Observable Hysteresis at Low Temperature in “Hysteresis Free” Organic–Inorganic Lead Halide Perovskite Solar Cells

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Supporting Information

ABSTRACT: In this paper we address the $J-V$ hysteresis behavior of planar organic–inorganic lead halide perovskite solar cells fabricated using PC$_{60}$BM as the cathode. At room temperature, these devices exhibit apparently hysteresis free $J-V$ scans. We observe that cooling the temperature to 175 K results in the appearance of substantial $J-V$ hysteresis. Employing chronoamperometric measurements, we demonstrate that the half-time for the relaxation process underlying this hysteresis slows from 0.6 s at 298 K to 15.5 s at 175 K, yielding an activation energy of 0.12 eV. We further demonstrate that by cooling a cell to 77 K while held under positive bias, we are able to “freeze” the cell into the most favorable condition for efficient photovoltaic performance. We thus conclude that changes to device architecture that appear to remove room temperature $J-V$ hysteresis may not remove the underlying process(es), but rather shift them to time scales not readily observable in typical room temperature $J-V$ scans.

Hybrid organic–inorganic lead halide perovskite photovoltaics offer the promise of inexpensive solar power generation from solution processed thin films. Solar power conversion efficiencies of 16–20% have been reported in a variety of configurations including dye-sensitized solar cell style architecture and planar heterojunctions, in which the cathode is either at the bottom or top of the layer stack deposited on a transparent conducting oxide. Perovskite solar cells fabricated with methylammonium lead iodide CH$_3$NH$_3$PbI$_3$ (MAPI) as the photoactive layer often exhibit hysteresis in their photovoltaic properties. Depending upon the scan speed, this can result in overestimation of the power conversion efficiency evaluated from the photocurrent as the voltage is swept from forward bias (FB) to reverse bias (RB) as opposed to determination from the steady state photocurrent at the maximum power point (mpp). Recently, several groups have demonstrated approaches to produce MAPI solar cells with apparently negligible hysteresis in the $J-V$ curves at room temperature. For example MAPI–Cl based cells in which a transparent conducting oxide cathode is coated with a thin mesoporous TiO$_2$ layer covered with a self-assembled monolayer of C$_{60}$ molecules gave steady state power outputs similar to that inferred from a $J-V$ measurements and almost independent of factors such as scan speed and prebiasing. MAPI cells with contact layers commonly used in organic photovoltaic (OPV) cells such as poly(3,4-ethylenedioxythiophene) polystyrenesulfonate (PEDOT:PSS), phenyl-C$_{61}$-butyric acid methyl ester (PCBM), and lithium fluoride (LiF) have also been reported not to show hysteresis effects under normal measurement conditions. Since the cathode is deposited on the top of the layer stack in these cells (similar to the standard configuration used organic photovoltaic devices), we will refer to this device architecture as fullerene top cathode cells. The reason for the apparent decrease in hysteresis, relative to devices where the MAPI is in contact with a metal oxide cathode at the bottom of the layer stack (‘bottom cathode” architecture), is not fully understood. It has been suggested that fullerene molecules may play a role in passivating the MAPI interface. This paper is concerned with investigating the apparent absence of hysteresis effects in such fullerene top cathode MAPI solar cells.

From an engineering point of view, cells that show no hysteresis at room temperature represent a significant improvement and a step toward commercialization. However, it is not apparent whether the use of the fullerene contact layers between the MAPI and the cathode has removed/reduced the magnitude of the underlying causes of hysteresis, or alternatively, whether the time scale of hysteresis has changed. If devices equilibrate on a time scale that is too fast to be resolved using typical $J-V$ measurement, then they would appear hysteresis free. Here, we investigate this possibility by cooling MAPI solar cells with fullerene top cathode architectures below room temperature to observe whether hysteresis can be

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identified in devices where the thermally activated kinetic processes have been slowed. We show that at lower temperatures the nominally “hysteresis free” devices do show significant hysteresis, and we investigate the kinetics of the relaxation of the photovoltaic properties to equilibrium to elucidate the origins of this phenomenon.

