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RESEARCH ARTICLE

Spectral and dynamical study of III–V triple junction solar cells and the application to multiflash I–V measurement

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ABSTRACT

This paper presents a method to predict the I–V characteristic of triple junction InGaP/GaAs/Ge solar cells when different illumination spectra are used, and it is based on the measurement of a set of commercial isotype cells together with numerical simulations. The study includes the utilization of continuous and pulsed light sources. Several spectra were considered for the continuous light sources, where different subcells limit the current of the tandem cell. For pulsed light sources, a dynamical analysis was carried out by simulating a triple junction cell through PSpice software. For the simulations, the subcell capacitances were estimated and introduced into an electrical model of the triple junction. When a fast pulse in the multiflash I–V measurement technique is used, dynamical effects associated with this kind of source were observed and accounted for by the simulations. It was established that the dynamical effects did not affect the I–V characteristics measured with this technique. Finally, the proposed method and analysis were successfully applied to the electrical characterization of the Aquarius/SAC-D Argentine satellite solar array modules.

KEYWORDS

multijunction; solar cell; transient effects; flash

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1. INTRODUCTION

Triple junction (TJ) solar cells based on III–V materials (InGaP/GaAs/Ge) are widely used in space applications mainly due to their high efficiencies and radiation damage resistance. These solar cells consist on epitaxial monolithic growth of three subcells interconnected in series trough tunnel diodes with a standard two-terminal contact. Thus, the subcells are not accessible separately, therefore challenging the determination of their I–V characteristics. This internal connection of the subcells produces a highly sensitive I–V response based on the illumination spectrum because the tandem current will be limited by the subcell with the lowest photocurrent.

In this sense it would be ideal accessing to each subcell from the TJ cell in order to obtain their I–V curve, and then using superposition to reproduce the I–V curve of the TJ cell for the desired illumination spectrum. There are some precedents where models and protocols were proposed for this when two terminal monolithic devices are studied and thereby the electrical contacts of subcells are not accessible. As an example, the work of Kurtz et al. [1] presents a method to obtain the individual I–V curve of a subcell from a double junction solar cell and then it uses superposition to obtain the multijunction I–V curve. However, the particular algorithm presented loses accuracy when it is applied to TJ cells. On the other hand, Dominguez et al. [2] propose a method to determine the I–V curve of a TJ solar cell as a function of the spectrum and irradiance. This complex method was only validated with a pulsed solar simulator for light intensities greater than 100 suns. Also, it does not assess the possible dynamic effects that may occur due to the use of a pulsed solar simulator. Previous reports have presented transient effects that modify the I–V response of a solar cell [3–5], but little is known about how such effects alter the cell response when I–V multi-flash method is utilized.

The utilization of a pulsed Xe flash is important not only for the measurements of concentration solar cells in a lab, but also is an inexpensive way of measuring large area modules, and it is also easily transportable (for example during a spacecraft test qualification campaign) [6]. The Xe flash spectrum differs from the AM0 standard, and it is difficult to perform a spectral distribution measurement due to the pulse short duration and the extended wavelength range associated to multijunction cells spectral response [7]. Therefore, it is necessary to simulate the I–V curve of a solar module illuminated under AM0 spectrum to determine the percentage error when such module is measured with other spectrum out of standard.

In this paper we propose a simple method to determine the I–V characteristic of an InGaP/GaAs/Ge TJ solar cell under any desired illumination spectrum and irradiance based in the measurement of the three isotype cells, using an inexpensive solar simulator. The method is experimentally validated by several measurements for different light spectra, included a pulsed solar simulator (Xe arc lamp). Also, a detailed dynamical analysis was performed for the case of a fast Xe arc lamp in order to evaluate transient effects due to the fast illumination pulse. To determinate the origin of these effects, a three diode based model for a triple junction solar cell was developed using PSpice software [8]. In this model, the capacitance of each individual subcell was included, and their values were estimated by C–V measurements of isotype cells. Finally, taking into account the two analyses presented, a solar array module of the SAC-D/Aquarius satellite [9–11] was simulated in order to estimate the errors made during measurements performed out of standard.

2. METHOD TO DETERMINE THE I–V CHARACTERISTIC OF A MULTIJUNCTION SOLAR CELL

For this work, four commercial III–V cells (Emcore Co.; area: 27 cm^2), were used: one triple junction InGaP/GaAs/Ge cell and three isotype cells corresponding to each single junction, top, middle and bottom isotypes. Strictly speaking, the GaAs cell material has 1% of In to achieve lattice matching with the Ge substrate; from now on, we mean GaAs cell as $Ga_{0.99}In_{0.01}As$ cell. The cell calibration was provided by the manufacturer for both, spectral response and short circuit current at 1.367 kW/m^2 AM0 irradiance. The isotype cells have an identical layer structure of the TJ, and consist of an InGaP cell (300–650 nm response) with an underlying Ge junction, a GaAs (650–900 nm response) cell also with an underlying Ge subcell and a homojunction Ge cell (900–1800 nm response). Thus, the spectral responses of the isotype cells are equal to that from each subcell in the TJ due to the optical filtering of the upper layers, and isotype InGaP and GaAs cells are actually InGaP/Ge and GaAs/Ge double junction cells. In this manner, the value of the photocurrents generated by the three components of the tandem, for a given light spectrum, could be estimated by measuring the short circuit current generated by each isotype cell if the Ge subcell does not limit the current for all cases.

