# EVALUATION OF PERFORMANCE MEASUREMENTS OF DIFFERENT TYPE PEROVSKITE DEVICES AT DIFFERENT MEASUREMENT CONDITIONS

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ABSTRACT: Perovskite solar cell devices are driving a re-evaluation of photovoltaic measurement techniques due to their inherent instabilities that complicate the application of traditional characterization approaches. Being a relatively novel technology, the experiences of measuring these devices contribute to their advancements in production. In this context, the work aims to contribute to the growing body of indoor test experiences by presenting indoor measurement results obtained from different perovskite technology modules. Three different types of perovskite technology mini-modules have been tested with different measurement performance strategies to investigate factors that might improve the reliability of performance measurements of perovskite devices. Impact of sweep rate, scan direction priority, time delay between forward-reverse scans, MPP and light preconditioning are some of the factors studied at the different technology perovskite devices. Measurements revealed that $MAPbI_3$ perovskite-based devices are more sensitive to sweep rate, scan direction priority and time delay between forward and reverse scans. An investigation of (IV) traces at different sweep rates is highly recommended in order to give an insight regarding the impact of ion migration effects in the perovskite devices under study and for the selection of the appropriate sweep rate.
Keywords: Characterization, Perovskite, Performance

## 1 INTRODUCTION

Due to the hysteretic behavior of most perovskite cells the indoor and outdoor characterization of those devices present several challenges. Their photocurrent density – voltage (J-V) demonstrates anomalous dependence on the voltage scan direction/rate/range, voltage conditioning history and device configuration [1]. For this purpose, the IEC has developed some guidelines on how to measure perovskite devices. This work is described in IEC standard 63228 which presents the measurement protocols for photovoltaic devices based on organic, dye-sensitized or perovskite materials. Although a large body of research work has demonstrated the impact of various measurements factors on perovskite performance [2], [3], more experience of those studies in several types of perovskites is still needed. The collection of IV traces at different sweep rates will demonstrate the interplay between ion migration and capacitance effects and the impact of perovskite composition on the response of the device will be established. This will lead to improvement of the existing measurement strategies for the measurement of perovskites with specific active layer compositions.

To investigate in more detail other factors that may improve the reliability of performance measurements, current-voltage (IV) characteristics of perovskite devices of different technologies have been studied under different conditions. Particularly, three different types of perovskites have been utilized for these studies: $MAPbI_3$ (methylammonium lead iodide) (type A module), and 2 different types of two-cation perovskite CsFaPbIBr: type B module and type C module. Different measurement strategies have been applied to give insight into the impact of ion migration on the performance curves of different perovskite active layers. Impact of sweep rate, scan direction priority, time delay between forward-reverse scans, MPP and light preconditioning are some of the factors studied in this paper during the performance measurements of the different technology perovskites.

Measurements have revealed the effect of sweep rate and scan direction priority in $MAPbI_3$ perovskite-based devices. Using a lower sweep rate minimizes hysteresis and brings those devices towards their steady-state operating conditions. Moreover, the scan direction priority in these devices determines their power output. Different steady-state conditions exist during forward-first and reverse-first studies even at low sweep rates. On the other hand, type B perovskite devices are not affected by sweep rate or scan direction priority. Finally, in type C perovskite devices, a reduction of hysteresis was found at higher sweep rates indicating the dominance of ion migration of slow-moving ions. An investigation of (IV) traces at different sweep rates is highly recommended in order to give an insight regarding the impact of ion migration effects in the perovskite devices under study and for the selection of the appropriate sweep rate.

## 2 EXPERIMENTAL APPROACH

The module performance was measured by using a Sol3A Class AAA solar simulator from Newport using a light power at $1000W/m^2$. The current at the contacts of the module was collected using a Keithley 2430 source meter driven by a python script. A temperature-controlled base was utilized to keep the temperature of the samples at 25°C. Different perovskite devices have been utilized for the investigation of the appropriate testing techniques for performance measurements. This is necessary in order to understand how the different testing conditions affect each perovskite structure and to extract a general conclusion for the parameters that affect the performance measurements of those devices. Perovskite modules were preferred over cells for these performance studies as they exhibited better stability over time. The different types of perovskites studied are the following: $MAPbI_3$ (type A module), and two different types of 2-cation perovskite CsFaPbIBr: type B module and type C module. The type A modules consist by six (6) cells and the overall dimensions of the modules are 8.5 x 3.5 $cm^2$. The type B and type C modules consist by seven (7) cells and their overall dimensions are 3.17 $cm^2$.

