Thin-Film light-trapping enhanced Quantum Dot photovoltaic cells (TFQD): an enabling technology for high power-to-weight ratio space solar arrays

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Solar Cells Requirements Specification and Test Flow Specification

Lead Partner: TAS-I

Contributing Partners: POLITO, RBU, TF2 Devices B.V., TUT, UCL

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Abstract

The present document provides the specification of the Solar Cells Requirements and of the Test Flow of the demonstrators that will be realized during the project. The document also outlines the Device information and Documentation that shall accompany the fabricated and tested demonstrators. Test flow and Device Documentation have been specified based on the **European Cooperation for Space Standardization** "ECSS-E-ST-20-08C - Photovoltaic Assemblies and Components", with a proper tailoring based on the project needs.

Change Records

Table 1-1

Issue	Date	Change Record	Author
Draft	11/02/2016	First Release	M. Cimino
1.1	22/02/2016	Second Release	F. Cappelluti-M.Cimino
1.2	24/02/2016	Third Release	F. Cappelluti-M.Cimino

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List of Acronyms

BOL: Begin Of Life
EI: Electron Irradiation
EOL: End Of Life
EP: Electrical Performances
EQE: External Quantum Efficiency
TBC: To Be Confirmed
TC: Temperature Coefficient
TFQD: Thin Film Quantum Dot
TRL: Technology Readiness Level

1. INTRODUCTION

The specific objective of TFQD is to develop and demonstrate up to TRL4 thin-film light-trapping enhanced quantum dot solar cells matching the following specifications:

- absolute efficiency larger than 30%
- eightfold increase of power-to-weight ratio vs. triple junction III-V solar cells
- bending radius lower than 3 cm

Demonstration up to TRL4 will be carried out through on ground testing under representative "in orbit" conditions over a batch of 44 bare cell prototypes with minimum area of 1cm x 1cm.

The aim of the present deliverable is to provide a detailed description of the demonstrators required performances that have been identified by TAS-I to secure the exploitation opportunities for the devices developed in TFQD, and a description of the tests and device characteristics required for acceptance and characterization of the demonstrators.

The document is organized as follows. Section 1 summarizes the key performance requirements and space characterization tests for the demonstrators. Section 3 identifies the information to be reported in the technical description of the bare cells, and finally Section 4 provides a description of the tests that will be carried out in the frame of the project to demonstrate the achievement of the targeted performances.

2. KEY SPACE PERFORMANCE REQUIREMENTS AND CHARACTERIZATION TESTS

A set of **key performance requirements** has been identified by TAS-I to secure the exploitation opportunities for the solar cell developed in TFQD:

- Absolute efficiency (AM0) not lower than 30%
- Average weight ≤ 12 mg/cm^2
- Active device thickness < 10 μm
- Bending radius < 3 cm
- Low Temperature Coefficient TC: $d\eta/dT$ = -0.025%/°C[1]
- Radiation hardness at least comparable to standard multi junction cells.

[1] The temperature range to be taken into account for "standard" missions (GEO, LEO and Lagrangian L2 orbits) is [-100÷140] °C. Lowest temperatures are reached during eclipses and therefore solar cells are not operating. Due to that fact, it has to be guaranteed that solar cells do not suffer lower temperatures (from mechanical and thermal point of view). During transition from eclipse to illumination, solar cells will begin to operate at low temperature; due to the transient nature of this aspect, solar cells are required to operate at low temperature, while performance requirements has to be guaranteed in a narrower temperature range (i.e. temperatures reached during illumination).

The space characterization tests to be performed on demonstrators foresee two different batches of cells with different test flows. For these tests the minimum cell area shall be on the order of 1cm^2. Details of the demonstrator batches are:

- A first batch (composed of 20 cells) will be used to evaluate the Begin-Of-Life (BOL) parameters in terms of electrical performances, spectral response and temperature coefficient.
- A second batch (composed of 24 cells) will be used for the Electron Irradiation test to evaluate the End-Of-Life (EOL) parameters. In order to have a single transport to EI facilities, the second batch will be split into three sub-groups (8 cells each) that will be subjected to different electron total dose.

Methods and requirements for the characterization tests in Figure 1 are detailed in Section 4.