This method supposes that the I–V curve from the isotype cells matches the I–V curve of each subcell in the multijunction structure, and also it neglects the impact of the tunnel junctions on the I–V characteristics. The following steps are used in order to determine the I–V curve of a triple junction InGaP/GaAs/Ge solar cell under any desired illumination source:

1) *Measure the I–V curve of the three isotype cells using a continuous and stable solar simulator, at an irradiance close to 1.367 kW/m^2 and at a fixed temperature.* It is not necessary that the light source spectrum concurs with a standard one, allowing the solar simulator to belong to class C for instance. There is just one limitation: if the Ge subcell of the isotypes limits the photocurrent for a given spectra, the application of this method would be incorrect. The I–V curves of the isotype cells are just measured once.
2) *Subtract the I–V curve of the Ge isotype cell from the InGaP/Ge and GaAs/Ge isotype cells I–V measurement.* The calculating method is described in [1] and it consists on subtracting the voltages of the I–V curves at a fixed current value for each point, i.e.:

$$V_{\mathrm{InGaP}}(I) = V_{\mathrm{InGaP/Ge}}(I) - V_{\mathrm{Ge}}(I) \quad (1)$$

$$V_{\mathrm{GaAs}}(I) = V_{\mathrm{GaAs/Ge}}(I) - V_{\mathrm{Ge}}(I) \quad (2)$$

where $V_{\mathrm{InGaP/Ge}}(I)$, $V_{\mathrm{GaAs/Ge}}(I)$ and $V_{\mathrm{Ge}}(I)$ are the I–V curves measured at the previous step. The result of this subtraction gives numerical InGaP and GaAs I–V subcell curves ($I_{\mathrm{InGaP}}(V)$, $I_{\mathrm{GaAs}}(V)$ respectively). This correction is not necessary for the Ge subcell since it is already a single junction cell.

3) *Subtract the short circuit current from the numerical I–V subcell curves*. These new curves are considered as the dark I–V curves ($I_i^{\mathrm{dark}}(V)$):

$$I_i^{\mathrm{dark}}(V) = I_i(V) - I_{SC,i} \quad (3)$$

where $I_{SC,i}$ is the short circuit current of i subcell, with i equals to InGaP, GaAs and Ge subcells.

4) *Using the desired light source, measure the three short circuit currents of the isotype cells.*

These values ($I_{SC,i}^{\mathrm{desired}}$) are used as photocurrent of the subcells, and will be added to the previous dark curves to obtain the illuminated I–V subcell curves with the desired spectrum ($I_i^{\mathrm{desired}}(V)$):

$$I_i^{\mathrm{desired}}(V) = I_i^{\mathrm{dark}}(V) + I_{SC,i}^{\mathrm{desired}} \quad (4)$$

Another way to estimate the short circuit currents is by using equation 5 if the spectral response of each subcell and the spectral irradiance of the light source are well known,

$$I_{SC,i}^{\text{desired}} = \int SR_i(\lambda) f(\lambda) d\lambda \qquad (5)$$

where $SR_i(\lambda)$ is the spectral response of each subcell, $f(\lambda)$ is the spectral irradiance of the desired light source and λ is the wavelength.

5) *Sum the three I–V subcell curves to obtain the modelled TJ I–V characteristic for the desired spectrum.* This is achieved by adding the subcell voltages at a fixed current for each point, as described in step 2:

$$V_{TJ}(I) = V_{\text{InGaP}}^{\text{desired}}(I) + V_{\text{GaAs}}^{\text{desired}}(I) + V_{\text{Ge}}^{\text{desired}}(I) \qquad (6)$$

It must be noted that the predicted I–V curve is valid for the same temperature at which the isotype cells were measured. The corresponding temperature corrections will be necessary to predict the I–V curve at a different temperature. The correction details can be found elsewhere [2,12,13].

3. VALIDATION OF THE MODEL FOR CONTINUOS SOLAR SIMULATORS

In order to validate the proposed method, various measurements with different light spectra including dark conditions were performed. The illumination sources used in this work were: a tungsten halogen lamp with a dichroic back reflector, named 'dichroic lamp' from now on, a TS-Space 'close match AM0' solar simulator, dark conditions, and finally a commercial flash lamp that will be studied in the next section. For clarity, we will refer as *top*, *middle* and *bottom* cells for the InGaP, GaAs and Ge subcells, respectively, throughout the paper.

