CHEOPS	Title **Demonstration of patterning processes allowing to achieve dead area width < 500 µm**	Deliverable Number **D1.3**
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CHEOPS – Production technology to achieve low Cost and Highly Efficient phOtovoltaic Perovskite Solar cells

Deliverable D1.3

Demonstration of patterning processes allowing to achieve dead area width < 500 µm

WP1 – Perovskite single junction development

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Revision History

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Aldo di Carlo (CHOSE), Fabio Matteocci (CHOSE)	Revision 1	12.07.2017
Soo-Jin Moon (CSEM)	Final version	17.07.2017

Contents

Acronyms

CHOSE Università di Roma Tor Vergata
CSEM Centre Suisse d'Electronique et de Microtechnique
FF Fill factor
Fraunhofer Fraunhofer Institute for Applied Polymer Research
GFF Geometric fill factor
H2020 Horizon 2020
HTL Hole transport layer
Jsc Short circuit current
MPP Maximum power point
PK Perovskite
SEM Scanning electron microscope
TCO Transparent conductive oxide
Voc Open circuit voltage
WP Work Package

Executive Summary

The objective of this deliverable is achieving dead area width of the perovskite module segment < 500 µm by using fully laser patterning process. This deliverable was reached by demonstration of PK mini-module with dead area width of ~ 400 µm.

Need for the Deliverable

In order to minimise efficiency losses from small cell to module, dead area where interconnection lines are patterned should be as small as possible since this area is no longer active to contribute to energy conversion. Patterning interconnection lines by laser process enable to achieve a very small dead area below 500 µm.

Objectives of the Deliverable

In order to achieve highly performing perovskite modules, power and optical losses should be minimised by reducing the interconnection area losses which are inactive to generate current and by decreasing the electrode sheet resistances which lead to electrical losses during current extraction. To this end, using a highly selective laser process is required to increase GFF:

$$GFF = \frac{Active\ area}{Aperture\ area} = \frac{Wa}{Wa + Wd}$$

Such a process can be optimised by modifying the following laser parameters used for P1, P2, and P3 such as spot size, scan speed, wavelength, and repeatability frequency

Outcomes

By tuning laser parameters for P1-P2-P3 scribing and optimising scaffold thickness we achieved dead area of 403 µm corresponding to a GFF of 92%. Moreover P3 scribing on metal contact has been improved to avoid issue of metal delamination while P3 processing which led to increased current.

Finally efficiency of PK mini-module patterned by laser process reached 16% in aperture area of 14cm^2.

Next steps

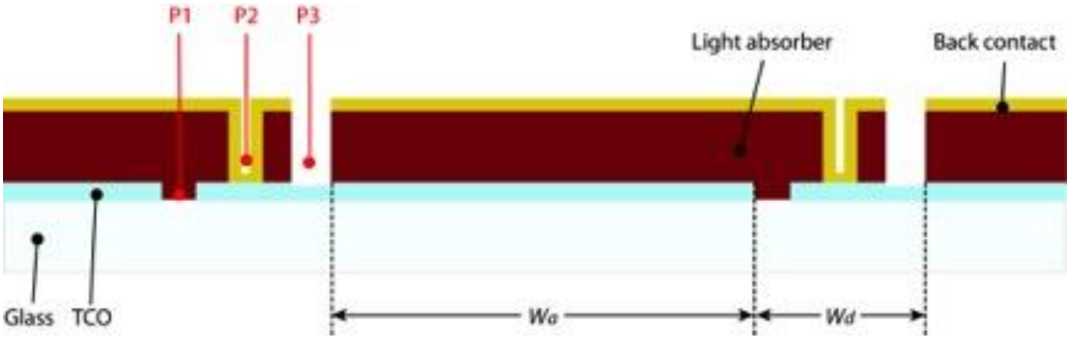
We will further optimise laser conditions to increase GFF up to 95-97%.

