Outdoor study of Photovoltaic Mini-Modules with different perovskite compositions

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Abstract — **A long-term outdoor study of photovoltaic mini-modules with different perovskite compositions was undertaken to detect differences in their long-term performance that could be attributed to their composition. Diurnal efficiency degradation and overnight recovery was observed over the outdoor testing period. In addition, the performance recovery of the mini-modules was investigated after their removal from the field to detect differences in the reversible process mechanisms between the different module compositions. Light current-voltage (IV) scans, Raman spectroscopy techniques and spatially-resolved Electroluminescence (EL) measurements were utilized for this purpose.**

I. Introduction

Perovskite photovoltaic devices offer excellent prospects for delivering a very low cost, environmentally benign energy source. Despite achieving excellent power conversion efficiencies, these devices suffer from poor stability under real opeating conditions[1]. Since limited experience of long-term monitoring of perovskites is available in the literature so far, increased experience of measuring these devices outdoors under their intended opeating conditions is sought by the scientific community. To this end, Imec and FOSS along with several other partners have undertaken exploratory perovskite measurements of several mini-modules with different compositions in the field. Furthermore, performance recovery of the modules was investigated after their removal from the field by employing light current-voltage (IV) scans, Raman spectroscopy and spatially-resolved Electroluminescence (EL) technique at regular time intervals during their storage in the dark. With this approach, long-term trends in defect evolution are studied by comparing spatially-resolved EL images taken at regular intervals after exposure (during performance recovery process).

II. Experimental Approach

Four (4) perovskite mini-modules with composition $Cs_{0.18}FA_{0.82}PbI_{2.82}Br_{0.18}$ and four (4) perovskite mini-modules with composition $Cs_{0.05}FA_{0.85}MA_{0.10}Pb(I_{0.97}Br_{0.03})_3$ have been studied outdoors. The complete set of mini-modules were tested in the period between the end of May 2022 and the end of July 2022 while four (4) mini-modules (two from each type) were left in the field until the end of September 2022 for extended outdoor testing. Several identical modules of the same structure were tested to have better statistical data from samples of the same type. Alongside the current-voltage (IV) traces of the devices, environmental sensors have been used to collect solar irradiance in the plane of array, ambient and device temperature, wind velocity and humidity/precipitation levels. The IV traces were recorded every 10 minutes and both forward and reverse sweeps were performed each time at a fixed sweep rate of 1 V/sec. Between IV scans the devices were kept at open circuit. Control modules of each type were kept indoors in the dark.

The electrical measurements have been acquired by a single current-voltage source-meter multiplexed to take sequential measurements from the devices under test. LabVIEW software was used to record the IV-traces at global normal irradiance (GNI) levels above 400 W/m^2. Forward-first IV sweeps have been used in all instances and for all modules under test.

After their removal from the field, performance recovery studies were carried out using current-voltage (IV) scans, Raman Spectroscopy and spatially-resolved EL measurements. These techniques were applied to the mini-modules once per month for the first four months after their removal from the outdoor site and during their storage in the dark. For the EL images a high-performance CCD matrix camera cooled at -5°C was used. Dedicated software was utilized to collect the EL images and record the test parameters. For the current-voltage (IV) curves, a SOL3A solar simulator from Newport was employed at 1000 W/m^2 while for the Raman measurements, a LabRam HR800 spectrometer from Horiba Scientific was used in a backscattering geometry under ambient conditions at room temperature. Raman spectra were acquired at distinct positions using a 50× objective (NA 0.55, Leica), a laser excitation wavelength of 532 nm, a probing micro-beam diameter of ≈1.5 μm, and a laser power in the range 0.86 μW – 4.3 mW.

