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Outdoor performance monitoring of perovskite solar cell mini-modules: Diurnal performance, observance of reversible degradation and variation with climatic performance

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ABSTRACT

The outdoor performance monitoring of two types of perovskite solar cell (PSC) mini-modules based on two different absorbers - $CH_3NH_3PbI_3$ (MAPI) and $Cs_{0.05}FA_{0.83}MA_{0.17}PbI(_{0.87}Br_{0.13})_3$ (FMC) is reported. PSC modules displayed markedly different outdoor performance characteristics to other PV technologies owing to the reversible diurnal changes in efficiency, difference in temperature coefficient between absorber layers and response under low light conditions. Examination of diurnal performance parameters on a sunny day showed that whereas the FMC modules maintained their efficiency throughout the day, the MAPI modules peaked in performance during the morning and afternoon, with a strong decrease around midday. Overall, the MAPI modules showed a strongly negative temperature coefficient (TC) for PCE, whereas the FMC modules showed a moderate positive temperature coefficient performance as a function of temperature due to the increase in J_{SC} and FF. Outdoor monitoring of the MAPI modules over several days highlighted that the reduced over the course of the day but recovered overnight. In contrast the FMC modules improved slightly during the daytime although this was too reversed overnight. This paper provides insight into how PSC modules perform under real-life conditions and consider some of the unique characteristics that are observed in this solar cell technology.

1. Introduction

Research into Perovskite Solar Cells (PSCs) has grown exponentially over the last decade as PSCs provide the potential for low cost and solution-based production, on flexible substrates, and at lower temperatures than silicon cells, thus reducing the embodied energy. At present PSCs only moderately lag silicon based solar cells in terms of power conversion efficiency (PCE), with the best reported cells possessing a PCE of 22.7% and mini-modules reported up to 16% (Green et al., 2018; NREL, 2017).

In order for these emerging PV technologies to become commercially viable it is important that it is understood how they perform under real world conditions. Such testing is crucial for understanding how performance is affected by climatic changes such as irradiance level and allows technologists to evaluate the challenges in integrating the technology with existing energy and building infrastructure. Furthermore, it provides valuable information on stability; in the outdoors, the solar cell experience multiple stresses, rather than just one, that continuously vary with time including light, temperature, condensation, wind as well as humidity, temperature and light cycling. Numerous studies have addressed instability of perovskite and transport- layers in PSCs induced by heat (Niu et al., 2015), UV light (Melvin et al., 2018; Anizelli et al., 2017), electric field and humidity (Bryant and et al., 2016) and in real outdoor operational conditions many of these factors simultaneously act upon the PSC. However, there are relatively few reports of outdoor performance monitoring of PSCs. This is for a number of reasons including amongst others the problems of scalability, such as the higher sheet resistivity of transparent conducting oxides leads to drops in PCE (Jørgensen and et al., 2013), as devices get larger. Specialised equipment is needed for the characterisation of large area modules that is not readily available in most PV laboratories. Furthermore, small devices are difficult to measure outdoors with high accuracy, as the currents involved are small (nA), especially at lower irradiances, and require the use of specialist test equipment, which has impeded studies on outdoor testing (Bristow and Kettle, 2015, 2018).

Misra et al. (2015, 2016) were one of the first groups to use sunlight and study the degradation giving invaluable insight to the community towards the stability of the PSC to light-induced degradation. In 2015 Li et al. (2015) demonstrated the first results from PSCs exposed outdoors

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with no UV filtration in Saudi Arabia following the ISOS O1 protocol and showed stable performance for up to 7 days with no drop in performance. In 2016 Reyna et al. (2016) presented their work on mixed halide PSCs mounted on a solar tracker with over 1000 h outdoor exposure, showing that $T_{80\%}$ occurred at 846 h and also demonstrated the enhanced stability of $FAPbI_3(0.85)MAPbBr_3(0.15)$ over conventional $MAPbI_3$ perovskite devices. Nevertheless, even this composition for PSCs was found to be highly susceptible to UV light and quality of edge-sealant, which were deemed to be the main causes for degradation.

In this work, a comparison of performance parameters as a function of irradiance and temperature for Single cation, single halide $MAPbI_3$ (MAPI) and triple cation, mixed halide (FMC) perovskite mini-modules are reported. Furthermore, the dependence of module temperature rise above ambient as a function of irradiance is analysed for both PSC modules and compared to c-Si modules, leading to calculated values for the Ross coefficient. The effect of wind speed on the Ross coefficient is also examined. Also, the reversibility of certain PSC degradation processes is reported by comparing PV performance on consecutive days. Stability studies on PSC modules are also presented showing that long-term stability is achievable, although performance is inhibited by a temporary reversible degradation during the initial burn-in period.

2. Experimental details

2.1. Active layer fabrication details

Mini-modules manufactured with $CH_3NH_3PbI_3$ (MAPI) and $Cs_{0.05}FA_{0.83}MA_{0.17}PbI(_{0.87}Br_{0.13})_3$ (FMC) perovskite mini-modules were used in this work (Solaronix, 2018). The final manufactured modules were 5 cm × 5 cm in size and consist of five serially connected cells with 2.7 cm^2 per cell and 13.5 cm^2 total active area, device geometric fill factor was 0.54.