1 Laser patterning process of perovskite module

1.1 Series interconnection patterned by laser

Module serial interconnection is realised by three individually scribed lines called P1, P2, and P3. Different laser sources can be used for selective scribes, for instance, UV or IR lasers for TCO and green laser for light absorber. Figure 1 shows a scheme of series interconnected module. In modules, the area required for the interconnection, called dead area, is no longer available for photocurrent generation. The dead area width, W_d is the total width of all scribe patterns including the margins in between and the width of remaining area, W_a is the active area width. To reduce relative loss of efficiency from cell to module, dead area width should be as small as possible, while the active area itself should be optimised to avoid electrical losses during the current extraction through the TCO electrodes.

(a)



(b)

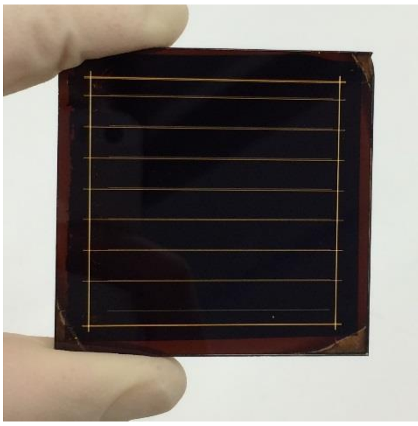


Figure 1. (a) Schematic of the interconnection showing the P1-P2-P3 lines for a PK module (b) A photo of the PK module where 7 segments are series-interconnected.

1.2 Optimisation of laser scribing conditions

We already reported preliminary laser scribing condition and optimisations for the perovskite module[1]. The P1 scribe was done by UV laser (355 nm) and test lines were made by using different pulse energies, and scribe speed at constant 30 kHz pulse frequency and fixed focal distance. TCO isolation was confirmed by a microscope and a multimeter. The P2 scribing parameters done by green laser (532 nm, 35 kHz pulse frequency) were chosen based on microscope investigation and visual inspection. A spot size of P2 was around 50 µm. The Au deposited in the trenches made by P2 scribes forms the segment serial interconnection between the front contact and the back contact. P3 lines (532 nm, 35 kHz pulse frequency) were optimised in a similar way to provide proper back contact electrical isolation which was confirmed by the measurement of high photovoltage under low illumination condition.

Table 1 summarise laser sources and parameters which used for patterning PK modules. Figure 2 shows P1-P2-P3 interconnection lines by laser on a PK module.
In the first process iteration, 2 main issues related to laser scribing were identified:

1. Remaining scaffold after P2 patterning which led to low FF
2. Delamination of Au after P3 scribing which caused loss of active area.

Further optimisations of P2 and P3 were hence carried out to solve these issues.

Table 1. Summary of laser process condition for PK module.

Interconnection line	Laser source	Pulse energy (µJ)	Scribe speed (mm/sec)
P1	UV	22-26	400-800
P2	Green	33-37	1200-1600
P3	Green	28-32	1200-1800

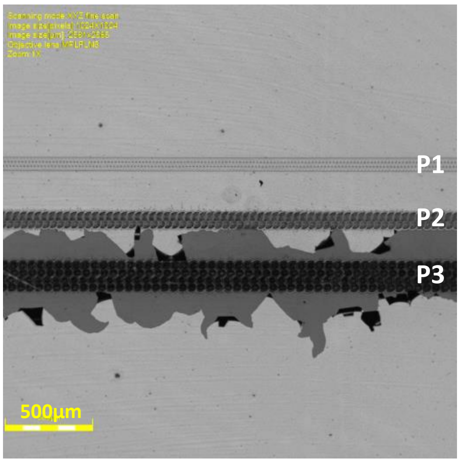


Figure 2. P1-P2-P3 interconnection lines before optimisation of P2 and P3.