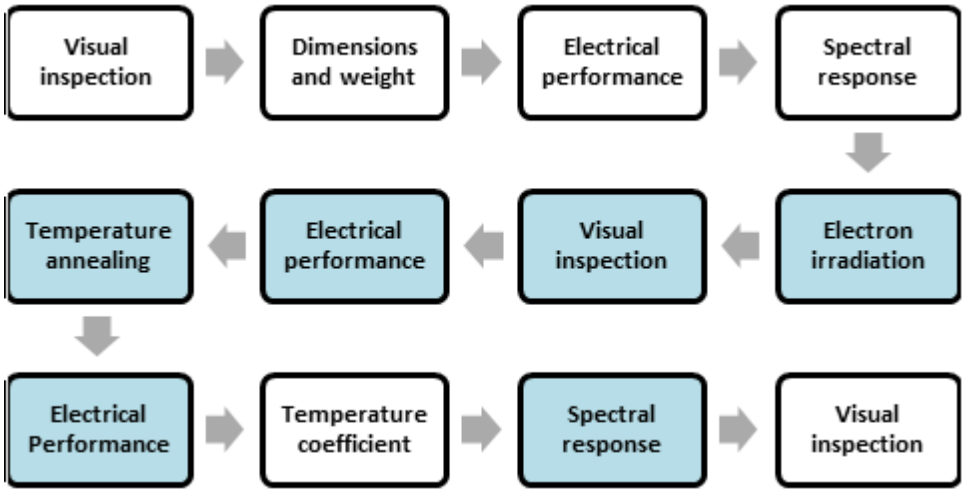

Figure 1 - Description of the test-flow for the testing of the BOL parameters (only white blocks) and of the EOL parameters (full sequence of white and coloured blocks).

The BOL and EOL test flow are outlined in Figure 1. Concerning the EOL test, for each of the three sub-groups of cells the test flow will be carried out as follows: electrical performances will be measured before and after irradiation as well as after annealing. By comparing the results, the losses due to irradiation and solar cells recovering after annealing will be evaluated.

3. TECHNICAL DESCRIPTION

The TFQD solar cells shall be accompanied by a document reporting all the relevant characteristics as specified in the following paragraphs. Where possible, the expected characteristics identified according to the preliminary design for the device development stage are indicated.

3.1. Materials

The description of the TFQD solar cells shall include the following characteristics:

Component	Material
Substrate	
Active Region	With specification of number of quantum dot layers, quantum dot density per layer
AR-coating	
Reflector	
Contacts	

Table 3-1 - Solar cell materials

3.2. Physical properties

3.2.1. Main dimensions

The TFQD solar cells main dimensions shall be indicated as per Figure 2. The area of demonstrators is required to be 1 cm x 1 cm. Two possible indicative values of thickness are foreseen:10 µm or 25 µm depending on the thickness of the Cu carrier.

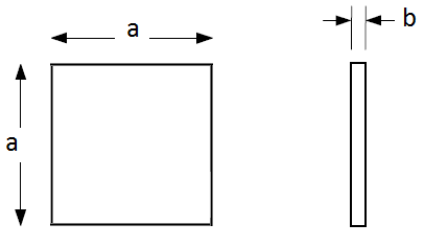

Figure 2 - TFQD solar cell main dimension

	a	b
Values	10,00±0,01 mm	10 µm / 25 µm

Table 3-2 - Solar cell physical properties

3.2.2. Contacts dimensions

On the front surface of the cell a pattern of metal parallel gridlines shall be applied, each gridline terminating in a collector with pads located at a cell edge. The number of pads and their position, identified for the preliminary development phase, are specified in Figure 3. These will possibly be revised and optimized for the sake of device optimization.

