OUTDOOR MONITORING AND ASSESSMENT OF PEROVSKITE MINI MODULES

Vasiliki Paraskeva[1](vparas01@ucy.ac.cy, tel: +35722894321), Matthew Norton[1](matthewn@ucy.ac.cy), Maria Hadjipanayi[1](hadjipanayi.maria@ucy.ac.cy), Afshin Hadipour[2](Afshin.Hadipour@imec.be), Aranzazu Aguirre[2](Aranzazu.Aguirre@imec.be), Rita Ebner[3](Rita.Ebner@ait.ac.at), George E. Georghiou[1](geg@ucy.ac.cy)
[1.] FOSS Research Centre for Sustainable Energy, Department of Electrical and Computer Engineering, University of Cyprus, 75 Kallipoleos St., Nicosia, 1678, Cyprus
[2]imec, Kapeldreef 75, 3001 Leuven, Belgium,
[3]AIT Austrian Institute of Technology, Center for Energy, Giefinggasse 2, 1210 Vienna,

ABSTRACT: The long-term performance stability of perovskite-based photovoltaic (PV) devices under real operating conditions remains in question since these devices are sensitive to moisture, illumination, temperature etc. Two groups of perovskite mini modules with different perovskite active layers in each group have been fabricated and exposed outdoors for the purpose of studying their outdoor performance stability and of identifying differences in their long-term performance that can be attributed to their composition. Preliminary results indicated differences in the long-term stability of the two groups of modules, one group exhibiting less degradation than the other. Furthermore, significant current losses have been detected in all modules under test whilst voltage and Fill Factor losses were found to be lower This assessment also studies long-term trends in defect evolution by comparing spatially resolved electroluminescence (EL) images taken indoors before outdoor exposure and after outdoor testing. Significant changes in EL emission have been detected in the modules before and after outdoor testing due to the increase of degradation pathways in the devices.

Keywords: perovskite, characterization, degradation, electroluminescence, PV module

1 INTRODUCTION

Over the last decade, perovskite-based solar cells have shown impressive power conversion efficiencies (PCEs) over 25.2% for single-junction cells [1]. However, the performance stability of those devices remains in question since perovskite-based devices are sensitive to moisture, illumination, temperature etc. [2]. Several indoor testing techniques have been applied to study performance degradation so far [3] while few papers have presented outdoor field-testing results [4]. With the improvement in materials and solar cell fabrication, some perovskite devices are now passing standardized test protocols such as IEC 61215 involving indoor tests in which modules are heated up to 85°C for 1000 hours at 85% relative humidity and undergo temperature cycling from -40°C to 90°C. The IEC tests for perovskite solar cells are summarized in [5]. These measurements and aging procedures are done to qualify to a minimum standard of initial performance, and they do not resemble the outdoor operational conditions where temperature, humidity and irradiance are continuously changing. Only limited experience of long-term outdoor testing of perovskite-based PV devices is available in the literature due to the relative novelty of this technology [6], [7]. Furthermore, the long-term outdoor study of different structure perovskite modules by using a well-defined measurement procedure with numerous samples is essential for the establishment of reliable long-term stability and performance from perovskite samples.

In this context, this paper aims to characterize the output of several perovskite mini modules of different structure under real operating conditions. Alongside these devices, measurements of irradiance in the plane of array were taken in combination with other environmental factors. Such measurements help to investigate degradation processes and their correlation with environmental parameters over the same period. This assessment also studies long-term trends in defect evolution by comparing spatially-resolved electroluminescence images taken indoors before outdoor exposure and at regular intervals after field exposure.

