EXTERNAL QUANTUM EFFICIENCY AND FIRST RESULTS OF ELECTRIC PERFORMANCE MEASUREMENTS ON A QUADRUPLE JUNCTION SPACE SOLAR CELL

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ABSTRACT

External Quantum Efficiency (EQE) and Current-Voltage (I-V) measurements of a monolithic quadruple junction (4J) space solar cell AlGaInP (J1)/ AlInGaAs (J2) / InGaAs (J3) / Ge (J4) manufactured by CESI (Milano, Italy) have been performed at INTA-Spasolab. In order to determine electrical cell performance of this 4J solar cell type under AM0 irradiance and cell temperature standard conditions, the external quantum efficiency (EQE) measurement system and steady-state solar simulators at the cell testing laboratory INTA-Spasolab are to be upgraded. The purpose of this work is to present both the upgrading of INTA-Spasolab facilities and the results of the characterization of a 4J solar cell under development.

1. INTRODUCTION

Electrical performance characterization of new coming space multi-junction solar cells have required solar simulators to evolve from basic, single source systems to multi-source systems capable of providing test illumination conditions much closer to the reference AM0 spectrum. For accurate I–V measurements of monolithic multi-junction (MJ) solar cells, the spectrum of the solar simulator has to be adjusted such that each sub-cell of the MJ cell generates the same photocurrent as under the reference spectrum. The procedures to adjust the multi-source systems [1-4] usually involve the calculation of the so-called spectral mismatch factor for each junction for which EQE measurement of the sub-cells are necessary.

Manufacturers of space solar cells are working on increasing the number of junctions of III-V semiconductor based solar cells by a combination of semiconductors with different band-gaps to further improve the already high efficiencies of InGaP/InGaAs/Ge triple junction solar cells (above 30% in AM0 conditions) widely used in space applications due to their radiation resistance. Solar simulators are to be conditioning by adding and/or adapting spectrally their light sources in order to provide an accurate AM0 spectral match according to specific devices.

CESI is investigating the design of a monolithic quadruple junction (4J) space solar cell AlGaInP/ AlInGaAs/ (In)GaAs/ Ge that can be grown entirely by MOCVD toward the optimization of a 32% 4J lattice matched solar cell solution for space applications [5]. The approach to optimise the final four junction device is an iterative one: the solar cell structure is designed and simulated by the code, and then the solar cells are manufactured and tested. The experimental results from characterisation provide the feedback needed to improve the input parameters to the code and then to restart optimisation. The InGaAs junction was found to be the limiting sub-cell in the first four junction devices samples that have been manufactured and tested. This sub-cell determined a low radiation resistance in such devices. A 4J solar cell with modification of the former InGaAs structure [6] has been characterized at INTA-Spasolab.

2. TEST EQUIPMENT

2.1 EQE Measurement System

The EQE measurement system of INTA-Spasolab as well as the electrical characterisation method of multi-junction solar cells is described elsewhere in [2, 7]. As depicted in Fig. 1, bias light illumination can be easily adapted by optical bandpass filter change, so that measurements can be switched quickly from three junctions to four junctions III-V cells.

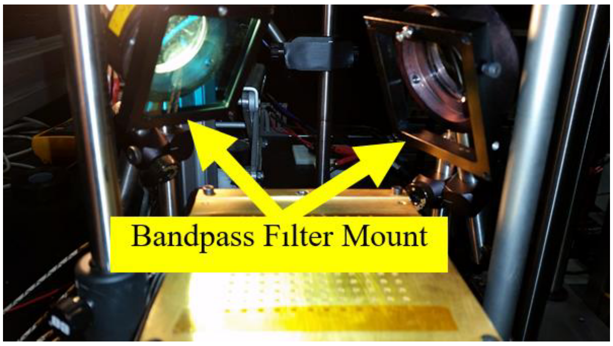

Figure 1. Optical Bandpass Filter Mount.

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Long (LP) and short (SP) bandpass filters used on bias light sources for EQE measurements on 4J sub-cells are listed in Tab. 1.