## 3 RESULTS AND DISCUSSION

### 3.1 Impact of sweep rate

The impact of sweep rate and voltage sweep order was initially investigated in type A modules ($MAPBI_3$). Forward-first and reverse-first measurements have been applied during those studies to spot differences in the IV curves using different scan direction priorities. The measurements (Figure 1) indicate that reverse and forward curves differ significantly in devices that exhibit high levels of hysteresis. Reverse IV sweeps provide higher maximum power output in agreement with previous reports[4]. The lowest sweep rate in both forward-first and reverse-first approach presented the lowest level of hysteresis and was found to move both reverse and forward curves towards the expected steady state performance and seems to be the best choice for performance measurements. The MPP value at steady state conditions in the forward-first approach (indicated by a green dot in Figure 1a) was found by collecting a full forward IV curve at very low sweep rate. Particularly, at each voltage point, the waiting time was set to 5 minutes which corresponds to a sweep rate of 0.001 V/sec. This point (green dot in Figure 1a) approaches the MPP of both forward and reverse curves in the forward-first approach at low sweep rates.

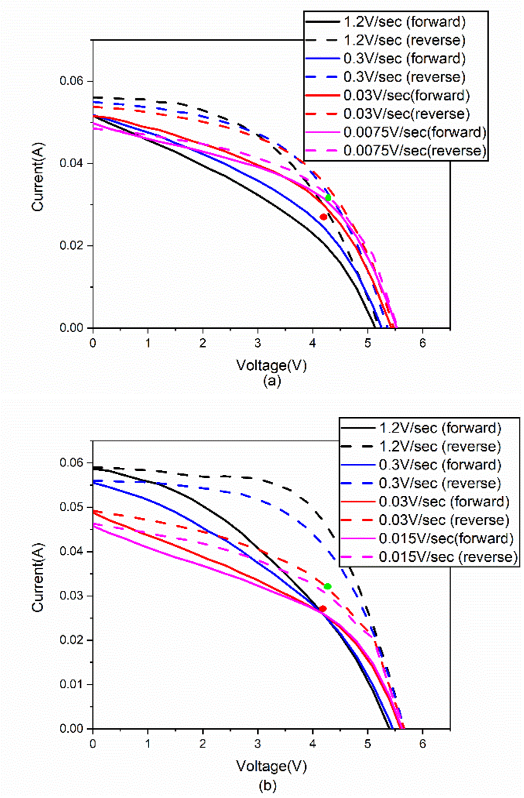


**Figure 1:** Performance measurements of perovskite type A at different sweep rates and in (a) forward-first and (b) reverse-first approach.

In the same manner, the MPP value at steady state conditions during reverse-first measurements (indicated by a red dot in Figure 1) was found by collecting a full reverse IV curve at the same sweep rate (0.001 V/sec). At this sweep rate, the maximum power in reverse-first curves was found to be smaller than the maximum power found in the forward-first ones. Therefore, it can be deduced that the steady state conditions are determined not only from the sweep rate but also from the voltage sweep direction. Forward-first measurements at low sweep rates seems to provide higher output power compared to reverse-first measurements at the type A samples. Moreover, the voltage sweep rate, which minimizes hysteresis effects and brings the samples towards their steady state conditions in both cases (forward-first and reverse-first), is found to be lower than 15 mV/sec. The impact of scan direction priority was also found during the outdoor testing of those devices as well [5].

In type B devices, no change of the current-voltage characteristics is obtained at different sweep rates and at different scan direction priority (see Figure 2). Moreover, both forward- first and reverse-first measurements have been applied but no difference was obtained between the data.

