Integration of semi-transparent conducting oxide electrodes in perovskite solar cells architecture

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In the recent years, perovskite-based solar cells (PSCs) have rapidly increased their power conversion efficiency (PCE), achieving certified performances comparable to that of silicon-based solar cells: 26.1% for single junction perovskite [1]. Thanks to their broad optical properties and low fabrication cost at large scale, PSCs have been considered for a variety of applications [2]. Among them, the tunable transmittance of Semi-Transparent PSCs (ST-PSCs) triggered important interest for silicon on tandem solar cells, which reached certified conversion records up 33.7%.

This intended application requires semitransparent electrodes displaying good tradeoff between conductivity and transmittance, appropriate energy levels, chemical stability, and low cost. However, once the suitable candidate is developed, new challenges may arise from the integration of such layer as a top electrode in the perovskite cells: damages on perovskite materials and charge transport layers or loss of overall cohesion of the cell architecture such as cracks or delamination.

The main purpose of this study is, first to compare the integration of sputtered transparent conducting oxide (TCO) as the semitransparent top electrode in various perovskite cells architectures developed at IPVF[3], then highlight the stumbling block to overcome and finally suggest remedial actions. Advanced material characterization (XRD, SEM, XPS, PL) allowed to consider the impact of TCO integration on the quality of stack materials while IV characterizations were performed to assess the power conversion efficiency and the stability under illumination tracked at maximum powerpoint tracking (MPPT).

As expected, the chemistry of the last exposed layer, either way electron transport layers (ETL) or hole transport layer (HTL) proved to be the main influence. Organic materials such as BCP are damaged by the sputtering power of TCO deposition. However, this phenomenon is partially reversible for doped or oxidized materials such as Spiro or PTAA. Inverted perovskite architecture (PIN) based on inorganic ETL was the most resilient right after fabrication, but similar PCE (>17%) and long-term stability (> 85%, 900h, 1 sun) could be achieved as well with (NIP) architecture based on organic HTL by the means of thermal and storage corrective post-treatments. Additionally, the cohesive behavior of the TCO with the stack under environmental stress turned out to be liked not only to the last layer but to the complete architecture. Mesoporous NIP cells based on HTL TiO_2 nanoparticles are more durable than those based on planar SnO_2 HTL. In this configuration, the failures are irreversible and preventive actions such as implementing proper buffer layers are mandatory.

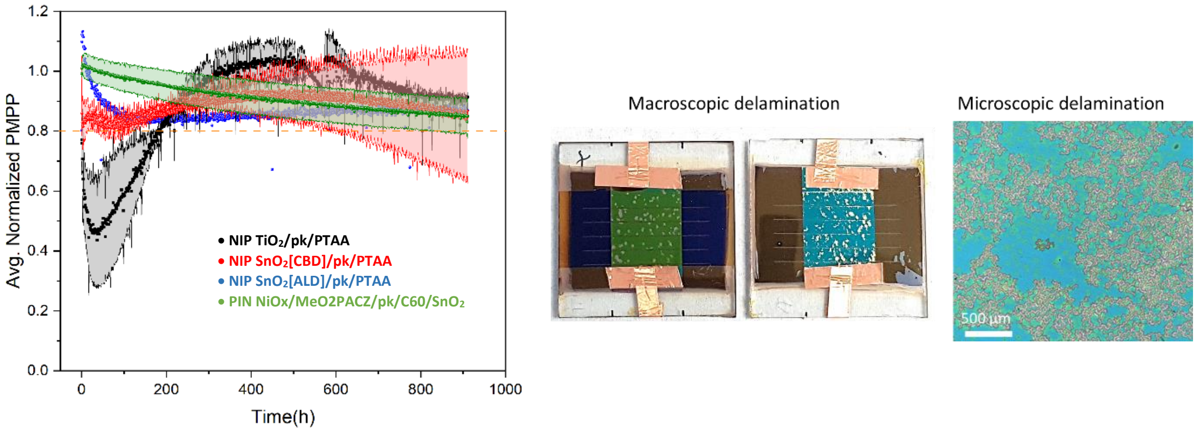

***Fig. 1** (Left) Normalized Pmax variation as a function of accelerated ageing time of different PSC architectures, (right) picture of macroscopic delamination of the TCO layer observed on perovskite solar modules (4*4cm^2) under an optical microscope.*

(1) *Best Research-Cell Efficiency Chart*. https://www.nrel.gov/pv/cell-efficiency.html.

(2) Patil, P.; Sangale, S. S.; Kwon, S.-N.; Na, S.-I. Innovative Approaches to Semi-Transparent Perovskite Solar Cells. *Nanomaterials* **2023**, *13* (6), 1084. https://doi.org/10.3390/nano13061084.

(3) Raoult, É. Semi-Transparent Perovskite Solar Cells for Large Area 4-Terminal Silicon-Based Tandem Devices. These de doctorat, université Paris-Saclay, 2022. https://www.theses.fr/2022UPAST078 (accessed 2023-09-15).