CHEOPS	26% PK/silicon tandem solar cell with 1 cm^2 area	Deliverable Number **D4.4**
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CHEOPS – Production Technology to Achieve Low Cost and Highly Efficient Photovoltaic Perovskite Solar Cells

Deliverable D4.4

26% PK/silicon tandem solar cell with 1 cm^2 area

WP4 – PK/c-Si SHJ tandem device development

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Revision History

Author Name, Partner short name	Description	Date
Arnaud Walter (CSEM)	Draft deliverable	25.01.2018
Thorsten Rissom (OXPV)	Revision 1	29.01.2018
Arnaud Walter (CSEM)	Final version	29.01.2018

Contents

Acronyms and abbreviations

CSEM	Centre Suisse d'Electronique et de Microtechnique *(CHEOPS Beneficiary 1)*
EPFL	École polytechnique fédérale de Lausanne *(CHEOPS Beneficiary 7)*
EQE	External Quantum Efficiency
FF	Fill factor
HTM	Hole transport material
IQE	Internal Quantum Efficiency
ITO	Indium-doped Tin Oxide
IZO	Indium-doped Zinc Oxide
J_{SC}	Short-circuit current
MPP	Maximum power point
NiO	Nickel Oxide
NIR	Near infrared
OXPV	Oxford Photovoltaics Ltd. *(CHEOPS Beneficiary 10)*
PCE	Power conversion efficiency
PK	Perovskite
PV	Photovoltaic
SHJ	Silicon heterojunction
SST	Single side textured
TMM	Transfer Matrix Model(ling)
V_{OC}	Open-circuit voltage
WP	Work Package

Executive Summary

This deliverable aims at demonstrating a PK/silicon tandem device having an efficiency of 26% on 1 cm^2 active area. However the best efficiency achieved to date at CSEM is 23.3% on 1.43 cm^2. EPFL reached 25.6% on the same area. While slightly lower than the objective set by the project, these efficiencies surpass the reported record efficiencies obtained by other actors of the field. Moreover, recent developments within the frame of CHEOPS follow a steady pace that lets one foresee higher efficiencies in a near future.

Need for the Deliverable

In order to produce high efficiency tandem devices, several key parameters have to be adjusted, starting from the choice of charge transport materials and recombination junction, their respective thickness, to the bandgap of the PK absorber and the light trapping schemes used.

Thus, the PK top cell will require:

1) Minimized NIR absorption,
2) Suitable bandgap and thickness to match current in the bottom cell.

The SHJ bottom cell needs:

1) Appropriate front passivation,
2) Back texture for improved light management.

Moreover, a recombination junction that will insure a good light coupling between both sub-cells while minimizing shunt paths is required.

The deliverable will therefore validate the choices made in WP4 and pave the way towards high efficiency tandems.

Objectives of the Deliverable

With this deliverable, we aim to demonstrate optimized parameters leading to record tandem efficiencies. The meaningful size (>1 cm^2) of the device should make it a milestone for the further developments of tandem PK/SHJ solar cells.

Outcomes

We demonstrated a 23.3% PK/SHJ tandem cell on SST bottom cell, with current matching between the two sub-cells. When moving to a fully textured bottom cell, we show a 25.6% (24.8% MPP tracked) tandem cell.

Next Steps

In order to further improve the efficiencies demonstrated here, it is crucial to optimize the different transport and recombination layers. Simulations based on TMM are notably going to help adjusting the thickness of the layers, providing valuable insight as how to better control the light coupling into the cell. Moreover, by improving extraction of the charges through the different contacts, it is expected that the series resistance will be decreased which in turn will lead to an increased FF.

1 PK/SHJ tandem architecture

Previous achievements in WP4 (see Deliverable 4.1) featured single junction PK cells in an n-i-p polarity. Using spiro-OMeTAD as the HTM, these devices achieved high PCEs. Used in a tandem cell, this architecture implies that this HTM would be placed at the top transparent contact of the PK subcell. However, spiro-OMeTAD absorbs strongly the light in the blue part of the spectrum leading to significant reduction of the device's the photo-generated current. Therefore, a p-i-n polarity has been now adopted as the preferred architecture for tandems within this WP.