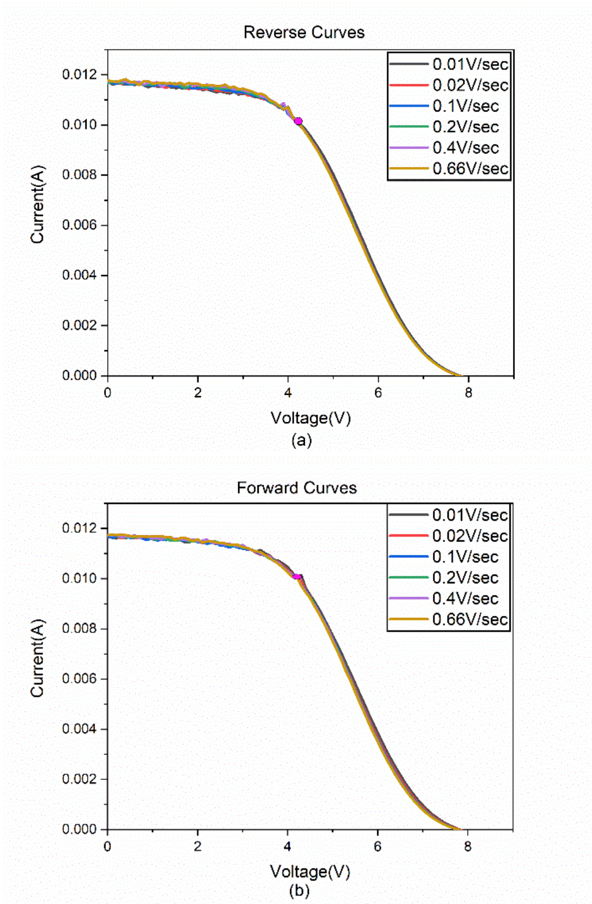


**Figure 2:** (a) Reverse and (b) forward curves of perovskite type B device at different sweep rates. Reverse-first approach was used.

Finally, a type C perovskite module was studied at different sweep rates in order to explore their effect on another type of perovskite device. Only forward-first measurements have been conducted on that device. As can be obtained from Figure 3, in this type of module hysteretic behavior is obtained at lower sweep rates.

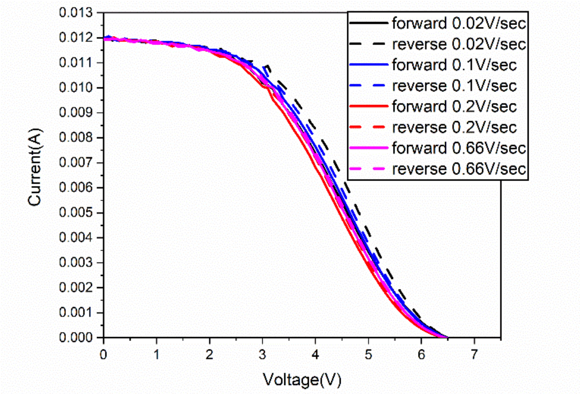


**Figure 3:** Performance measurements of type C device at different sweep rates. The results indicate the dominance of ion migration of slow-moving ions.

Particularly, hysteresis is obtained at sweep rates lower than 0.1 V/sec. This effect shows opposite behavior compared to the data obtained for type A perovskite as presented above. It is believed that ion migration of slow-moving ions might be the dominant mechanism for this observation. What is interesting in this case is the same power output obtained from the perovskite module at the different sweep rates, which indicates that the application of different sweep rate does not affect the overall output of the device.

3.2 Impact of time delay between forward-reverse curves

Time delay between forward and reverse curves has been introduced to see its impact on the current-voltage curves. Forward-first measurements have been applied in this case. In the forward-first approach the time delay between forward and reverse curves is expected to affect only the reverse curves.

Initially, type A device was studied. The reverse curves at different time delays have been collected and compared with the steady state curve of the cell. The current in this curve was collected at very low sweep rates (0.001V/sec) and it is assumed that those conditions are the steady state conditions for the sample. Time delay between forward-reverse curves in forward-first measurements move the reverse curve away from the steady state condition (see Figure 4).

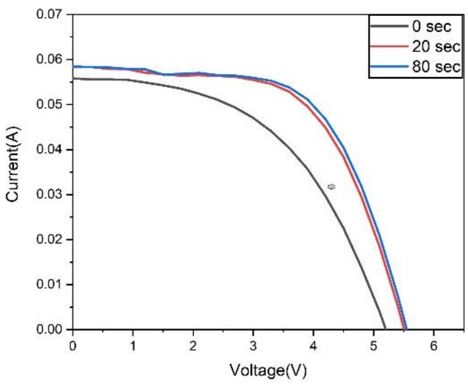


**Figure 4:** Reverse curves of type A module at different time delays between forward and reverse curves in forward-first measurements.

The same procedure was applied in type B devices. Time delay between forward and reverse curves was introduced and reverse curves were collected at each case. The results are depicted in Figure 5. No significant change is obtained at the different time delays applied between forward and reverse curves indicating that the addition of time delay between forward and reverse curves does not have an impact in this type of perovskite devices.

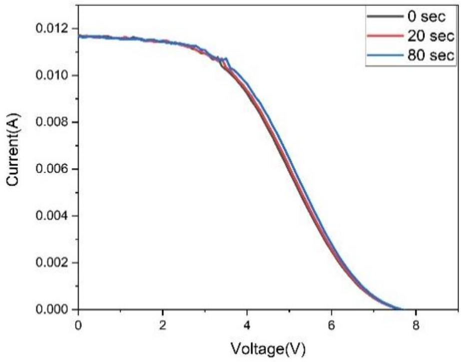


**Figure 5:** Reverse curves of type B module at different time delays between forward and reverse curves in forward-first measurements.