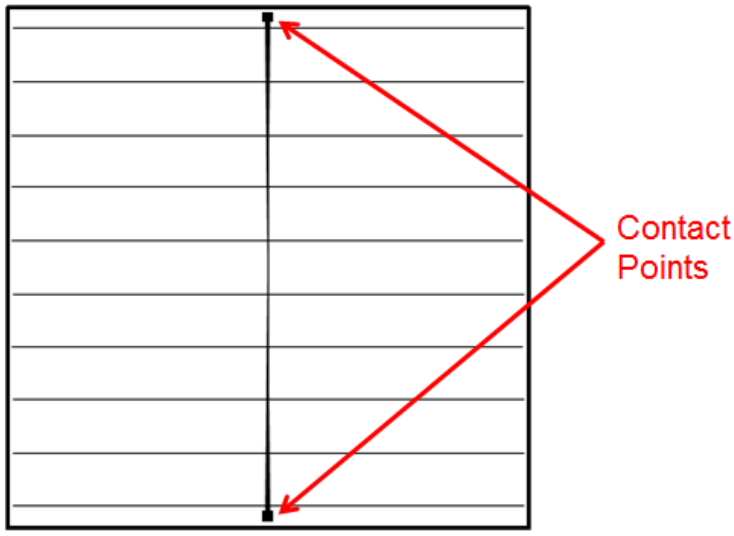

Figure 3 - Front contacts dimensions

The two contact points on the front side are 200 µm x 200 µm; the distance between contact points and solar cell edges is 100 µm.

The rear side electrical contact will be the whole rear side of the cell completely covered by the metal.

3.2.3. Weight

The TFQD solar cells average weight shall be specified here. Target values are 12 mg/cm^2 and 25 mg/cm^2 for the 10 µm and 25 µm thick cell, respectively. .

3.2.4. Bending radius

The TFQD solar cells bending radius shall be specified here. The target bending radius is < 3 cm.

3.3. Electrical performances (EP)

3.3.1. Begin Of Life (BOL) performances

The minimum electrical performances of the solar cell at BOL shall be indicated as in Table 3-3 and Table 3-4 at T= 25°C under AM0 illumination of 1 S.C (WMO spectrum). The indicated Power at Maximum Power point, P_{MP}, is the project target value (30% efficiency).

Parameter		Requirement
P_{MP}	[mW]	41

Table 3-3 –BOL electrical characteristics

In Table 3-4, only for the sake of reference, examples of voltage and current values allowing for the power target have been listed. These values are not target of the project and are only indicative.

Parameter		Requirement
V_{OC}	[V]	1,025
I_{SC}	[mA]	48,5
V_{MP}	[V]	0,9
I_{MP}	[mA]	45,5

Table 3-4 –BOL electrical characteristics - Voltage and current reference values

3.3.2. Temperature Coefficients (TC)

The output power shall be measured at different temperatures in accordance to Table 3-5. The indicated values correspond to the target maximum TC of -0.025%/°C.

Parameter	25° C	40° C	60° C	80° C
P_{MP}/P_{MP0}	1	0,99625	0,99125	0,98625

Table 3-5 - Output power measured at different temperatures

3.3.3. End Of Life (EOL) performances

One of the project goal is to demonstrate that the performances of the TFQD solar cells in terms of radiation hardness are comparable to the ones of the state of art solar cells. The minimum electrical performances of the solar cell at EOL shall be measured in the conditions indicated in Table 3-6, at T= 25°C under AM0 illumination of 1 S.C (WMO spectrum).
The listed values are in line with the performances of state of art space solar cells.

	1 MeV equivalent fluences [e^-/cm^2]		
Parameter	1E14	3E14	1E15
P_{MP}/P_{MP0}	0,95	0,92	0,875

Table 3-6 - Fraction of BOL power

3.4. Acceptance criteria - Visual Inspection

3.4.1. Test equipment

Solar cells shall be inspected with an equipment with a resolution which is 5 times higher than the minimum allowed defect size to verify the requirements for defects on solar cell and contacts.

3.4.2. Solar cell defects

1) The location and maximum dimensions for allowable defects related to edge chips, corner chips and surface nicks shall be in conformance with Figure 4 and Table 3-7. Values in Table 3-7 have been extrapolated from Table 7.3 in [1].

2) The cumulative area of all edge chips, corner chips and surface nicks shall not exceed 5 % of the total cell area.

3) Edge chips, corner chips and surface nicks shall not be present in the contact weld area.