2 EXPERIMENTAL APPROACH

Two different types of perovskite modules (three of type A and four of type B) have been mounted outdoors in a fixed plane (see Figure 1) and current-voltage (I-V) measurements have been collected at regular intervals. The active layer of the type A module is a two-cation perovskite ($Cs_{0.18}Fa_{0.82}PbI_{2.82}Br_{0.18}$) with no additives while type B modules have the same perovskite active layer with formamidinium chloride (FACl) additives inside. The purpose of studying several modules of the same structure is to have better statistical data from samples of the same type. Open-circuit (V_{oc}) loading was applied between the IV scans. A dummy module was placed alongside the 7 modules under study for the collection of temperature at the backside of the modules. Forward and reverse voltage sweeps were applied to the module during each IV measurement. The outdoor testing of the samples started on the 12th of January 2021 and lasted for 17 weeks. Alongside the IV traces from 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 electrical measurements have been acquired by a single current-voltage source-meter multiplexed to take sequential measurements from the devices under test. A LabVIEW program was created to record the IV-traces every 5 minutes at high Global Normal Irradiance (GNI) conditions (GNI > 400 W/m^2). Both forward (< 0 V to > V_{oc}) and reverse ((> V_{oc} to < 0 V) voltage sweeps have been applied to the devices. Forward sweeps were performed first on all modules under test. The voltage sweep rate was chosen to be 1V/sec.

For type A perovskite modules studied outdoors, a control module of identical structure was kept indoors under dark, controlled conditions to help distinguish the degradation that occurs outdoors from the aging degradation processes occurring inherently within the device. The current-voltage characteristic of the control modules was measured at AIT with the OAI's TRI-SOL Solar Simulator, Class AAA, Xe Arc Lamp with 100 mW/cm^2 power output. The current at the contacts of the cell was collected by using a Keithley 2651A source meter and by applying the ivRider software. The temperature of the samples was kept at 25°C.

Figure 1: Perovskite mini-modules mounted outdoors on a tracker at the University of Cyprus site.

Alongside the collection of IV traces, spatially-resolved EL measurements were taken from the modules before outdoor exposure to look for changes occurring in EL images after outdoor exposure thus enabling the study of defect evolution at the different perovskite modules. A high-performance CCD matrix camera at -5°C was used during the EL studies. Dedicated software was utilized to collect the EL images at the same testing parameters for comparable results.

3 RESULTS & DISCUSSION

During the whole period of outdoor exposure, no visible degradation due to humidity ingress inside the encapsulant material was observed in the modules. Over the same period significant rainfall was present at the test location but this seems not to have caused any distortion of the encapsulant material indicating the good quality of the encapsulation of these modules**.**

Figure 2 depicts the reduction in the normalized power conversion efficiency (PCE), Fill Factor (FF), open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}) observed in the first ten weeks of outdoor exposure from all 7 modules under test. These measurements were taken at reverse sweeps.

In Figure 2 modules labelled A, C, and I are of type A while modules O, S, P and Q are of type B. All parameters have been normalized to their initial values obtained outdoors.

