produced by each subcell (last row in Table 1). The fact that each subcell produces a different photocurrent, being the GaInP top cell the limiting subcell (in the beginning of life condition), implies that during the lighted I-V measurement the GaInP cell is, at some point, stressed under reverse bias. This is best explained considering the simulated lighted I-V curves of each component cell plotted in Figure 6b as red, green, and cyan dotted lines. When the top cell starts to limit the current of the device – i.e. around the maximum power point of the multijunction cell –, both the bottom and middle cell remain anchored at voltages close to their respective V_{OC} s, and only the voltage at the top cell (V_{TC}) decreases to produce a given multijunction solar cell voltage (V):

$$V_{TC} = V - V_{OC,MC} - V_{OC,BC} \quad (3)$$

As Equation (3) evidences, under illumination, the voltage at the top subcell is always lower than the overall voltage at the triple-junction by an amount approximately equal to the sum of the V_{OC} s of the bottom and middle cells (~ 1.3 V). For instance, when the multijunction is at I_{SC} ($V = 0$), this is the result of both middle and bottom subcell being very close to their respective V_{OC} , whereas the top cell being biased at exactly the opposite reverse bias to produce a net zero algebraic sum of voltages. In the case of Figure 6b this means that the initial lighted I-V measurement, which has reached a reverse bias of -3.5 V, has in reality subjected the top cell to approximately -4.8 V, whereas it has entailed no reverse bias stress for neither the bottom nor the middle subcells. As shown in Figure 4b, in our analysis of

isotype GaInP top cells, reverse voltages below -4 V brought about abrupt degradation events which modified the reverse and forward I-V of the top subcell. Figure 6a shows in solid squares the dark I-V of the same triple junction solar cell after the initial lighted I-V measurement. As expected, the dark I-V has changed showing evidence of some damage just after the lighted I-V measurement, which can be quantified by the change in the parameters shown in Table 3. So the mere lighted I-V measurement of the triple-junction causes a degradation that can be quantified as a decrease in the shunt resistance of the top cell and an increase in both its recombination currents I_{01} and I_{02} . The change in these parameters – sparked by a reverse bias of ~ -4.8 V – is in agreement with what was observed in the former section as it lies quantitatively in-between the changes observed in the isotype GaInP subcell for reverse bias of -4V and -5V (second and third column in Table 2, respectively). In addition, the degradation of the top subcell can be even appreciated in the reverse bias stretch of the lighted I-V curve. The red rectangle included as an inset in Figure 6b magnifies the lighted I-V curve and its fit between -3V and -3.5V. In this range, the experimental I-V curve (open circles) lies clearly above the fit (blue line), evidencing that the leakage currents in reverse bias are larger than those considered in the fit and this is compatible with a decrease in the effective shunt resistance in the subcell which is limiting the current, i.e. the GaInP top cell.

Table 3. Relevant parameters of the top cell in the triple-junction solar cell. The parameters that suffer some variation after the lighted I-V measurement are indicated in italic font

	Non-stressed	After lighted I-V
R_s [Ω]	0.15	0.15
R_{SH} [Ω]	$1.8 \cdot 10^5$	<i>$1.0 \cdot 10^5$</i>
I_{01} [A]	$5.5 \cdot 10^{-19}$	<i>$5.7 \cdot 10^{-19}$</i>
m_1	1.4	1.4
I_{02} [A]	$9.5 \cdot 10^{-12}$	<i>$1.5 \cdot 10^{-11}$</i>
m_2	2.65	2.65
I_L [A]	$6.7 \cdot 10^{-2}$	$6.7 \cdot 10^{-2}$

Figure 6. (a) Forward dark I-V curves of the triple-junction solar cell before any reverse bias (open circles), and right after the lighted I-V measurement (solid squares); the corresponding fits are included as solid lines. (b) Initial lighted I-V measurement of the triple-junction solar cell (open circles); the corresponding fit is included as a solid line, whereas the modelled I-V curves for each subcell as dotted lines.