III. Results and Discussion

A. Outdoor Studies

The normalized power conversion efficiency (PCE) and the open-circuit voltage from the devices under test during the outdoor exposure are depicted in Fig. 1. Modules 3A, 3B, 3C and 3D correspond to the three-cation perovskite composition $Cs_{0.05}FA_{0.85}MA_{0.10}Pb(I_{0.97}Br_{0.03})_3$ while the mini-modules 2A, 2B, 2C, and 2D correspond to the two-cation perovskite composition $Cs_{0.18}FA_{0.82}PbI_{2.82}Br_{0.18}$. Fig. 1 shows the recorded electrical parameters over the period between the end of May and beginning of September 2022. Modules 3C, 3B, 2A and 2B were left in the field for a more extended period while modules 3A, 3D, 2C and 2D were removed by the end of July 2022.

Statistically significant differences in the performance trends between the two cell types could not be detected. The two-cation perovskite devices generally showed an initial performance improvement over the first few days of outdoor exposure. Furthermore, the dataset suggests that the two-cation structures present better long-term stability. Three (3) out of four (4) three-cation structures exhibited a rapid initial drop in PCE. Only one three-cation device (3C) presented a (considerable) initial PCE improvement. The PCE drop in the three-cation structures is mainly related to voltage reduction observed in the first days of outdoor operation. Voltage losses up to 37% were detected in the three-cation samples indicating ion migration that results in defect formation. The presence of methylammonium (MA) species likely boosts ion migration effects in the three-cation devices. Another possible reason for the accelerated degradation of the three-cation perovskite modules could be the utilization of a gas quenching technique that is not optimised for the specific three-cation composition. By investigating trends in short-circuit current it was found that short circuit current losses are significant in all the two-cation perovskite mini-modules. However, this behaviour is not obtained in all the three-cation perovskite modules.

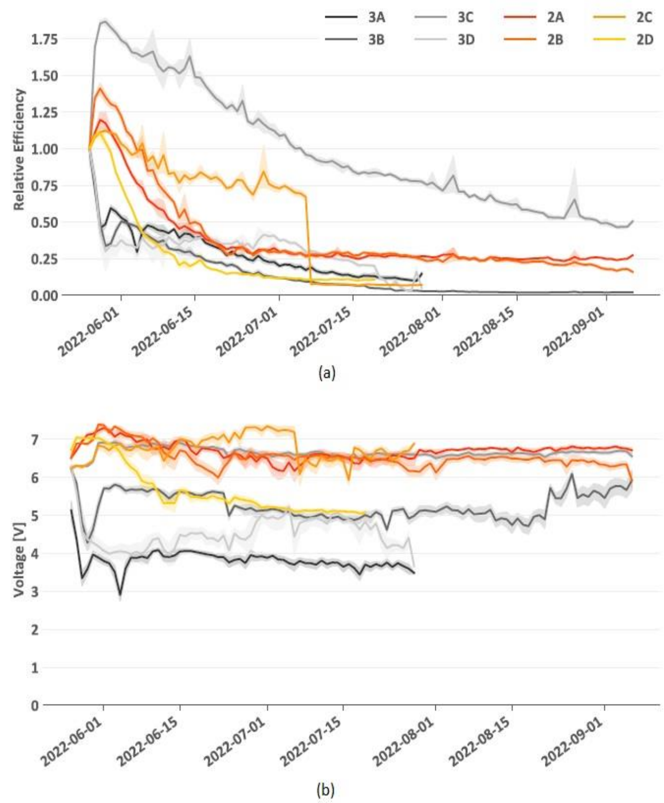

Fig. 1. (a) Normalized PCE and (b) open-circuit voltage of the perovskite mini-modules with different composition during the outdoor testing in the period between the end of May and beginning of September 2022.

Furthermore, diurnal efficiency degradation and performance recovery overnight were studied during the outdoor exposure of the mini-modules. The diurnal efficiency degradation values and trend differs from module to module with the two-cation perovskite composition modules presenting lower diurnal efficiency degradation and subsequent recovery compared to the three-cation perovskite structures. In the two-cation perovskites diurnal efficiency degradation up to 50% was detected. On the other hand, in the three-cation structures diurnal efficiency degradation up to 70% was found.