The first spectrum was provided by a 250-W dichroic lamp with a DC stabilized power source at an equivalent irradiance of about 1367 W/m^2. I–V measurements were performed with a Keithley 2602A SMU unit in the four wire mode, and the cell temperature was controlled at 28 °C. Under these conditions, the I–V curve of the three isotype cells and the TJ cell were measured, and the numerical dark I–V curve of the top and middle subcells were obtained according to steps 2 and 3 of the procedure mentioned in the previous section (Figure 1). Subsequently, by using the I_{SC} values of the isotype cells, the three illuminated I–V subcell curves were added in order to obtain the I–V model of the TJ cell. Figure 1 also shows the comparison of the I–V curves between the predicted and the measured TJ cell. The dichroic lamp spectrum causes the middle subcell to limit the tandem current, which is quite different from the solar AM0 spectrum where the limiting

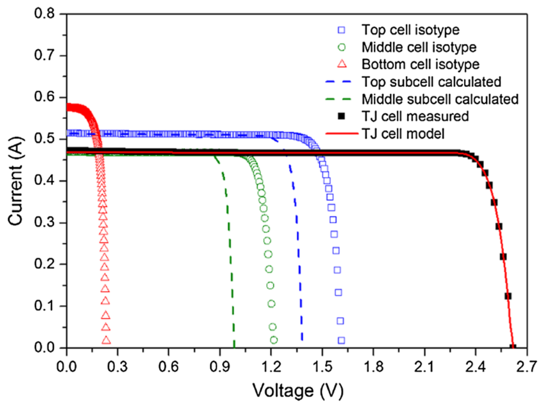

Figure 1. Measured I–V curves of the three isotype cells (hollow symbols), the calculated top and middle subcells (dashed lines), the measured and the modeled TJ cell are also illustrated (filled square and solid line, respectively). All measurements were performed at 28 °C using a 250-W dichroic lamp.

subcell is the top one. However, the proposed method reproduces the measured I–V curve of the TJ cell: the error estimation at the maximum power point (MPP) given by the percentage difference between the experimental and the modeled curve is −1.6%, while the RMS error calculated following the procedure used by Dominguez et al. [2] results 0.79%. The numerical dark I–V curves calculated with this spectrum will be used in this work in order to model the I–V curve of the TJ for the next spectra.

In the second case analyzed, an AM0 close match solar simulator (TS-Space) was used. This simulator provides a spectrum very similar to the standard AM0 and in this case the subcell limiting the tandem current is the top cell, as appreciated in Figure 2. The same figure shows the bottom subcell generating about the double photocurrent than the top and mid subcells. These two characteristics indicate that this spectrum is quite different than that of the dichroic lamp, and therefore it reflects a new condition to test the proposed method.

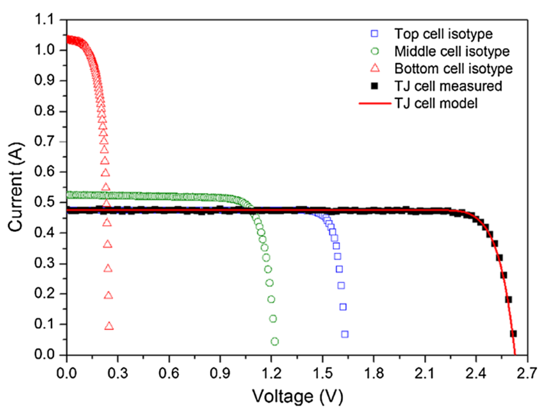

Figure 2. Measured I–V curves of the three isotype cells and the TJ with TS-Space solar simulator. The model for the TJ cell applied in this case is also shown.

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Using the values of I_{SC} measured from the isotype cells for this new spectrum, and according to the step 4 from the procedure detailed in section 2, the I–V prediction for the TJ cell under the TS-Space solar simulator spectrum was obtained and is shown in Figure 2 with a solid line. Despite the large spectral difference between the dichroic lamp and the TS-Space solar simulator, the new estimation shows also a good agreement with the experimental curve giving a percentage difference of 1.3% at the MPP respect to the measurement in the lab, while the calculated RMS error is 0.69%.

The third experimental condition to test the proposed method was dark condition. It means that the I_{SC} used for each subcell model were set to zero and the three I–V curves were directly added. The result is shown in Figure 3 with the experimental I–V curve of the TJ, showing also a good correlation between curves.

In summary, three different illumination conditions were considered, and the models were found in good agreement with the TJ I–V measurements, giving a good grade of validation to the proposed method. In the next section, another verification of the method is presented using a pulsed Xe light source.

4. USING THE MODEL FOR A XENON LAMP SPECTRUM

In this section the procedure described in section 2 is tested for the case of pulsed solar simulator. This kind of light source is based on a Xe arc discharge lamp and represents a very different spectrum scenario. Also this case will be very useful for the analysis addressed in section 6 where the I–V curve of one power module of Aquarius/SAC-D satellite solar array is simulated.

