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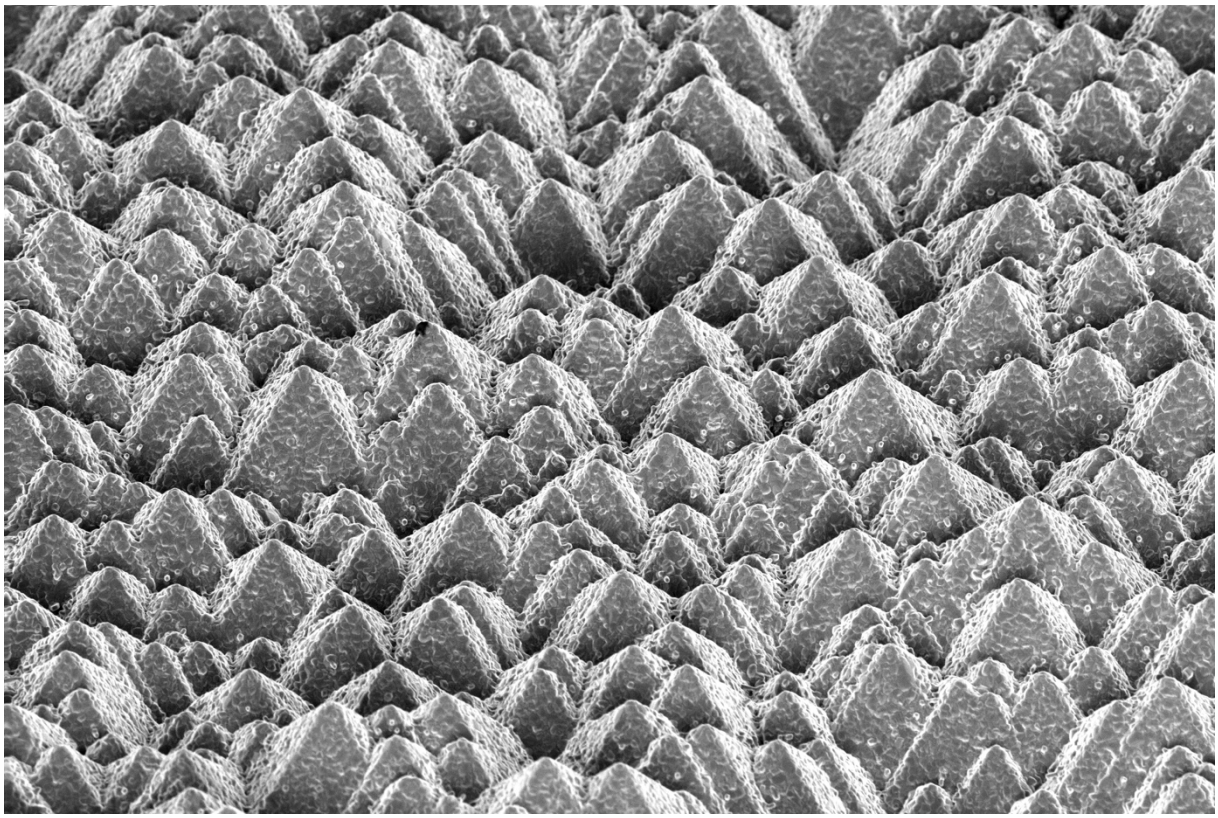
Interface engineering of perovskite/silicon tandem solar cells for improved performance and stability

Developments since the SFOE-project SYNERGY



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Summary

This report details the developments in the field of perovskite/crystalline silicon (c-Si) tandem solar cells at EPFL-PVLAB since the SFOE-funded Synergy project, which ended in 2017. They were obtained in the frame of the PV2050 PNR70 project. A key milestone in the development of the technology was achieved in June 2018 with the demonstration of 2-terminal monolithic perovskite/Si tandem solar cells that feature a silicon heterojunction bottom cell textured on both sides for optimal light management. This novel cell design enabled to increase the cell efficiency from 22.7% for a configuration with a bottom cell mechanically polished on its front (status at the end of the Synergy project) to 25.2% for the fully textured cell architecture. This novel tandem design opens the path towards efficiencies >30% and is directly compatible with the Si heterojunction manufacturing process. But many challenges others than purely performance-related also need to be addressed before a commercial implementation of perovskite/c-Si tandems can be envisaged, notably with respect to long-term stability. This is the topic that this new SOFE-funded project aims to tackle: improving the stability of these state-of-the-art textured tandems, notably in reverse bias conditions, conditions that have so far led to an irreversible degradation of all the tested cells at EPFL PVLAB but also elsewhere[1].