B. Performance Recovery Studies

After modules were removed from the outdoor site they were kept in a desiccator in the dark and periodic light IV scans, Raman spectroscopy measurements and spatially-resolved

Electroluminescence images were collected for the study of performance recovery in the mini-modules. To evaluate the performance recovery of the mini-modules in time, samples 3A, 3D, 2C and 2D were selected to be monitored on a monthly basis for a duration of three (3) months (August, September, November) after outdoor testing. Illuminated IV characteristics and spatially-resolved Electroluminescence (EL) images of the samples were captured at FOSS while Raman spectroscopy measurements were implemented at the Fraunhofer Institute for Ceramic Technologies and Systems.

Among the four modules studied (3A, 3D, 2C, 2D) only one three-cation mini module (3A) exhibited performance recovery (according to light current-voltage scans) during its storage in the dark. All the other mini-modules investigated exhibited further performance degradation over time (see Fig.2).

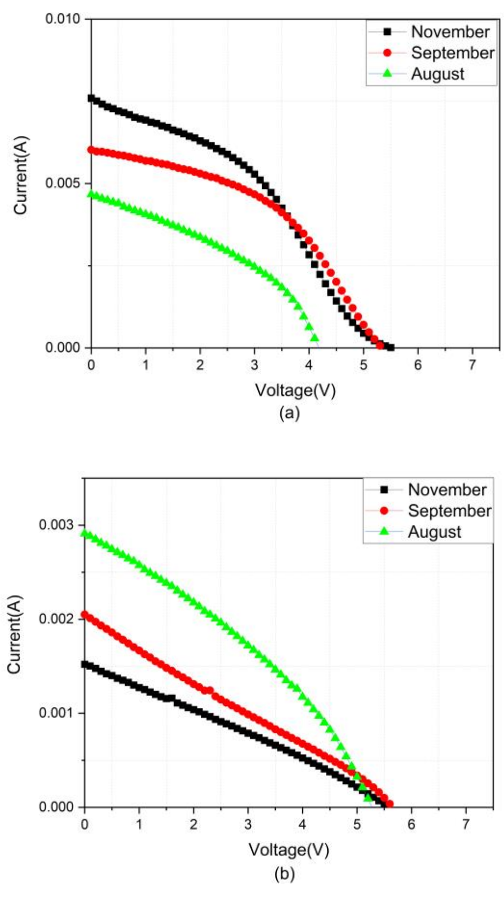

Fig. 2. Current-voltage scans of the mini-modules (a) 3A and (b) 2D during their storage in the dark after outdoor testing (May-July 2022).

The spatially-resolved EL measurements showed a reduction of the radiative EL emission in all the mini-modules during their storage indoors giving evidence of performance degradation in the modules. It is worth noting that a similar voltage was applied during the systematic EL studies for comparison purposes.

The Raman spectroscopy technique was used to detect changes in the chemical composition of the samples attributed to reversible processes and performance recovery. The Raman spectra of the two-cation perovskites (2C,2D) was difficult to interpret since none of the peaks presented in their Raman spectra are related to the layers composing the mini-modules. However, the peaks presented in the Raman spectra of the three-cation perovskites can be associated to particular vibrational modes of the molecule inside the multilayer structure. A change in the Raman peak located at 1850 cm^{-1} is visible in all the three-cation modules under test and is believed to be related with reversible processes in the mini-modules.

IV. Conclusions

Long-term outdoor testing of photovoltaic mini-modules with two different perovskite compositions has been performed. Statistically significant differences in the performance trends between the two perovskite compositions could not be detected in these samples. The three-cation perovskite structures exhibited a rapid initial drop in PCE that has been attributed to lower voltage output. Due to this the two-cation structures presented better long-term stability. Performance studies after outdoor testing and during their storage in the dark revealed performance degradation for the majority of the mini-modules. Spatially-resolved EL images presented a reduction of radiative emission over time in agreement with the current-voltage curves. Raman studies during the storage of the three-cation devices in the dark exhibited reversible change of the peak at 1850 cm^{-1}.

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References

[1] K. Domanski, E. A. Alharbi, and A. Hagfeldt, " Systematic investigation of the impact of operation conditions on the degradation behaviour of perovskite solar cells," *Nat. Energy*, vol. 3, pp. 61-67, 2018.