1.1 PK tandem at CSEM

The champion device made at CSEM featured a SST bottom cell. The top PK cell consists in an ITO/NiO recombination stack with a triple cations mixed halide PK absorber deposited by spin-coating. On the n-side, charges are extracted through a C60/SnO_2 bilayer to a front ITO layer. The Ag metallization is deposited by thermal evaporation through a shadow mask. An antireflective coating (MgF_2 by evaporation) ensures a proper light management at the front. Figure 1 shows a schematic of such a tandem device.

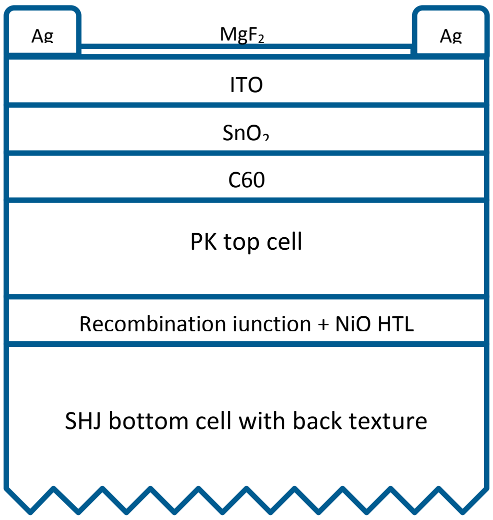

Figure 1. PK/SHJ tandem architecture using a SST bottom cell.

1.2 PK tandem at EPFL

In order to minimize reflection losses and hence maximize the light coupling into the bottom cell, it is necessary to replace the SST bottom cell by a fully textured one[1]. However, due to the size of the pyramidal texture (typically of the order of several microns), spin coating is no longer a suitable method to deposit the PK layer (or all the other subsequent layers). Therefore, EPFL developed and adapted a sequential evaporation deposition method described in Deliverable 4.1.

By evaporating part of the PK precursors, it is then possible to achieve a very conformal deposition of the PK over the textured bottom cell (see Figure 5 below). Figure 2 summarizes the layers stack for such a device.

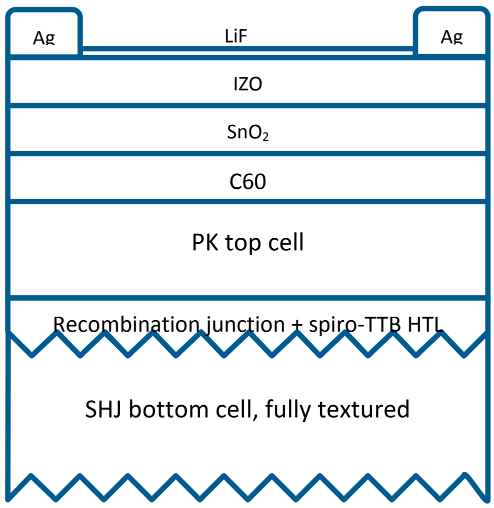

Figure 2. Tandem device with a textured bottom cell.

[1] J. Werner, L. Barraud, A. Walter, M. Bräuninger, F. Sahli, D. Sacchetto, N. Tétreault, B. Paviet-Salomon, S.-J. Moon, C. Allebé, M. Despeisse, S. Nicolay, S. De Wolf, B. Niesen and C. Ballif, "Efficient Near-Infrared-Transparent Perovskite Solar Cells Enabling Direct Comparison of 4-Terminal and Monolithic Perovskite/Silicon Tandem Cells", *ACS Energy Lett.*, **2016**, *1* (2), pp 474–480.