Table 1. Bandpass filters for EQE 4J cell measurements

Sub-cell	Bandpass Filter
J1	LP700 nm
J2	SP540 nm + LP830 nm
J3	SP600 nm
J4	Coldglass KG5

2.2 4J Solar Simulator

A commercial steady-state solar simulator based on a short-arc xenon lamp (Xe) with a light set up so far used for measurements of state-of-art triple junction solar cells (3J) GaInP/ InGaAs/Ge has been upgraded. As depicted in Fig. 2, spectrally filtered halogen light sources can be placed and combined on an external ring as required to meet finally effective irradiance unity at each sub-cell of the 4J cell. In total, three sets of assembled halogen light sources (Ha1, Ha2 and Ha3) have been utilised. The incident angle of this supplementary-light illumination is fixed within 30º to maintain cosine signal response of solar cells.

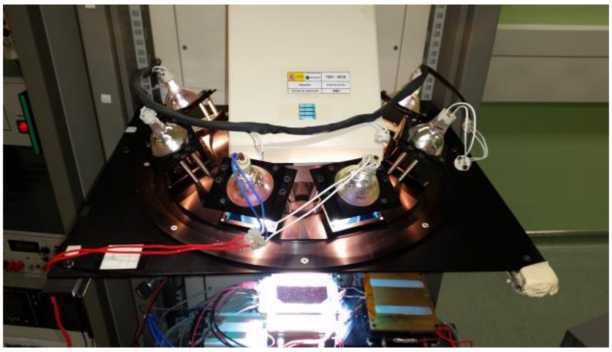

Figure 2. Additional halogen light sources for a single simulator solar simulator.

In order to achieve AM0 equivalent conditions of illumination with a four- light source simulator, a set of single-junction reference solar cells (SCRC) is used to adjust the irradiance level of each light source on the test plane in a way that the AM0 calibration value of each reference cell is achieved. The selected 4J SCRC set represent a spectral response range similar to the 4J cell to be tested, which is shown in Fig. 3. This set is comprised by the following:

- CESI model CTJ-4J, 80x40mm² with 30.15cm² active area: AlInGaP/Ge (J1), AlInGaAs/Ge (J2) and InGaAs/Ge (J3). All of them with active Germanium sub-cell.
- AZUR SPACE 3G28, 80x40mm²: Ge (J4)

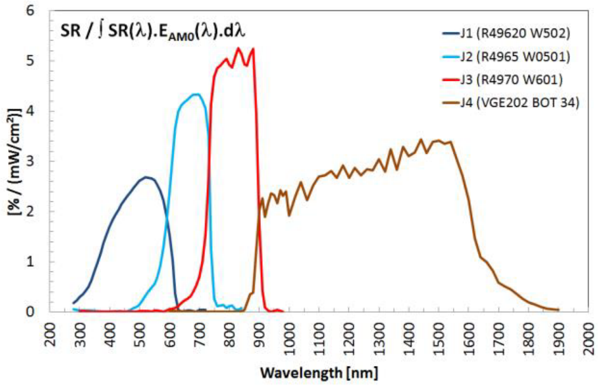

Figure 3. Spectral Response curves of the 4J single component reference cells (SCRC) set.

The spectral distribution curves of each light source of the 4J solar simulator at AM0 conditions are depicted in Fig. 4.

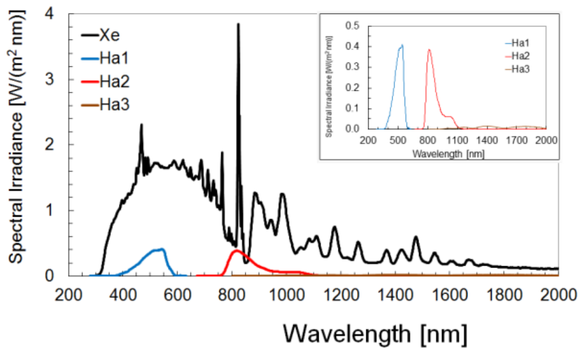

Figure 4. Spectral distribution of light source sets

The contribution of the different light sources of the 4J solar simulator to the short circuit current of each SCRC at AM0 equivalent illumination is indicated in Tab. 2

Table 2. Contribution of each light source to the short-circuit current of the SCRC at AM0 equivalent illumination

Light Source	J1	J2	J3	J4
Xe	90%	99%	83%	87%
Ha1	10%	1%	0%	0%
Ha2	0%	0%	17%	3%
Ha3	0%	0%	0%	10%

The nonconformity in the spatial uniformity (UF) of irradiance in the working plane for each junction and corresponding relevant class of solar simulator according to [8] is in Tab. 3.