The flash lamp used in this work has a very rapid pulse (less than a fraction of ms), and consequently it is very difficult to measure the entire I–V characteristic from a single shot. Therefore, it is necessary to use the multiflash method [3], where the cell or module under measurement is connected to a variable resistor, which biases it from almost short circuit to open circuit conditions. For each load condition a flash discharge is produced and the device voltage and current is captured with an oscilloscope (the current is calculated by sensing a voltage drop across a calibrated resistor). The I–V pair is obtained from the maximum of the cell voltage and current signals. Finally a reference triple junction cell is used in order to monitor the light intensity of each discharge.

For this measurement we used a Philips 1500-W XOP-15-OF flash lamp, an oscilloscope (Tektronix TDS 3054C) and several discrete resistors ranging from 0.75 Ω to 100 Ω. In Figure 4 the short circuit currents generated by the isotype cells under flash illumination as a function of time are shown. The three measurements show almost the same waveform, corresponding to a fast lamp discharge followed by an exponential decay. To discard spectral shift in the zone of interest (at the maximum of the light pulse) the three curves from Figure 4 were normalized and compared. Although some shift at the decay part of the pulse due to the gas cooling was observed, this shift does not affect the position of the maximum. The top isotype cell waveform presents a small shoulder at the upward stage of the discharge: this effect is related with the dynamic behavior of the cell, and it is analyzed in the next section. Finally, to apply the proposed method, the maximum values reached by each isotype cell under flash illumination are used as I_{SC} values for the model of the TJ I–V curve.

Also, an estimation of the photocurrent of each subcell was performed using the integration of the flash light spectrum, reported by the lamp manufacturer, and the spectral response of each calibrated subcell using equation 5. For convenience, relative values were adopted by dividing all photocurrent by the top cell one. Values obtained are shown in table I, together with the proportions obtained trough pulse amplitude measurements and those calculated

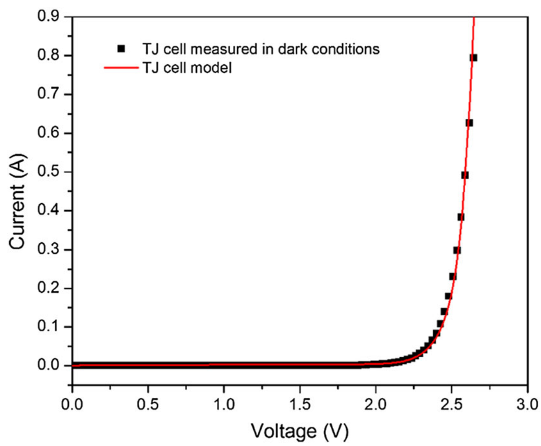

Figure 3. Comparison between the dark I–V curve of a TJ cell and the model with the same conditions using the proposed method.

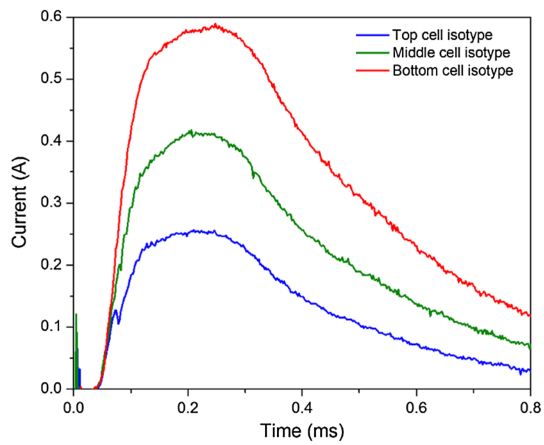

Figure 4. Current pulses obtained at close short circuit conditions for the three isotype cells under flash illumination.

Table I. Relative photocurrents generated by each TJ subcell under flash spectrum, calculated using 5 and measured on isotype cells with the flash lamp. Values corresponding to AM0 spectrum given by the manufacturer are also shown.

	Flash		
Subcell	Calculated	Measured	AM0
Top	1	1	1
Middle	1.7	1.6 ± 0.2	1.1
Bottom	2.4	2.4 ± 0.2	1.9

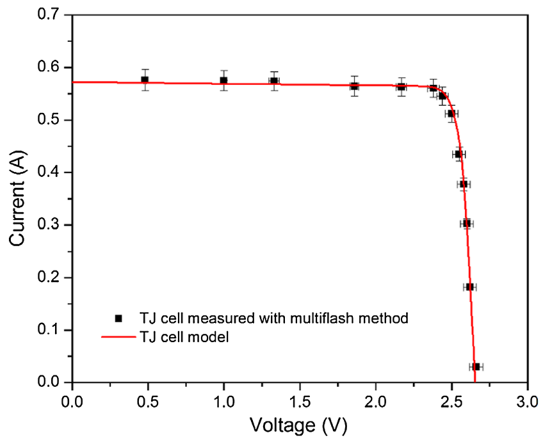

Figure 5. Measured I–V points and the model for a TJ solar cell for the flash spectrum case. The measurements errors correspond to the uncertainty of the oscilloscope.

using the calibrated AM0 I_{SC} given by the manufacturer. As expected, the results of the ratio of the photocurrents are consistent with those measured in the lab. These values suggest that the flash spectrum causes a photocurrent of about +50% for the middle cell and +30% for the bottom case when they are compared to the standard AM0 spectrum. This evidences that the flash lamp spectrum has a bigger relative content of red and infrared light.