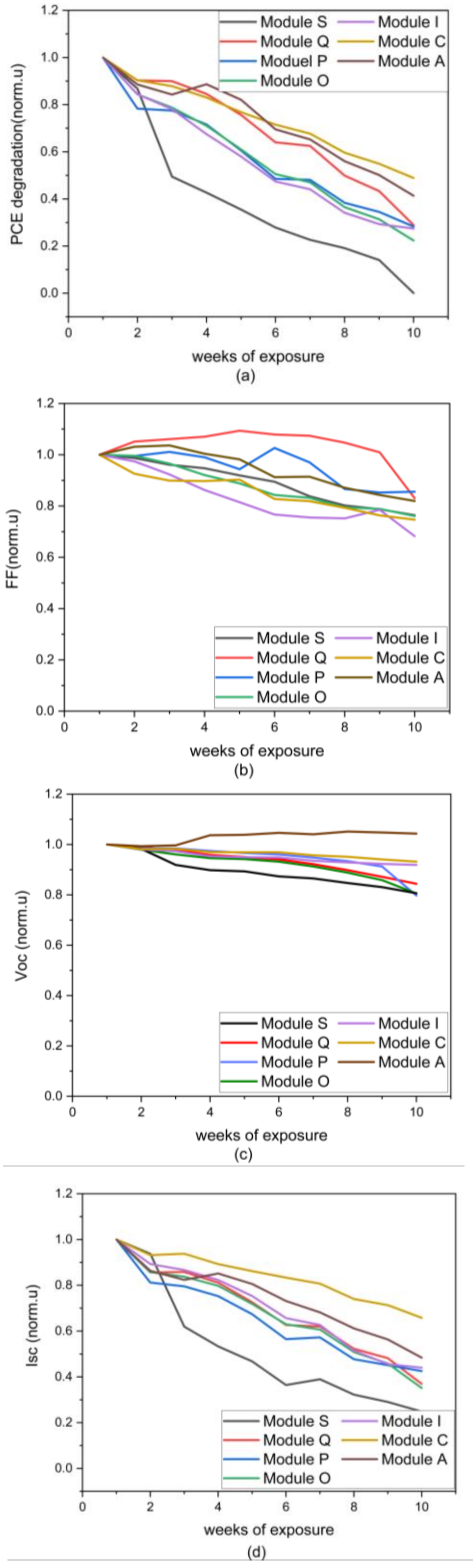

Figure 2: a) Efficiency (b) Fill Factor (c) Open-circuit voltage and (d) Short-circuit current degradation of perovskites mini-modules of type A and B the first 10 weeks of outdoor exposure. All parameters have been normalized to their initial values.

The majority of type A modules present similar degradation rates over the first 10 weeks of outdoor exposure (module A, module C). However, in type B modules more deviations exist in efficiency degradation. Only two out of four type B modules present similar efficiency degradation levels (module O, module P) while the rest of the type B modules present higher (module S) or lower (module Q) efficiency degradation. Having a closer look on the efficiency behavior of the modules the testing period can be classified into two periods: the initial burn-in period which lasts up to 3 weeks after the modules' installation and the period after the 3rd week of operation. During the initial burn-in performance period type B modules degrade more than type A modules while after the 3rd week of operation the degradation rate is the same for the two types of modules under test.

To identify the root cause of efficiency degradation of the modules, all the other electrical parameters (Fill Factor, open-circuit voltage, short-circuit current) have been plotted over the testing period (see Figure 2). Figure 2(c) demonstrates that voltage losses are not significant in all the modules under test. The maximum open-circuit voltage reduction obtained in the devices was 20%, with type A modules presenting slightly lower open-circuit voltage losses than type B modules. The mean voltage losses in type B modules was calculated to be 19.5% while voltage losses in type A modules are 5.2%. It is worth noting that one module of type A (module A) presents a small open-circuit voltage enhancement over the testing period. This result agrees with the indoor data under the solar simulator at standard testing conditions. The origin of the open-circuit enhancement in module A is unclear and more investigation is underway. An investigation of Fill Factor changes over the testing period has been carried out and plotted in Figure 2(b). The maximum Fill Factor reduction of 30% was present. The majority of type A modules present higher Fill Factor losses, but this is not a clear trend since large fluctuations in FF are present in all modules under test. Short-circuit current losses were detected in all modules under study indicating that the major cause of the efficiency degradation is the current (Figure 2d). Current losses up to 75% were detected during outdoor exposure. The mean short-circuit current loss in type B modules was 60.5% while for type A modules it was 47.6%. The fastest short-circuit current degradation rate was obtained in the first two weeks of outdoor exposure in most modules. After that time the degradation rate for current decreases. These results indicate that a 'faster' degradation mechanism occurs in devices just after the exposure to light and temperature levels outdoors and this is replaced by a 'slower' degradation mechanism after some time.

By studying the efficiency behavior of the modules over a day it can be observed that their performance presents changes over a day depending on whether the data was collected in the morning or afternoon. The modules in most cases perform better in the morning hours than in the afternoon on the days under examination. The efficiency drop during the day is mainly attributed to current reduction. In some cases, Fill Factor losses are detected over the day but this was obtained only in some modules. The current drop is most likely related to irradiance since the first hours after following exposure there is a rapid current degradation. The decrease of current over the day could be also attributed to temperature rise of the module, however, after data analysis we have found that the impact of temperature on current reduction is a minor effect. The improved performance in the morning hours suggests that the devices present some form of recovery overnight. This result was obtained in the outdoor assessment of perovskite modules recently [7].