Table 3. Nonconformity of irradiance uniformity

4J Solar Simulator	J1	J2	J3	J4
UF Nonconformity	±5%	±2%	±6%	±3%
Class	B	A	C	B

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3. TEST RESULTS

3.1 External Quantum Efficiency

EQE measurement results of the aforementioned 4J solar cell obtained using the EQE system previously described are presented in Fig. 5.

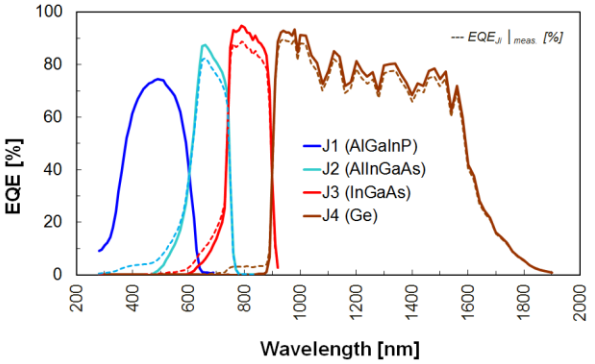

Figure 5. EQE results of the 4J solar cell

Measured EQE curves for the higher bandgap junctions show artefacts in the spectral range of the lower bandgap junctions. The presence of non-desired parasitic EQE when performing EQE measurement of a sub-cell could be related either to low shunts resistance of the sub-cell under test [9] or to luminescence coupling [10]. EQE measured values are then to be corrected to remove such artefacts. Although the physics involved are different, the mathematical procedure in [9, 10] to correct such artefacts is similar. The measured EQE values of the higher band junctions have been then corrected to get the actual EQE values. The results in Tab. 4 show the contribution of actual EQE values to the measured EQE ones.

Table 4. Contribution of actual EQE values to the measured EQE for each sub-cell of the 4J cell

$EQE_{Ji}\|_{meas}$	EQE_{J1}	EQE_{J2}	EQE_{J3}	EQE_{J4}
J1	**100%**	-	-	-
J2	5.9%	**94.1%**	-	-
J3	0.6%	10.4%	**89.0%**	-
J4	0.0%	0.15%	4.35%	**95.5%**

3.2 Current-Voltage Curve

The testing procedure to establish AM0 equivalent illumination conditions for multi-junction solar cells applied at INTA-Spasolab is described in [2, 4]. This procedure requires the measurement of the relative spectral irradiance of each light source at different lamp intensities to compute the corresponding spectral mismatch correction factor for each junction using relative spectral measurements of both, SCRC and related junction of the 4J cell, from the previously measured EQE in Fig. 3 and Fig. 4. The spectral mismatch parameter for each junction was found to be the same for the full operating range of each source.

The spectral mismatch factors to be applied when adjusting the 4J solar simulator to AM0 equivalent illumination conditions for the 4J solar cell are given in Tab. 5.

Table 5. Applied Spectral Mismatch Factors (M)

Light Source	J1	J2	J3	J4
Xe	1.005	0.999	1.000	1.026
Ha1	0.970	0.782	-	-
Ha2	-	0.183	1.003	0.932
Ha3	-	-	-	1.004

During the 4J solar simulator setting process, the AM0 effective irradiance for each sub-cell junction is computed by using the measured short-circuit current values of the 4J SCRC set and applying the corresponding spectral mismatch factor. Effective irradiance results are given in Tab. 6, where the junction used to set the different light sources in bold is highlighted.