In Figure 5, the measured I–V curve of a TJ cell with multiflash method is shown and compared with the modeled curve. For the modeling, the ratios between the subcells I_{SC} currents were taken from the curves presented in Figure 4. The modeled curve (continuous line) and multiflash measurements (discrete points) show differences of 1.2% at the MPP and an RMS error of 0.84%, which validates the applicability of the model for the multiflash method.

5. DYNAMIC ANALYSIS

In the previous section it was shown that the top isotype cell showed some dynamic effect (small shoulder) that occurs at about 70 μs when it was exposed to the flash light pulse (Figure 4). Some studies observed similar effects, but the authors make no mention of it [2,7,14]. To understand the origin of these effects, dynamic simulations using PSpice software [8] were carried out.

In order to study the transient behavior of the triple junction cell when it is excited with the flash pulse, it is necessary to estimate the capacitance of each subcell. Once the values of these capacitances are estimated they are incorporated in a PSpice based dynamic triple junction model. The first step to estimate each subcell capacitance is the measurement of C–V curves from the isotype cells. The work of Ruiz et al. [15] shows that the multijunction cell capacity decreases when illuminated. But since we need to obtain an upper limit for the values, capacitance measurements were performed at dark conditions. The C–V measurements were acquired with an Agilent E4980A LCR meter, and the frequency was set as the inverse of the typical time duration of the flash pulse (200 μs), i.e. 5 kHz.

Figure 6 shows the C–V curves obtained for the three isotype cells and the TJ cell. The qualitative behavior of the four curves is similar, showing a slow growing and an abrupt falling, as previously reported. [15,16].

As it is known, the inverse of the capacity of a multijunction cell (C_{TJ}) is the sum of the inverses of each subcell (C_i),

$$\frac{1}{C_{TJ}} = \sum_i \frac{1}{C_i} \tag{7}$$

In particular, the top and middle cells are isotype double junction, so that their respective capacities are given by

$$\frac{1}{C_{top\ \ isotype}} = \frac{1}{C_{top}} + \frac{1}{C_{bottom}} \tag{8}$$

$$\frac{1}{C_{mid\ \ isotype}} = \frac{1}{C_{mid}} + \frac{1}{C_{bottom}} \tag{9}$$

In order to establish a minimum and a maximum value for each subcell capacitance for the TJ model, the

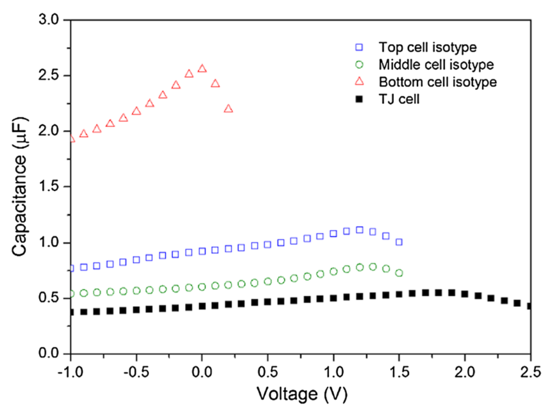

Figure 6. C–V curves of the three isotype cells and TJ with an area of 27 cm^2. Measurements were taken at 5 kHz, under dark conditions and at room temperature.

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following analysis was performed. The maximum and minimum values for the Ge subcell are directly taken from their own C–V curve. For the top and middle capacitances, their maximum values are estimated considering the minimum Ge capacitance and the maximum capacitance from the isotype cells, using equations 8 and 9. Finally, the minimum values for the top and middle capacitances are estimated considering the maximum Ge capacitance and the minimum value from the isotype cells. The estimated values of capacitances for the InGaP subcell were 1 μF to 2.6 μF, for the GaAs subcell 0.7 μF to 1.5 μF and for the Ge cell 1.9 μF to 2.5 μF (all cells have a 27 cm^2 area).

For the simulation of the dynamic behavior of the TJ cell, the model used consists of a diode in parallel with a capacitor for each subcell, as schematized in Figure 7. This model neglects the effects of the two tunnel junctions and also the capacitances are considered fixed (do not vary with the junction voltage as usually do). The numerical I–V curves of InGaP, GaAs and Ge subcells obtained in section 2 were introduced as the models of the diodes in PSpice software.

In order to simulate the flash pulse waveform in the PSpice model, the waveform of the short circuit current of a small silicon solar cell was captured using the flash pulse and then introduced in the equivalent circuit. Thus, the current generators of the subcells (I_{top}, I_{mid} and I_{bot}) describe the same waveform, with the appropriate proportions presented in Table I.