In summary, the analysis of the lighted I-V of the triple junction reveals that, as a result of the current imbalance between subcells, the top subcell suffers from a reverse bias stress even during a mere one-sun measurement under forward bias. Such a reverse bias stress sparks a degradation that follows the same behaviour as observed in isotype GaInP subcells.

Additional experiments are ongoing in order to gain further insight into the physical processes behind the atypical behaviour and sudden parameter changes observed during the measurements taken during the realization of this this work.

4. Conclusion

In this work we have carried out a detailed analysis of the most relevant changes observed when reverse biasing the three different isotype single junction cells that constitute a GaInP/Ga(In)As/Ge triple-junction solar cell. To this end, the cells were submitted to increasing reverse bias stress steps, I-V curves were measured under light and dark conditions

afterwards, and their characteristic parameters were fitted using Shockley's equation for the forward region and Spirito-Albergamo model for the reverse bias.

The analysis showed that each subcell changed its behaviour in a different manner after the reverse bias stress. Specifically, the isotype Ge bottom subcell followed closely the Spirito-Albergamo model and the subcell parameters showed almost no change after the reverse bias test. Thus this subcell suffers no significant damage in reverse bias, fact that could be related with the high leakage currents naturally present in Ge solar cells, which somewhat protect the device from further damage.

The isotype Ga(In)As subcell did not manifest significant changes in its I-Vs after the reverse bias test either. However, in this case its reverse I-V curve could not be reproduced with the classic Spirito-Albergamo model. Only if a dynamic R_{SH} is considered—in particular an effective R_{SH} value decreasing exponentially with voltage under reverse bias—, then a very accurate fit can be achieved. Such a dynamic behaviour of R_{SH} only affects the reverse bias, turning to its “normal” value when the device is forward biased again. Our hypothesis is that this phenomenon may be associated to a small concentration of crystal defects present in the material, which turn into low resistance paths when the reverse bias is high enough, rapidly boosting the leakage currents of the device. However, small concentrations of defects are to be expected in any semiconductor and thus they should not be considered as an indicator of a low-quality device.

In the isotype GaInP top subcell showed clear degradation signs after each step in the reverse bias test. As with the Ga(In)As middle cell, a variable effective R_{SH} needed to be included in the Spirito-Albergamo model to reproduce the reverse I-V. At low reverse voltages, the R_{SH} decreased its value exponentially, returning to its usual value once the device was forward biased again (analogously to what was observed in the middle subcell). However, after certain reverse voltage threshold, the device showed an abrupt and irreversible decrease in R_{SH} (and increase in recombination currents I_{01} and I_{02}). Further reverse biasing of the cell led to new

abrupt damage event or even to the catastrophic failure of the device. This type of sudden degradation event was observed in all the GaInP devices measured, as well as one of the Ga(In)As isotype cells (middle subcell). Although the exact physical process behind this sudden change is yet to be understood, our hypothesis is that the energy provided by high reverse bias changes the structure of a defect site flipping to a state of minimum resistance, which abruptly increases leakage currents. Such structural change remains measurable altering both the reverse and forward I-V of the subcell. However, the original non-degraded I-Vs of the cells can be recovered (at least partially) if the cells are left stored unbiased for several hours.

Finally, complete triple-junction solar cells were tested in the dark and under AM0 spectrum reaching a moderate reverse bias. The initial dark measurements could be reproduced quite accurately combining the parameters obtained for each isotype subcell. The analysis of the lighted I-V revealed that, as a result of the current imbalance between subcells, the top subcell suffers from a reverse bias stress even during a mere one-sun measurement under forward bias. Such a reverse bias stress sparks a degradation that follows the same behaviour as observed in isotype GaInP subcells. However, the degradation observed in this work occurs at reverse bias voltages which will never be reached in the in-orbit operation of the triple junction solar cell, thanks to the protection provided by the bypass diode. Further experiments are ongoing to clarify the physical origin of the degradation events observed.

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