To compare the degradation of the modules tested outdoors with the concurrent degradation of the control modules kept indoors, the control modules were tested regularly under the solar simulator over the timespan of the outdoor studies. Figure 3 illustrates the changes in the current-voltage characteristics of a control module kept indoors and a module located outdoors. The changes in all electrical parameters of the device are more severe in the modules kept outdoors. The efficiency degradation of the module exposed outdoors reaches 58.5% while at approximately the same time interval the control module degradation was 15.7%. It is assumed that this degradation originates from an innate aging process occurring within the devices under the environmental conditions present during storage (humidity, temperature etc.).

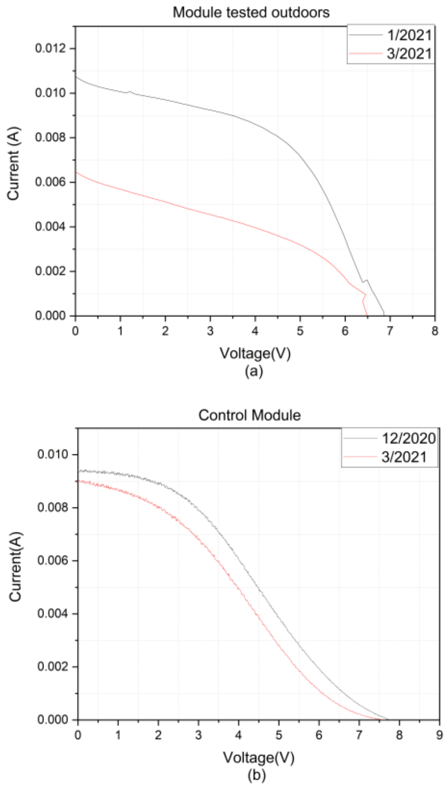

Figure 3: Current-voltage characteristics of a (a) control module and a (b) module exposed outdoors at different times during outdoor campaign.

For the investigation of long-term trends in radiative emission and defect evolution, a spatially-resolved EL imaging technique has been used prior to and after field testing. EL images have been collected from all modules under test before and after outdoor exposure. It is worth noting that all the modules have been left outdoors for in total 17 weeks and the EL images were collected before their installation outdoors and after the 17th week of operation. The EL images before and after outdoor testing from two modules of type A and two modules of type B can be found in Figure 4 and Figure 5 respectively. The same voltage applied in all devices before outdoor testing for comparison purposes.

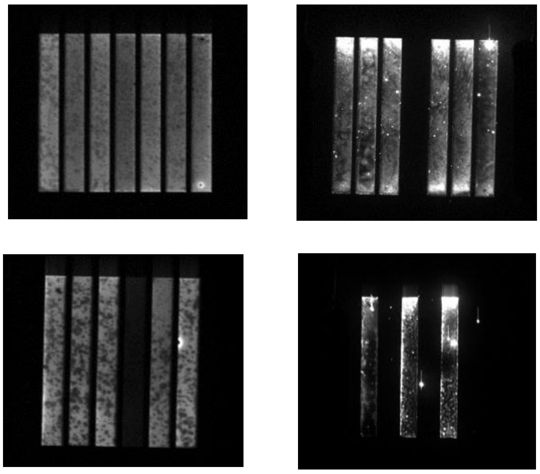

Figure 4: Spatially-resolved EL images before (left) and after 17 weeks of outdoor testing (right) for two modules of type A.