The measurements were compared with the simulations for different load conditions: short circuit (SC), maximum power point (MP) and open circuit, at an intensity slightly higher than 1 sun AM0 (Figure 8a, 8c and 8d, respectively) and another in SC with an intensity of about 0.5 sun (Figure 8b).

At first, the simulations were performed with the minimum capacitances values obtained previously, i.e. $C_{top} = 1$ μF, $C_{mid} = 0.7$ μF and $C_{bot} = 1.9$ μF. With these values, the time position of the simulated shoulder is lower than the one measured at SC condition. For that reason, the capacitance values were ranging around the limits established before in order to match both waveforms. Finally, a good

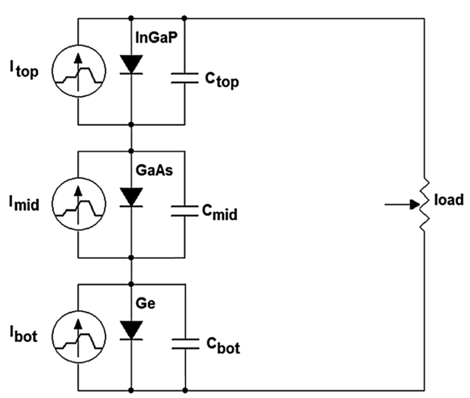

Figure 7. Schematics of the equivalent circuit of a TJ cell used in the dynamic simulations.

correlation for all load conditions was found with the following values: $C_{top} = 3$ μF, $C_{mid} = 2$ μF and $C_{bot} = 1.9$ μF, which are consistent with those obtained through C–V measurements. Also, simulation results showed to be sensitive to the top and middle subcell capacitances values but independent to the bottom cell capacitance value. In particular, for the two cases of SC (Figure 8a and 8b) the simulations match very well the experimental curves including the dynamic behavior observed. In addition, simulations without capacitances were performed and the shoulder does not manifest. This outcome evidences that the dynamic effect is caused by the capacitive effects of the subcells when the cell is excited with a fast light pulse. If we assume that each subcell has an associated capacitor in parallel with some initial charge condition, when the flash pulse excites the TJ, each subcell will generate a photocurrent pulse, and the capacitors will begin to acquire charge. During a very short time period, while the light intensity is rising, the photocurrent generated by the two subcells that generates the bigger photocurrent will pass through the capacitor of the limiting subcell (in this case the top cell). As a result, the TJ cell can deliver a current slightly larger through the external circuit during a very short time. When the capacitor associated with the top subcell is fully charged, the current flowing through it vanishes, and TJ current experiments an abrupt decrease reaching the value of the photocurrent generated by the top cell.

Similar comparisons between simulated and experimental curves were performed at the maximum power point and near open circuit, which are shown in Figures 8c and 8d. For the maximum power case the shoulder is also observed, but the effect appears smaller. In this case the simulation does not properly match the time position of the shoulder, probably due to the use of fixed capacitance values instead of voltage dependant capacitances. For the open circuit case the shoulder does not manifest, but the associated subcell capacitances affect the signal decay making it slower, simulations also reproduce this effect. Due to this effect, the method proposed by Keogh et al. to measure I–V curves using the pulse decay [3] could introduce some errors associated to the transient regime in the interval between maximum power point and open circuit.

The duration of the observed shoulder in SC and MP for illumination conditions of 1 sun is 45 μs in both cases. Instead, for SC with intensity of 0.5 sun the duration of this transient effect is a somewhat larger, about 65 μs. This means that this duration is independent on the electrical bias point of the cell, but dependent on illumination intensity. Furthermore, simulations have shown that the duration of this effect is dominated by the capacitance of the top subcell, wich limits the tandem current. This agrees with the previous explanation about the causes of the transient shoulder.

These dynamic effects are much faster than the duration of the maximum of light pulse and indicate that the TJ cell can follow the light intensity variations. Thus, dynamic effects do not alter the measurements performed with multiflash method. This statement was validated by transient and steady state simulations performed with PSpice. For