Both MAPI and FMC were prepared from solution on ITO-coated glass (7Ω/sq). A NiO_x hole transport layer is obtained by spin coating a solution of 0.22 M nickel acetate tetrahydrate dissolved in a 1:0.012 vol ratio of 2-methoxyethanol:ethanolamine at 3500 rpm for 30 s. The formed layer was annealed at 250 °C for 60 min before cooling to room temperature. The MAPI precursor solution was prepared by dissolving 576 mg PbI_2 and 199 mg MAI in 0.8 ml DMF and 0.2 ml DMSO. The FMC solution was prepared by dissolving PbI_2 (0.35 g), FAI (0.12 g), MAI (0.035 g), CsI (0.026 g) and $PbBr_2$ (0.09 g) in 0.8 ml of DMF and 0.2 ml DMSO. Both structures were deposited using a one-step method using ethyl acetate as antisolvent. The electron transport layer used in this work was $PC_{60}BM$, spin coated from a 20 mg/ml solution in chlorobenzene at 2000 rpm for 30 s. A bathocuproine (BCP) (0.5 mg/ml in anhydrous ethanol) contact layer was spin-coated at 6000 rpm for 15 s. Finally, 100 nm Ag contacts were added by thermal evaporation. For module patterning, the P1 was defined by laser scribing of the substrate ITO, P2 was scribed using a scalpel blade, and P3 was defined by evaporating the electrode metal though a shadow mask. Finally, a light curable epoxy (Ossila) and a thin glass cover were used for encapsulation. Wires were soldered to the Ag contacts and then covered by a UV-curable epoxy (Threebond) which acted as edge sealant.

2.2. Module encapsulation

Six modules were tested for this work and bonded to the centre of a 205 mm × 160 mm glass backplane and were covered with a commercially available UV filter (Solaronix, 2018) which filters the UV component of sunlight. Data is presented for the median device. After the UV filter was added, the final stage of the encapsulation was concluded by sealing the edges of the modules with low temperature two part fast curing sealing epoxy supplied by Dyesol UK ltd (now Greatcell Solar Ltd.) (Dyesol).

For this experiment, all modules were initially tested indoors using a Newport 94021A class ABB standard AM1.5G solar simulator, to ensure that all devices showed consistent performance prior to outdoor testing. The modules were then laminated onto glass substrates and covered with a UV filter before being retested. The average device photovoltaic performance of each type was as follows: MAPI - short-circuit density (J_{SC}) = 2.38 mA/cm^2, open-circuit voltage (V_{OC}) = 5.20 V, fill factor (FF) = 39.9%, power conversion efficiency (PCE) = 4.92%; FMC − J_{SC} = 2.55 mA/cm^2, V_{OC} = 5.40 V, FF = 43.0%, PCE = 5.92%.

2.3. Outdoor setup

The outdoor experiments were performed over two campaigns in April and June 2017 at the School of Electronics, Bangor, Gwynedd, North Wales at coordinates latitude 53.228°N, longitude −4.129°W and altitude approximately 20 m above sea level. The performance monitoring of the poly-Si module is conducted using a PVMS250 PV measurement system (Egnitec, UK) and the perovskite mini-modules were measured using a Botest SMU. The poly-Si modules are kept at maximum power point in between periodic current-voltage (IV) sweeps (once every minute). Each module has a PT100 temperature sensor fixed to its backplane. Current and voltage at the maximum power point (I_{MPP}, V_{MPP}) and temperature measurements are taken every 15 s. The perovskite mini-modules were kept at open-circuit between IV sweeps conducted once every 15 min. All mini-modules also had PT100 sensors constantly reading the module temperature. For these tests, all monitored modules were mounted in-plane towards the sun at an angle of 36° (the optimum for this latitude).

During the outdoor testing, the incident irradiance was monitored using IMT silicon solar reference cells. The weather conditions were constantly recorded using a dedicated weather station setup. The outdoor measurement setup conforms to the ISOS-O2 outdoor measuring protocol (Reese et al., 2011). The data were analysed using a combination of MySQL, MS Access, and MS Excel.

3. Results

3.1. Diurnal performance

PSCs were monitored in the period from the 12th June 2017 until the 12th July 2017. Throughout the entire period of this investigation the incident irradiance, weather conditions and module temperature were monitored alongside the IV date from the modules. The measured relative humidity levels were 80% with an average maximum of 90% and average minimum of 61%. The average mean UV index was 1.19 with an average minimum of 1.07 and an average maximum of 5.45. The mean irradiance was 278 W/m^2 with an average maximum of 858 W/m^2, and the average daily insolation over this period was 466 MW h/cm^2.

Initially, an evaluation of the diurnal performance was conducted; therefore, a sunny day was identified during the first week of the measurement campaign (17/06/2017, see Fig. 1) and the performance of the PSC modules was compared against a polycrystalline-silicon

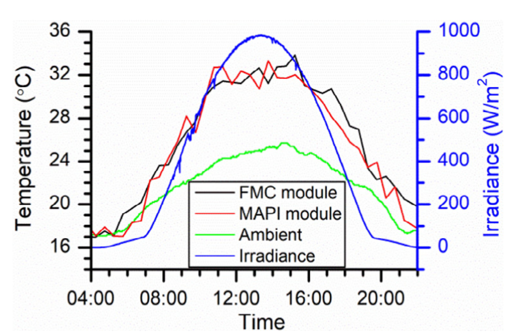

Fig. 1. Irradiance (in-plane), ambient and module temperatures on selected sunny day (17/06.2017).