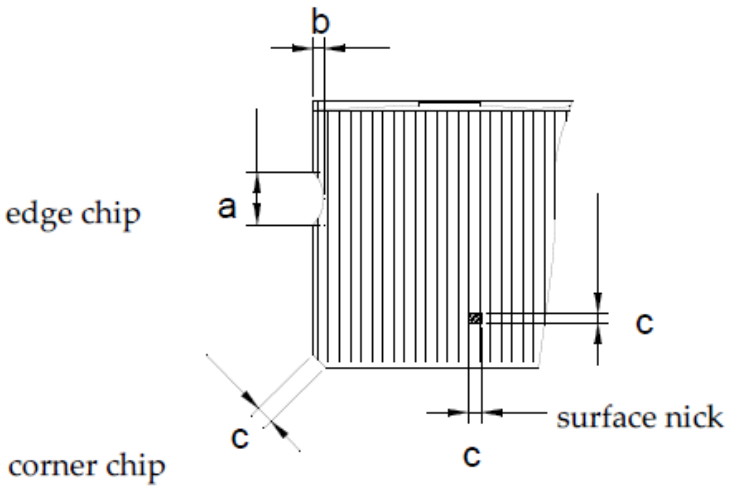

Figure 4 - Definition of solar cell defects

Dimensions of cell defects (mm)		
a	**b**	**c**
2	0,6	1

Table 3-7 - Maximum dimensions of corner chips, edge chips and surface nicks

3.4.3. AR coating

1) The maximum value of the total uncoated area, and the value of spatter and voids shall be lower than 3% of the active cell area.

2) The AR coating may contain discolourations.

4. CHARACTERIZATION TESTS

This Section is a tailoring of specifications for test methods, conditions and measurements of bare solar cells reported in [1].

4.1. Dimensions and weight

1) The overall lateral dimensions of the cell (including thickness), contact dimensions shall conform to the requirements stated in Sect. 3.2.
2) The weight of the solar cell shall be verified by determination of the average weight per characterization lot.

4.2. Electrical performances

1) The electrical current of solar cells under 1 S.C. (AM0) shall be measured and recorded digitally, at least at 50 points, at a solar cell temperature of 25 °C.
2) The electrical parameters measured and identified in Table 3-3 shall be derived from the full curve.
3) The accuracy of the bare solar cell measured parameters (I_{SC}, V_{OC} and P_{MP}) shall be provided.
4) During measurement, the cells shall be kept at a constant temperature (+/- 0,5 °C).

4.3. Temperature coefficient

1) The electrical performance test described in Sect. 4.2 shall be repeated, as a minimum, in the temperature range between 25 °C and 80 °C with intermediate temperatures at 40 °C and 60 °C.
2) Data for all electrical performance parameters at the different solar cell temperatures shall be included in the test report.
3) The temperature coefficients of short-circuit current, open circuit voltage, voltage at maximum power and maximum power shall be derived by least-square curve fitting.

4.4. Electron Irradiation

1) The solar cells shall be subjected to 1 MeV electron irradiation.
2) The flux density and energy shall be uniform over the cell area within ±10 %.
3) During irradiation, the cells shall be protected from oxidation, using either vacuum (below 10^{-3} Pa) or a dry atmosphere of nitrogen or argon at a temperature of (20 ± 10) °C.
4) The nominal rate shall be lower than 5×10^{11} e^- cm^{-2} s^{-1}.
5) The following total dosages shall be applied:
   a) 1E14 e^- cm^{-2}
   b) 3E14 e^- cm^{-2}
   c) 1E15 e^- cm^{-2}
6) The electrical performances test described in Sect. 4.2 shall be repeated after Electron Irradiation.

4.5. Temperature annealing

1) After Electron Irradiation, the cells shall be subsequently temperature annealed for 24 h at 60 °C.
2) After Temperature Annealing, the electrical performances test described in Sect. 4.2 shall be repeated.

4.6. Spectral response

1) The External Quantum Efficiency (EQE) shall be measured under monochromatic irradiation in a wavelength range suitable for the solar cell optical bandwidth, indicatively 0,3 µm ÷ 1,2 µm.
2) The monochromatic irradiation shall be generated by continuous recording through a monochromatic probe based on broadband light source filtered by a monochromator. Typical wavelength sampling is 5 nm.
3) The irradiation intensity at all wavelengths shall be such as to ensure that the measurement is made in the region where the cell response short-circuit current versus irradiance is linear.

5. REFERENCES

[1] ECSS-E-ST-20-08C Rev.1, 18 July 2012, Photovoltaic assemblies and components