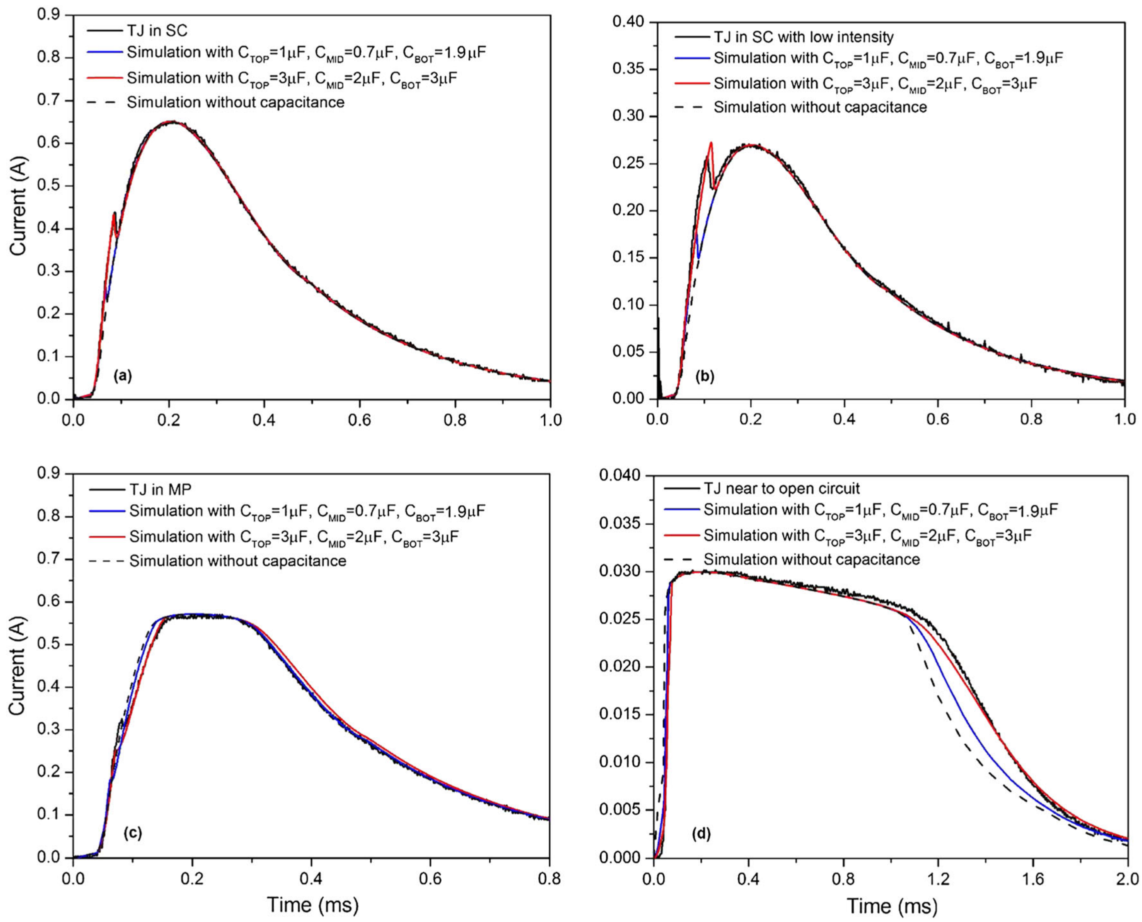

Figure 8. Flash current pulses of TJ cell for different load conditions (a) shortcircuit (SC) with an intensity slightly greater than 1 sun, (b) shortcircuit with an intensity of about 0.5 sun, (c) maximum power (MP) and (d) close to open circuit condition. The simulations performed with the PSpice model showed in Figure 7 are also presented for different capacitance values.

the steady state simulation, the same TJ model was used, and a DC sweep was considered. The results of the simulations are shown in Figure 9. Both values corresponding to transient and continuous regimes perfectly match for all load conditions, and indicate that there are no errors associated to transient effects during the measurement with 200-μs maximum peak flash pulse duration. This result also validates the I–V measurements with multiflash method (Figure 5), where no differences were observed between the measured transient and continuous model.

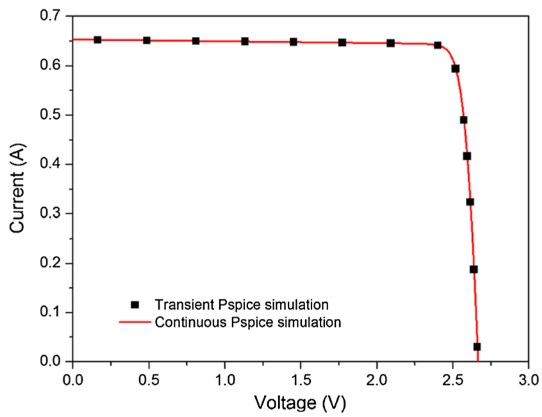

Figure 9. DC sweep of the triple junction model through PSpice and discrete I–V points obtained by considering the values of the I–V peaks on each transient simulation for different loads.

6. SIMULATION OF A POWER MODULE

Once the dynamic analysis ensures the pseudo steady state condition during the pulse peak, a final simulation considering the configuration of one power module of the SAC-D solar array was carried out. One typical SAC-D solar module (50 cm × 75 cm size) is composed by six strings in parallel, with eighteen cells connected in serial with a blocking diode [11]. The I–V curve of one blocking diode was measured in order to incorporate it into the simulations. First, we performed simulations of a TJ cell with the current values generated by the flash. The voltage was then multiplied 18 times to represent a string, and then the I–V curve of a blocking diode was subtracted from the simulated I–V string. Finally, to achieve the current module, the current values of the string are multiplied by six. The applied method assumes that there is a high degree of homogeneity in the electrical parameters of the cells conforming the module. This is in fact the case, as verified in ref. [17,18]. The simulated curve is then compared with the electrical test performed in various modules of the Aquarius/SAC-D solar array. The electrical verifications of the modules were done using the same commercial Xe flash lamp at lab temperature (22 °C) as described in reference [11].