2 Results

2.1 PK/SHJ SST tandem

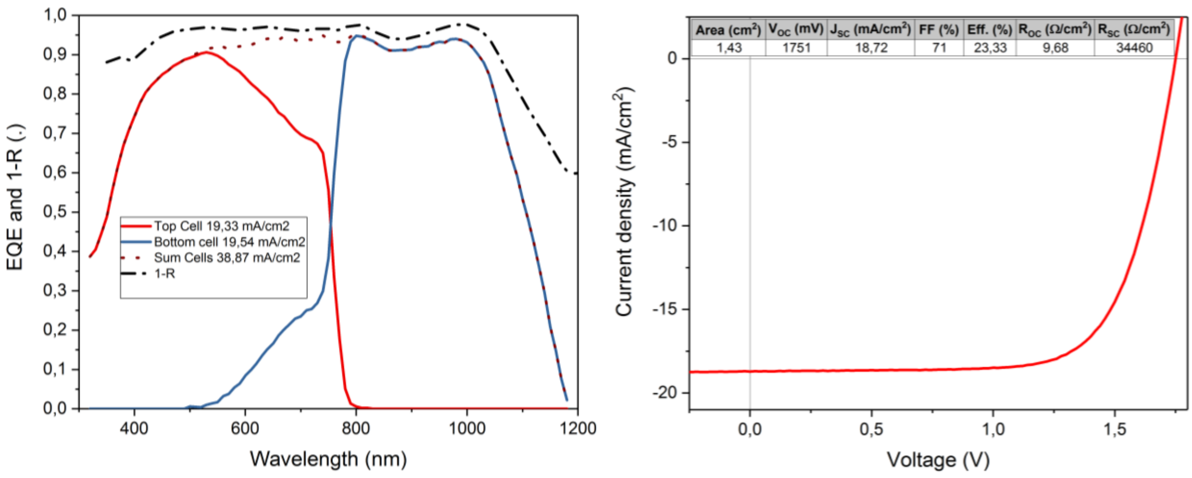

Figure 3. Tandem cell performances using a SHJ SST bottom cell. ***Left:*** External Quantum Efficiency measurement of top cell (red), bottom cell (blue), total current (dotted purple) and 1-Reflectance (dashed black). ***Right:*** current-voltage (IV) characteristics.

EQE measurement indicates a nearly matched current between top and bottom subcells. Moreover, reflective losses are minimized through careful selection of recombination layer thickness and optimized antireflection coating.

IV measurement confirms the current obtained by the EQE (minus shadow losses from the metal contacts, ~2.5% relative J_{SC}). V_{OC} is high, confirming the good top cell. The high series resistance however impacts the FF. All in all, the efficiency of 23.3% can be deemed high considering the lack of front texture and optimized contacts.

2.2 PK/SHJ tandem on fully textured bottom cell

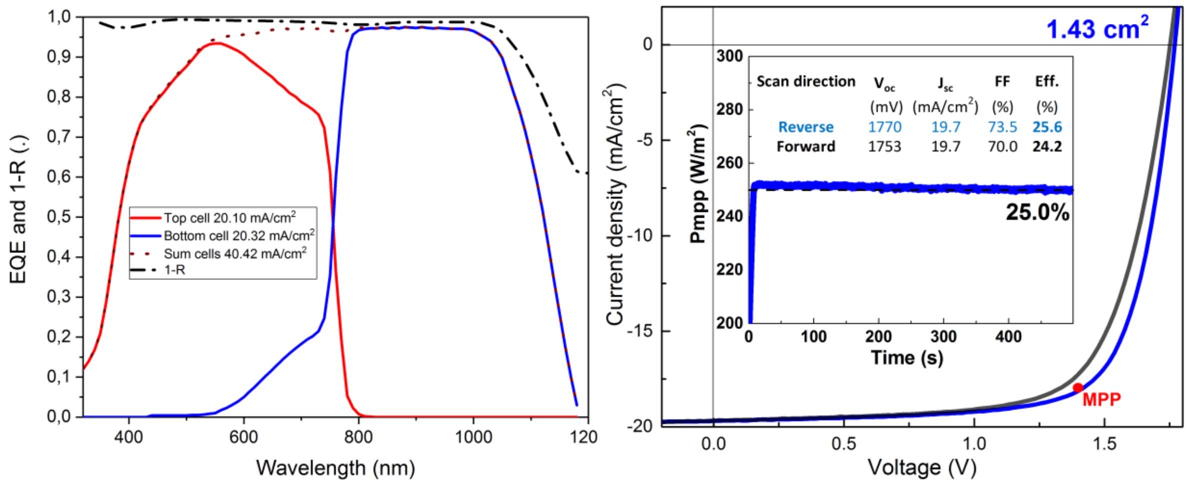

Figure 4. Tandem cell performances using a SHJ textured bottom cell. ***Left:*** External Quantum Efficiency measurement of top cell (red), bottom cell (blue), total current (dotted purple) and 1-Reflectance (dashed black). ***Right:*** current-voltage (IV) characteristics. The inset shows the MPP tracking over 10 min.

EQE and reflectance measurement shows minimized reflection losses due to the front texture of the bottom cell. This leads to increased current density in the bottom cell.