Table 6. AM0 effective irradiance for each sub-cell

AM0 effective irradiance	J1	J2	J3	J4
Xe	0.903	0.993	0.829	0.880
Xe+**Ha1**	0.999	1.000	0.824	0.888
Xe+Ha1+**Ha2**	0.999	1.000	1.004	0.919
Xe+Ha1+Ha2+**Ha3**[1]	**0.999**	**1.000**	**1.004**	**1.020**

[1] 4J Solar Simulator adjusted to 1sc-AM0

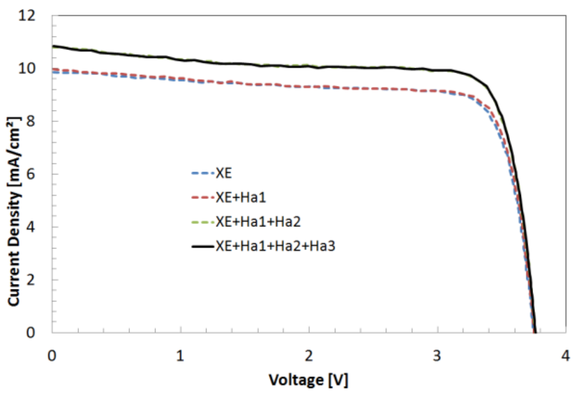

Figure 6. Current-voltage curves of 4J solar cell during the 4J solar simulator setting process.

Current-voltage curves of the 4J solar cell measured during the 4J solar simulator adjustment process are depicted in Fig. 6. These curves indicate that the InGaAs junction (J3) was the limited sub-cell under the Xe light source, because, when adding the second light source Ha1, no major impact in the I-V curve shape of the 4J cell is noticed. Nevertheless, adding the third light source Ha2 to achieve eventually AM0 equivalent illumination conditions in this sub-cell gives rise to an increased short-circuit current of the 4J solar cell. This is sustained as expected, when adding the fourth light source Ha3, since Ha3 only contributes to increase the irradiance level on the Ge sub-cell (J4). The limiting cell at AM0 illumination conditions as derived from the I-V curves of 4J SCRC set in Fig. 7 is AlInGaAs (J2). This has been also confirmed by further increasing the illumination level of Ha2 light source and noticing no relevant impact on the I-V curve shape.

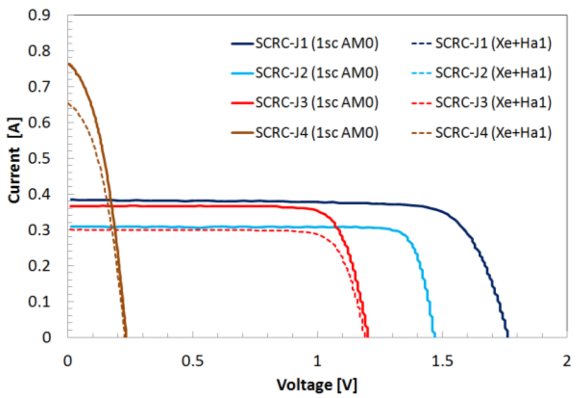

Figure 7. Current-voltage curves of 4J SCRC set during the 4J solar simulator setting process.

4. CONCLUSIONS

In this work external quantum efficiency (EQE) results of a 4J solar cell by CESI have been determined at INTA-Spasolab. The applied measurement method allows the EQE measurement system to be configured quickly, by changing optical bandpass filters, in order to switch from 3J to 4J solar cells. The EQE curves of higher bandgap junctions are reported including corrections of the parasitic EQE.

After adapting a solar simulator utilised so far for electric performance measurements on triple junction solar cells, first results of EP measurements of a 4J solar cell at 25°C have been obtained. The results confirm that the modified CESI 4J solar cell with the new proposed InGaAs structure [6] is not the limiting sub-cell under AM0 illumination conditions.

INTA-Spasolab future works are addressed to consolidate accurate effective irradiance adjustments. Spectrometric characterization as performed in [11] are planned to determine measurement uncertainty of electrical performance measurement at AM0 standard test conditions.

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