Due to the serial resistance of the cables connecting the strings and modules, and taking into account that the oscilloscope used was a three wire instrument instead of four, an additional serial resistance was needed in order to match the simulations with the experimental verifications. All the effects related to serial resistance are condensed in one serial resistor for each cell with a value of about 0.1 ohm. In addition, temperature correction was needed since electrical tests were made at laboratory temperature of 22 °C and the triple junction model was built using measurements performed at the controlled temperature of 28 °C, as mentioned earlier.

Figure 10 shows the simulation of one SAC-D power module under the flash spectrum illumination and the experimental electrical test on the panel. The simulation of the module I–V for the AM0 spectrum, using the proposed method, is also presented. It is observed that the simulated curve using the numerical model of a TJ cell for flash illumination is in good agreement with the experimental curve, while the simulation of the same module considering AM0 spectrum show some minor differences. The percentage differences of the maximum power point and the V_{OC} measured with multiflash method versus the standard AM0 spectrum are +2% and +0.7%, respectively.

7. CONCLUSIONS

A method to determine the I–V characteristic of a III–V triple junction solar cell under any illumination spectrum, based on single measurement of calibrated isotype cells, was developed and validated for dark condition and three different light scenarios: dichroic lamp, TS-Space close match AM0 solar simulator and a commercial Xe flash lamp. All of them have shown a good agreement with the I–V measurements performed on a triple junction (Emcore Advanced Triple Junction, ATJ) solar cell. Also, an extensive dynamical analysis was carried out to discard the possibility of transient errors when a fast flash is used as illumination source for I–V cell measurements. Estimations of the capacitance values for the three ATJ subcells were carried out, and these were introduced in the dynamical simulations performed using PSpice. Electrical current peaks were explained with the TJ model in terms of transient current flowing through the capacitance of the current limiting subcell. As conclusion, errors associated to transient effects when fast pulsed illumination is used in experimental I–V characterisation were not found for the case treated in this work (Emcore ATJ and the corresponding isotype cells, for 200 μs maximum peak duration flash).

The results of the electrical verifications on the modules of the Aquarius/SAC-D solar array, performed under a non standard spectrum, were interpreted in terms of the model developed in this work. In this case, the behavior of a triple junction cell was evaluated for the Xe flash spectrum case.

Furthermore, considering temperature corrections and the estimation of the serial resistance of the entire module, the simulated I–V characteristic of the SAC-D satellite solar modules was matched with the experimental electrical verifications carried out in the test and qualifying campaign of the solar arrays. Results obtained demonstrate that

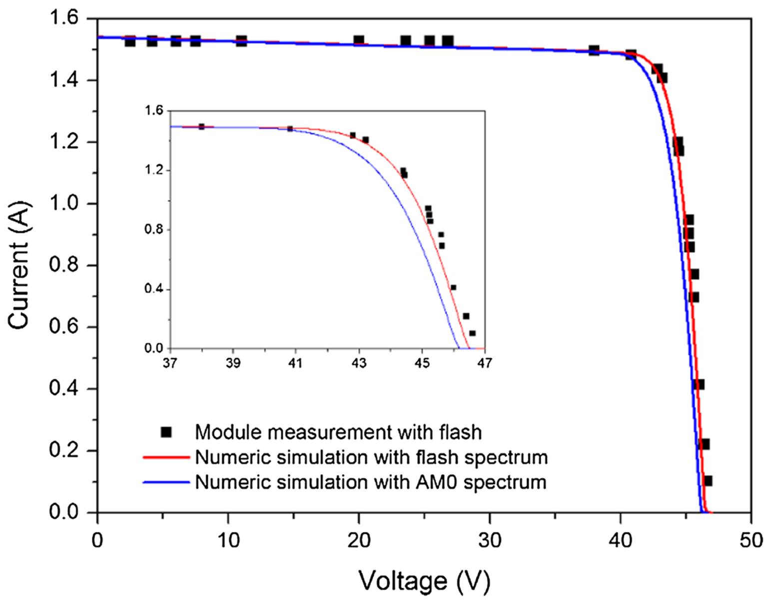

Figure 10. Simulations of one power module considering AM0 and flash lamp spectra. The measurements corresponding to the electrical verification test using the flash on one module is also shown. A zoom in near the V_{OC} is shown in the inset.

the observed differences between module I–V simulations using standard conditions (1 sun AM0) and the module I–V measurements performed under non standard conditions (flash lamp) originate on the spectral illumination differences. These differences were evaluated, and the estimation of the errors shows for the case of maximum power point, an error of about +2% and +0.7% for the V_{OC}, both higher than the values estimated using the numerical model for the AM0 spectrum. That means that the use of this kind of light source is a quite good tool for the estimation of power module generation.

Finally, the scope of this work could be used for electronics pulsed systems in which the electronics associated to the battery charger has to consider transient effects due the response time of solar cells.

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