IV characteristics display a slight hysteresis, pointing towards unbalanced extraction of the charges in the top cell. Nevertheless, the reverse efficiency reaches 25.6 %, falling short of 0.4 points of the 26% goal. In addition to that, the MPP tracking falls on the reverse curve. The MPP tracked efficiency value is however lower than the reverse IV value. The steady-state value of 25% reported here is the highest obtained by CHEOPS partners for 2-terminal devices within the frame of the project. Notably, it is also the first public report of a PK/Si tandem cell using fully textured bottom Si cell.

In order to assess the uniformity and the conformality of the PK coating over the pyramid-shaped bottom cell, SEM images have been taken (Figure 5). They show a very conformal coverage of the tips, edges and valley of the pyramids, with a uniform thickness. This is crucial to obtain the high current density values displayed here and to ensure proper light management.

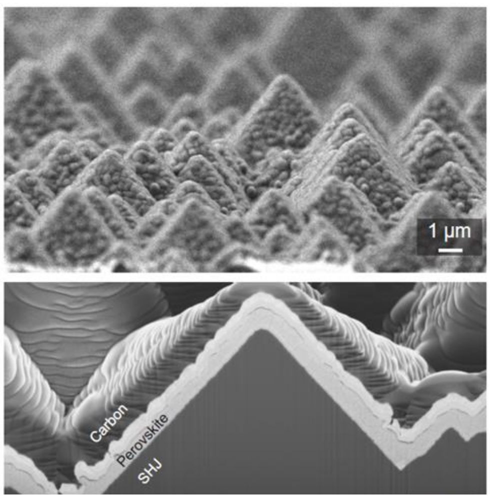

Figure 5. SEM image of the PK layer on top of the textured bottom cell. The lower image is a cross section obtained by focused ion beam. The carbon layer is here for protection purposes.

2.3 Comparison and considerations on front TCO optimization

Comparing the reflectance and EQE in Figure 3 and Figure 4, it is obvious that the front texture significantly reduces reflective losses, which in turn translates into a gain in current in both sub-cells. It is however interesting to consider the IQE, which accounts for the photon that are effectively absorbed by the cells (i.e. without reflection). Figure 6 compares the IQE spectra of the two tandems described above. Interestingly we see a significant discrepancy between the two devices at low wavelengths. This can be notably ascribed to the choice of front TCO. Indeed, IZO has much higher absorption than ITO in that range of wavelength due to its lower bandgap[2]. On the other hand, the larger mobility and lower free carrier absorption of IZO with respect to ITO translate into higher IQE at higher wavelengths. Moreover the reduced sheet resistance of IZO positively impacts the FF. All in all, this gives valuable information as to how we can further optimize the front contact of the cell.

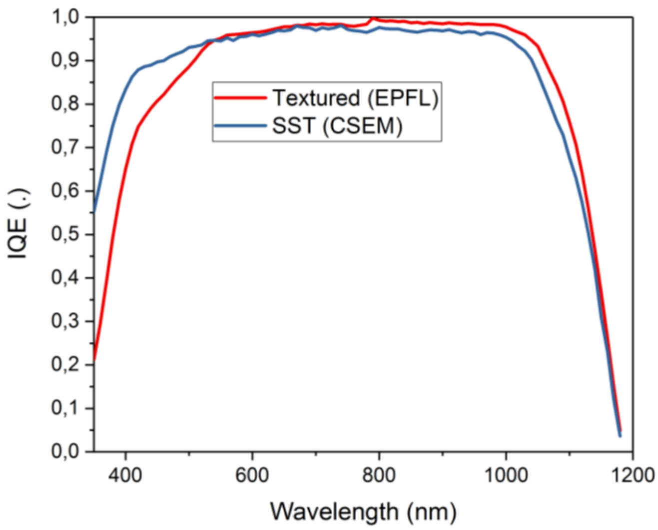

Figure 6. IQE spectra of textured and SST tandem cells.

[2] M. Morales-Masis, S. M. De Nicolas, J. Holovsky, S. De Wolf and C. Ballif. "Low-Temperature High-Mobility Amorphous IZO for Silicon Heterojunction Solar Cells", in *IEEE Journal Of Photovoltaics*, vol. 5, num. 5, p. 1340-1347, 2015.