List of abbreviations

SHJ	Silicon heterojunction solar cell
Si	Silicon
c-Si	Crystalline silicon
KOH	Potassium hydroxide
MPP	Maximum power point
PVSK	Perovskite

1 Updates since the Synergy project

The texture on the front side of a c-Si cell, which takes the form of pyramids of a few microns in height, is essential to achieve efficiency targets >30% as it reduces reflection losses and promotes light trapping. This texture, which is created by etching the c-Si in a KOH solution, is an essential part of the process flow of SHJ, the c-Si technology that demonstrates the highest efficiency[2]. When making perovskite/Si tandems, this texture complicates the processing of the top cell as the perovskite absorber is usually deposited by spin coating precursors dissolved in a solution. And as the perovskite layer is typically one order of magnitude thinner than the height of the pyramids it needs to cover, it accumulates within the pyramid valleys, leaving the summits uncovered (Figure 1). This discontinuous coating leads to the formation of shunts and hence low cell performance. In addition, all the carrier-selective and electrode layers, which are sometimes only a few nm in thickness, must also be deposited in a conformal way on the Si texture. These difficulties have led most research groups to use silicon bottom cells that are mechanically polished on their front side to be compatible with today's mainstream solution-based perovskite deposition processes. But the use of wafers with a flat front-side, even smoothened by an industrially compatible chemical etching process rather than mechanical polishing, will result in a lower energy yield compared to standard KOH-etched wafers[3] and also higher industrial implementation costs as the standard SHJ process flow will have to be modified.

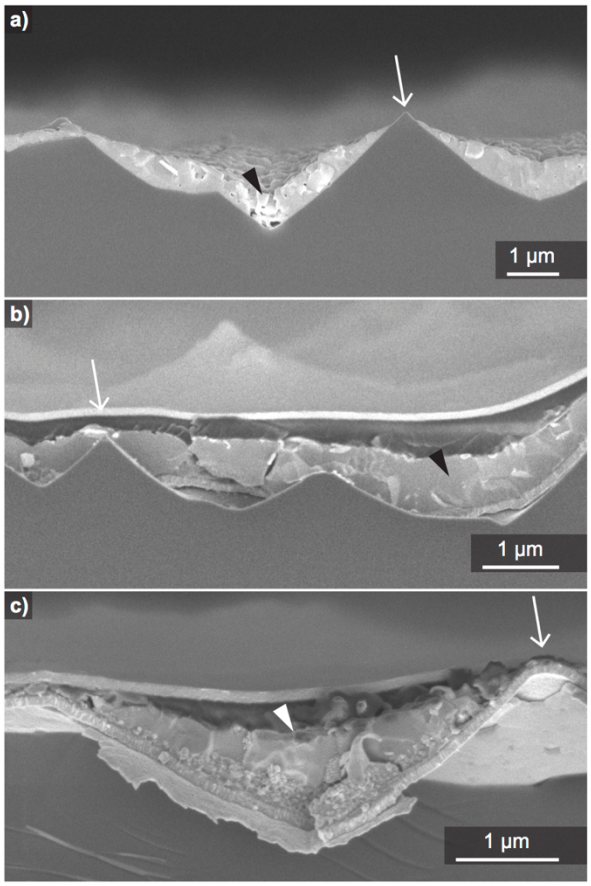

Figure 1: (a-c) Perovskite absorber and contacts spin coated directly on the Si pyramids. Arrows indicate regions where shunting will occur, while arrowheads show regions where the perovskite layer and contacts accumulated[4].

To ensure a full compatibility with the SHJ process flow, EPFL-PVLAB developed an innovative top cell fabrication process, which combines charge carrier-selective contacts and electrode layers deposited by thermal evaporation, atomic layer deposition and sputtering with a perovskite absorber deposited using a hybrid method to ensure its conformality on the Si texture. This method involves the evaporation of a template composed of lead iodide and caesium bromide, which is spin coated by a solution of formamidinium iodide and formamidinium bromide. The perovskite absorber is then crystallised through an annealing step at 150 °C, which is the maximum possible temperature of this perovskite top cell deposition process (to ensure that the SHJ bottom cell remains intact). This approach enables to fully cover the Si texture as shown in Figure 2.