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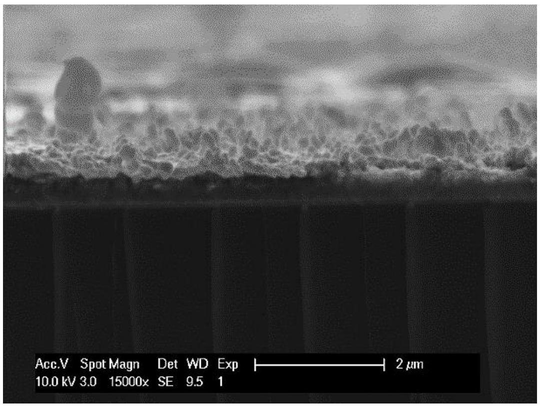
[1] S.-J. Moon, J.-H. Yum, L. Löfgren, A. Walter, L. Sansonnens, M. Benkhaira, S. Nicolay, J. Bailat and C. Ballif, "Laser-Scribing Patterning for the Production of Organometallic Halide Perovskite Solar Modules," *IEEE Journal of Photovoltaics,* vol. 5, no. 4, pp. 1087-1092, 2015.

1.2.1 Optimisation of P2

In the first test of PK module batches, quadruple P2 lines were scribed to ensure sufficient surface contact between front and back side electrodes. However, FF < 60 % was measured which was attributed to remaining resistive TiO_2 scaffold. Therefore, in order to improve device FF, TiO_2 scaffold thickness was reduced from 300 nm to 150 nm and different pulse energy was applied to ensure a complete removal of the TiO_2 scaffold.

Figure 3 shows cross-sectional SEM images of P2 lines of the modules before and after P2 optimisation with (a) 300nm thick scaffold with 27 µJ and (b) 150nm thick scaffold with 35 µJ. Au layer grown on the P2 line of the module with 150nm scaffold looks obviously smoother than that of module with 300 nm thick scaffold.

(a)



(b)

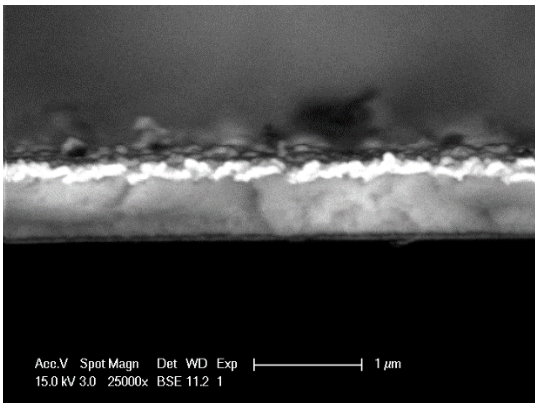
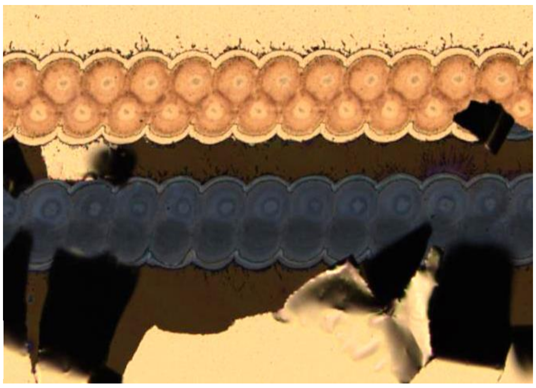


Figure 3. Cross-sectional SEM images of P2 line of module with (a) 300 nm thick TiO_2 scaffold and (b) 150 nm thick TiO_2 scaffold.

1.2.2 Optimisation of P3

Thermally evaporated Au layer has a very poor adhesion on HTL of spiro-OMeTAD. After P3 scribing through glass side, it was first observed that Au back contact was delaminating along the formed P3 lines (Figure 4a) leading to a loss of current generating area and potential Au flakes forming shunts in between two consecutive segments. To overcome this issue, scribing P3 line from the Au side was tested and it indeed decreased the issue of Au delamination (Figure 4b).