3.3 Impact of MPP and light Preconditioning

The impact of MPP and light preconditioning on device output was investigated next. Type B perovskite devices were studied in this case. During those studies, an initial IV curve was collected and then the device was exposed to conditions close to MPP for 5 minutes under light and then the performance measurements were repeated again. In this manner the devices were exposed to light soaking for another 5 minutes and in the presence of MPP voltage and then output of the device was collected. The maximum power point voltage (Vmp) of the device under test found from previous performance measurements was around 4.2V and this have been applied in the device during MPP preconditioning tests. In that voltage the corresponding current has been collected.

**Table 1:** Major electrical parameters extracted from reverse-first curves at different sweep rates in the presence and absence of MPP and light preconditioning.

| | Imp (A) | Vmp (V) | Pmax (W) |
|---|---|---|---|
| | | | |
| Sweep rate: 0.66V/sec | | | |
| No MPP | 0.01009 | 4.2 | 0.04238 |
| MPP | 0.01006 | 4.5 | 0.04527 |
| Sweep rate: 0.4V/sec | | | |
| No MPP | 0.01015 | 4.2 | 0.04262 |
| MPP | 0.01004 | 4.5 | 0.04516 |
| Sweep rate: 0.2V/sec | | | |
| No MPP | 0.01014 | 4.2 | 0.04257 |
| MPP | 0.01007 | 4.5 | 0.04532 |
| Sweep rate: 0.1 V/sec | | | |
| No MPP | 0.01011 | 4.2 | 0.04245 |
| MPP | 0.01001 | 4.5 | 0.04506 |
| Sweep rate: 0.02 V/sec | | | |
| No MPP | 0.00991 | 4.3 | 0.04260 |
| MPP | 0.01004 | 4.5 | 0.04516 |
| Sweep rate: 0.01 V/sec | | | |
| No MPP | 0.01007 | 4.3 | 0.04329 |
| MPP | 0.01018 | 4.5 | 0.04580 |

During that procedure, it was obtained that the maximum power point obtained before MPP and light preconditioning was no longer valid and a new maximum power point value was exhibited from the measurements which was larger than before. Reverse-first measurements at different sweep rates have been collected in the presence and absence of MPP and light preconditioning. Table 1 summarizes the main parameters obtained from reverse-first curves at different sweep rates in the presence and absence of MPP and light preconditioning.

As can be obtained in Table 1 at all sweep rates the output power of the device shifts towards higher values in the presence of MPP and light preconditioning. This result was confirmed through repeatable measurements and indicates that the combination of MPP and light preconditioning in those devices affects their output.

3.4 Maximum power-point (MPP)-first measurements

In an attempt to study if keeping the perovskite device at maximum power-point before current-voltage measurements can result to more reliable performance collection, the samples have been initially set to MPP conditions (for 5 minutes) and then started to collect their IV curves at different sweep rates starting from that point. Type A devices were studied with this approach. In almost all cases studied in the past, the starting point of the IV curves was either at voltage 0 V (which corresponds to short-circuit conditions) either the Voc (open-circuit voltage) [4]. The first case corresponds to forward-first measurements and the last one to reverse-first measurements. In our case, MMP-first measurements have been applied. Since the starting point is at MPP, different scan directions should be applied. Figure 6 represents the possible scan directions in the case where the initial point in the IV curve is the MPP. In Figure 6(a) the currents in forward direction have been collected first and then a complete reverse curve was captured. The second case (Figure 6b) starts from MPP and the currents are collected in reverse direction first and then collect currents in forward curve. In this case the reverse curve is collected first and the forward curve is collected second. In all cases the MPP is selected to be the value found in forward-first measurements at low sweep rates presented above (section 3.1).