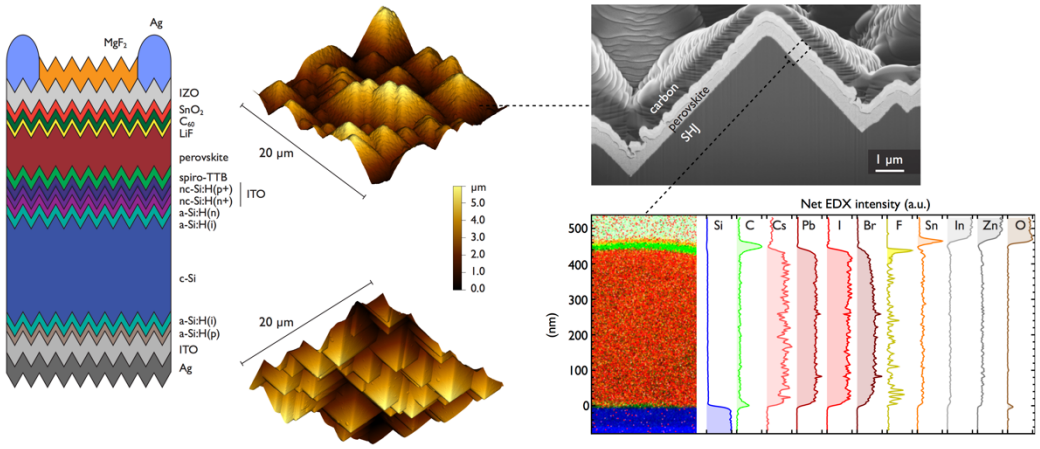

Figure 2: (From left to right) Fully textured perovskite/Si tandem cell architecture, atomic-force microscopy 3D reconstructions of the top and bottom texture of the tandem cell, focused ion beam cross-section and chemical mapping (by scanning transmission electron microscopy energy-dispersive X-ray spectroscopy). All the layers fully cover the Si pyramidal texture[4].

This design led to a gain in optics, as highlighted by a short circuit current of 19.5 mA/cm^2, and to an efficiency of 25.24% (independently certified by Fraunhofer ISE CalLab, Figure 3).

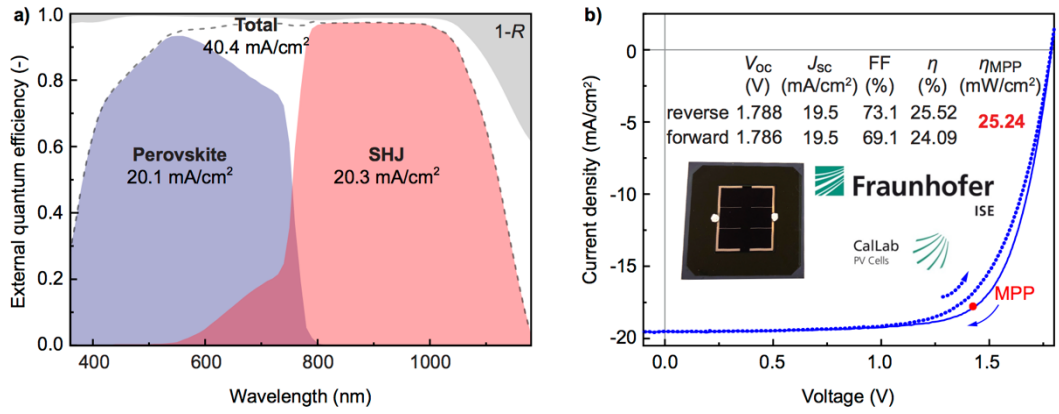

Figure 3: (a) External quantum efficiency and (b) current-voltage (J-V) properties of the record device certified by Fraunhofer ISE CalLab[4]

Finally, capitalising on this ability to coat the Si texture and on the tuneability of the perovskite absorber bandgap energy, EPFL-PVLAB pushed this concept one step further by demonstrating a

fully textured Si-PVSK-PVSK triple-junction solar cell with an open circuit voltage of 2.7 V, a first step towards low-cost high-efficiency triple-junction photovoltaics[5].