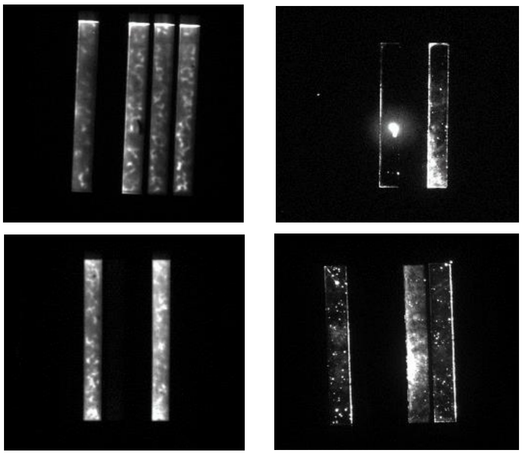

Figure 5: Spatially-resolved EL images before (left) and after 17 weeks of outdoor testing (right) for two modules of type B.

Similar EL image patterns were obtained over the modules of the same type. Some cells within the modules did not luminesce prior to the outdoor testing, indicating a degree of degradation of the modules before their exposure outdoors. The majority of type A modules presents better EL emission compared to emission from type B modules in studies prior to field testing giving an indication of the presence of more non-radiative paths and thus lower material quality in type B modules. EL images after outdoor testing demonstrate lower emission and more inhomogeneities within the modules.

4 CONCLUSIONS

The long-term outdoor performance of different perovskite mini-modules installed side-by-side was studied. Preliminary results indicated differences in the long-term stability of the two groups of modules with less efficiency degradation obtained in modules without additives in the active perovskite layer. The type B modules were shown to degrade over the course of 10 weeks to around 20% of their initial value while type A modules degrade to around 39% of their initial value. The statistical differences in the efficiency degradation of two different types of perovskite cell structure under continuous on-sun exposure suggests that the test methodology used will be successful in revealing which cell type is better suited to long term outdoor use. Significant current losses were obtained in all modules under study while voltage losses were insignificant. Results have indicated that the encapsulation of these devices successfully protects against degradation mechanisms associated with atmospheric exposure. Control modules were tested indoors in parallel with the outdoor campaign and indicated an efficiency degradation of 15% which arise from innate aging processes within the devices. Finally, spatially-resolved EL measurements of the modules were undertaken before and after field testing which demonstrated significant changes in the EL emission of the test devices.

6 AKNOWLEDGEMENTS

This work was co-financed by the European Regional Development Fund and the Republic of Cyprus through the Research & Innovation Foundation (Grant No.: INFRASTRUCTURES/1216/0043).

7 REFERENCES

[1] NREL, “Best efficiency chart Photovoltaic Research,” *https://www.nrel.gov/pv/cell-efficiency.html*, 2019.

[2] 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.

[3] S. Kundu and T. L. Kelly, “In situ studies of the degradation mechanisms of perovskite solar cells,” *EcoMat*, vol. 2, no. 2, pp. 1–22, 2020, doi: 10.1002/eom2.12025.

[4] M. Jošt *et al.*, “Perovskite Solar Cells go Outdoors: Field Testing and Temperature Effects on Energy Yield,” *Adv. Energy Mater.*, vol. 10, no. 25, 2020, doi: 10.1002/aenm.202000454.

[5] P. Holzhey and M. Saliba, “A full overview of international standards assessing the long-term stability of perovskite solar cells,” *J. Mater. Chem. A*, vol. 6, no. 44, pp. 21794–21808, 2018, doi: 10.1039/C8TA06950F.

[6] V. Stoichkov, N. Bristow, J. Troughton, F. De Rossi, T. M. Watson, and J. Kettle, “Outdoor performance monitoring of perovskite solar cell mini-modules: Diurnal performance, observance of reversible degradation and variation with climatic performance,” *Sol. Energy*, vol. 170, no. June, pp. 549–556, 2018, doi: 10.1016/j.solener.2018.05.086.

[7] M. Norton, M. Kohlstädt, M. Hadjipanayi, V. Paraskeva, U. Würfel, and G. E. Georghiou, “Experiences of continuous on-sun performance measurements of perovskite mini-modules,” 2020.