(a)



(b)

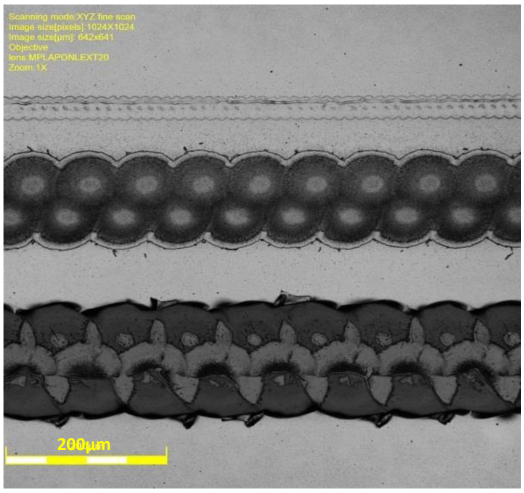


Figure 4. Confocal microscopy images (a) Au delamination along P3 line (b) P3 scribing on Au side.

1.3 Dead area width

After optimising P2 and P3 lines, all scribed patterns, including the gaps between them, resulted in dead area width W_d of ~ 400 µm which was confirmed by microscope imaging (Figure 5).

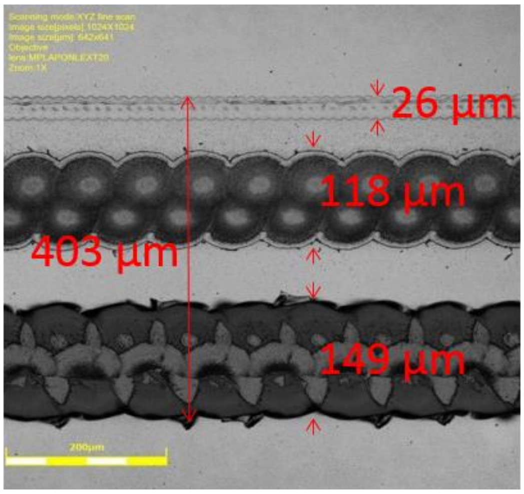


Figure 5. Confocal microscope image of P1-P2-P3 interconnection lines of the PK module (from top to bottom, respectively).

2 PK module result

Eventually, perovskite mini-module patterned using the optimised laser conditions achieved a steady-state (MPP tracked) efficiency of 16 % on 14 cm^2 aperture area with a dead area width of ~ 400 µm. **Such a high efficiency on this aperture area scale is regarded to be a record for a single junction perovskite module.**

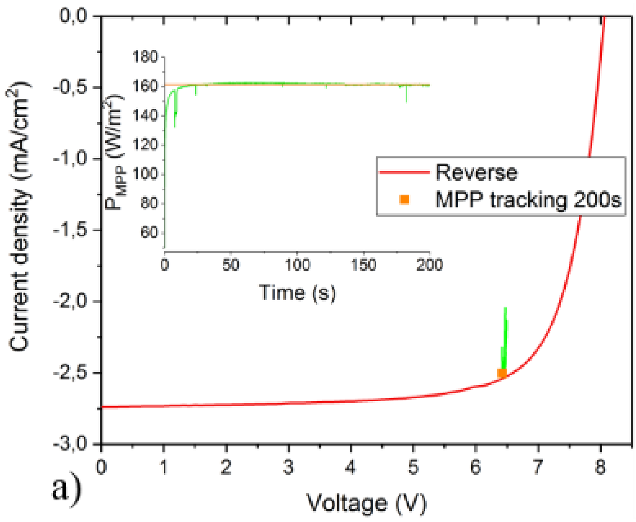


Figure 6. I-V characteristics of the PK mini-module on an aperture area of 14 cm^2. The inset shows the MPP tracking.

Table 2. Summary of the cell and module data.

Aperture Area [cm^2]	Scan Direction	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	Eff. [%]	Stabilised MPP Eff. [%]
1.04	Reverse	1164.80	20.50	71.96	17.18	16.74
	Forward	1151.90	20.64	69.69	16.57	
14	Reverse	8060.60	2.74	74.97	16.55	16.00
	Forward	7755.20	2.73	61.98	13.14	