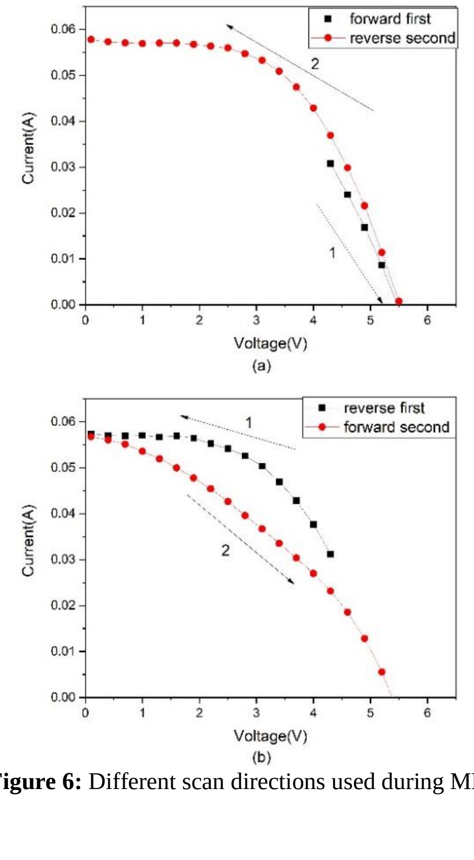


**Figure 6:** Different scan directions used during MPP-first measurements of type A devices.

The IV curves at the different directions have been studied at different sweep rates in an attempt to find if one of the curves is approaching the steady state curve. The steady state curve of the perovskite device corresponds to the forward first IV curve at very low sweep rates (0.001V/sec).

In the case of high sweep rates (2V/sec), the steady state curve of the device is not approached by any of the collected curves indicating that the performance measurements in both scan directions is far from the real one. The results are depicted in Figure 7.

Then the same procedure was repeated at lower sweep rate (Figure 8). As the sweep rate becomes lower all the curves are approaching each other: the steady state curve is approaching the forward second curve at low voltage biases and reverse second curve at higher voltage biases. However, none of those curves does not represent the steady state condition of the device at all voltage biases indicating that this testing technique is not appropriate for reliable performance testing of perovskites.

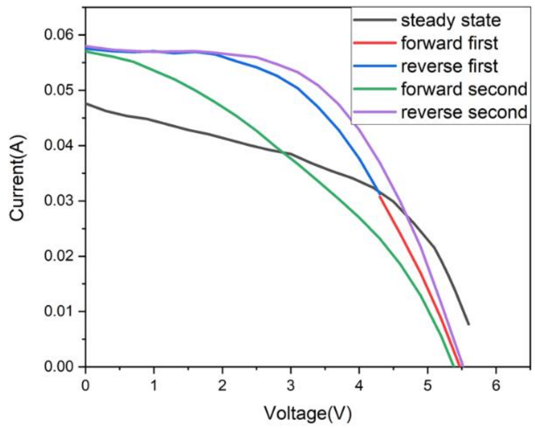


**Figure 7:** MPP-first performance measurements at sweep rate of 2V/sec in type A devices.

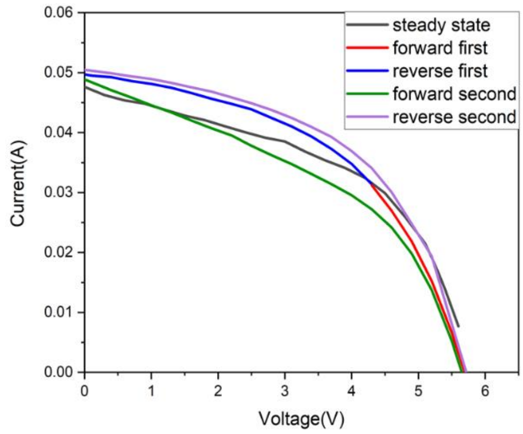


**Figure 8:** MPP-first performance measurements at sweep rate of 0.03V/sec in type A devices.

## 4 CONCLUSIONS

After a detailed study of several factors that might affect the performance measurements of different perovskite modules, it can be concluded that the most critical factor that affects the performance measurements is the sweep rate. By studying different types of perovskites, it is demonstrated that sweep rate in $MAPbI_3$ devices should be as low as possible in order to reach the device the steady state conditions. However, this behavior is not obtained in all perovskite devices since it was found that in CsFaPbIBr devices the sweep rate is not critical and the same output is obtained at different sweep rates. A careful study of the performance of the perovskite at different sweep rate is highly recommended for reliable performance studies. Regarding the scanning direction in $MAPbI_3$ devices (type A) the scan direction was found to affect the MPP of the devices. In our investigations it was found that the MPP during reverse first scan was lower in those devices and this is obtained even at very low sweep rates where steady-state conditions exist.

The impact of time delay between forward-reverse scans and vice-versa was found to affect mainly the $MAPbI_3$ devices (type A). Time delay between forward-reverse scans was found to move the efficiency of the type A perovskite away from the steady state conditions and should be avoided. Time delay between forward and reverse scans was not found to affect type B devices. CsFaPbIBr devices (type B) performance was found to be affected by the MPP and light preconditioning. Performance of those devices was shifted to higher values after MPP and light preconditioning for some minutes prior the IV collection.

Finally, MPP first measurements were not found to be an option for reliable performance studies, since none of the IV curves collected by applying this method didn't approach the steady state condition curves at all voltage biases in devices with strong hysteresis (type A).

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