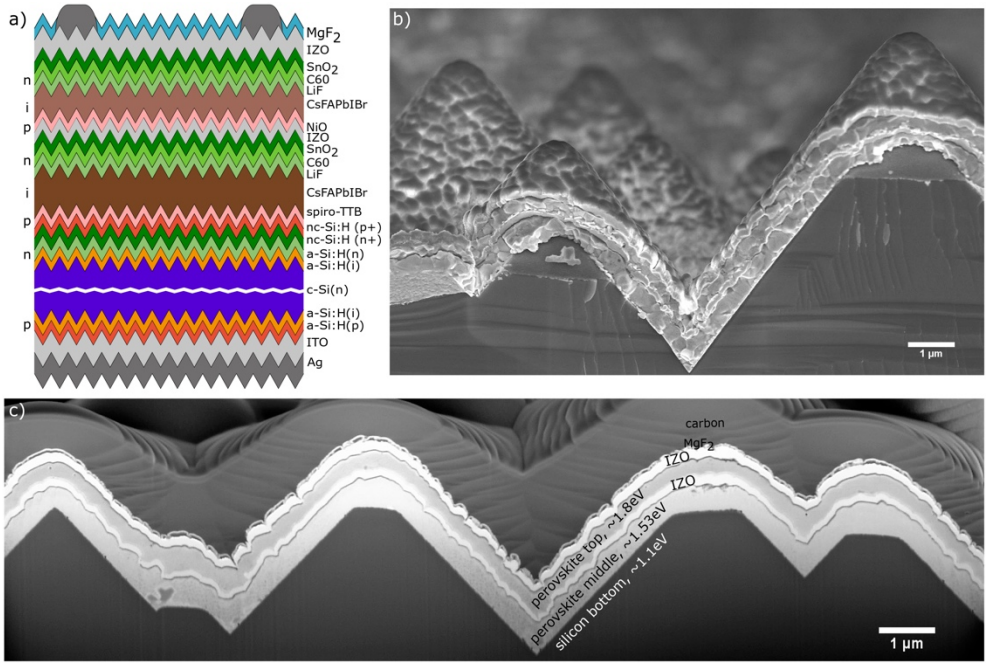

Figure 4: (a) Triple-junction cell architecture, b-c) scanning electron microscopy images of the cross-section of the cell, which were prepared either by cleaving the cell of by focused ion beam[6].

High-efficiency textured tandem cells were then subjected to various light soaking degradation tests in air and at room temperature, either as-such or encapsulated using a glass/glass/edge-sealant. Cells were electrically characterised at maximum power point under continuous AM1.5G illumination in ambient air (relative humidity level of 20–30%) at room temperature up to 61 and 240 hours for the bare and encapsulated cells, respectively. While the encapsulation scheme reduced the degradation rate from -0.15%rel to -0.03%rel, the results still indicate that a significant degradation is occurring. The Ag metallisation notably reacts with volatile iodine to form silver halide. Furthermore, hysteresis was found to increase with time, which could indicate an increased halide conduction due to various factors, e.g. the migration of halides to the contacts.

These stability aspects will be the central topic of the SFOE-funded INTENT project. More specifically, the aim will be to limit the migration of halides to the absorber (where there will anyway migrate due to the high ionic conductivity of the perovskite) and prevent their “leakage” into neighbouring layer or their volatilisation. Preventing this effect should greatly enhance the stability of these tandem cells, notably in reverse bias condition, conditions which trigger a fast degradation.

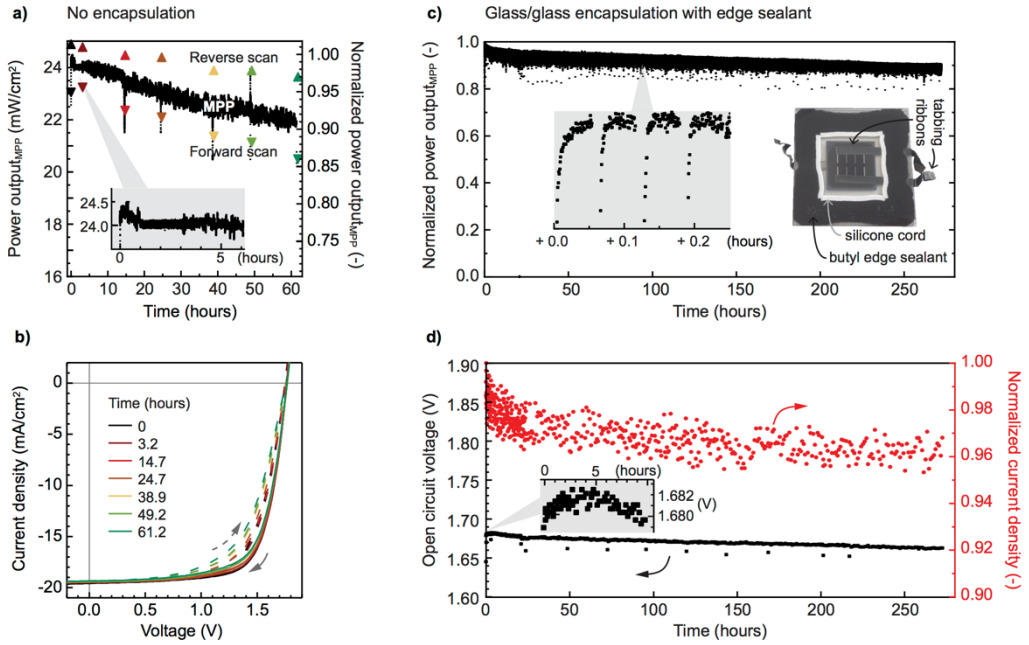

Figure 5: (a) Maximum power point (MPP) tracking of an unencapsulated tandem, b) its corresponding J-V parameters. c) normalised MPP tracking of a cell encapsulated with glass/glass and an edge sealant. The insets show the recovery behaviour after each J-V curve and a picture of the cell. d) Evolution of the open circuit-voltage and short circuit current density of the cell shown in c)[4].

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