Cells were fabricated according to a previously reported method to give fullerene top cathode cells consisting of planar layers of PEDOT:PSS, CH\textsubscript{3}NH\textsubscript{3}PbI\textsubscript{3} (MAPI) and PC\textsubscript{60}BM, as shown in Figure 1a inset. The room temperature JV curves in Figure 1a show near identical performance when scanning from FB to RB and from RB to FB at a rate of 0.125 V/s. These cells do not display the hysteresis typically observed in metal oxide bottom cathode architectures, as shown in Supporting Information Figure S1. Even when the scan rate is increased from 0.125 V/s to 4.75 V/s (Figure S2), there is little change in the JV curves, consistent with previous reports. The photovoltaic performance data as a function of scan speed is presented in Table S1. In particular, for the fullerene top cathode device, the degree of hysteresis metric (DoH), as defined by eq S1, showed a minor increase from 0.013 to 0.062 with increasing scan speed. This is in contrast to MAPI cells with metal oxide bottom cat architectures, where much larger DoH values are seen. The observation of a marginal increase in the DoH with increasing scan speed in our fullerene top cathode cells could suggest the presence of a hysteresis effect in the device that is hard to quantify at easily accessible JV scan speeds.

We now turn to temperature-dependent measurements. Fullerene top cathode devices were kept under vacuum in a cryostat to avoid cell degradation and water vapor condensing onto the cells at low temperatures. Cells were allowed to equilibrate at each temperature in the dark at open circuit for 20 min before measurement. Figure 1c shows a clearly observable hysteresis for all measurements below room temperature, even at the lowest scan speed of 0.125 V/s used in this study. The FB–RB JV sweeps (solid lines) show a significantly higher short circuit photocurrent relative to the RB–FB sweeps (dashed lines). Table S2 summarizes the solar cell performance parameters derived from these JV curves, including the degree of hysteresis, which varies significantly from 0.13 to 0.659 as the temperature is lowered to 175 K. At 77 K the photovoltaic performance of the cell is greatly reduced; however, the cells using this sweep rate show a reduced hysteresis with a degree of hysteresis of 0.115. In order to confirm the effect observed is a property of the perovskite based cells, and not an artifact of the cell architecture or measurement procedure, we performed the same experiments on a standard organic PV (OPV) cell. The key difference between the two cells was that the MAPI perovskite layer was replaced with the well-studied polymer:fullerene blend PCDTBT: PCBM. Figure S3 shows the JV characteristics of this OPV cell at 175 K. While the performance of this device is reduced (primarily due to resistance losses as reported in reference 1), the cell shows no sign of hysteresis.

The JV curves indicate that a hysteresis effect is still present within these fullerene top cathode cells. In such JV scans, it is difficult to decouple the effects of both voltage and time, as these are changing simultaneously. It has been shown previously that chronoamperometry can be employed to separate the effects of the response of perovskite devices to a change in voltage from its relaxation with time, and thereby interrogate in more detail the underlying process(es) causing the hysteresis observed in the JV scans. To undertake such experiments, the cell was held at a fixed forward bias of +1.2 V for 3 min in the dark before being illuminated at 1 sun equivalent intensity with white LEDs and simultaneously switched to short circuit. Following the synchronous switch to short circuit and illumination, the short circuit photocurrent (J\textsubscript{sc}) in the device relaxes toward a steady state condition, allowing the relaxation processes underlying the hysteresis observed in the JV data to be quantified in terms of a time constant and magnitude as discussed previously. Photocurrent decays from the fullerene top cathode device measured at different temperatures (ranging from 175–293 K) can be seen in Figure 2a. Two things are immediately obvious from the curves. First it is apparent that the relaxation time for J\textsubscript{sc} to reach steady state increases as the temperature decreases, with decay half times ranging from 0.6 to 15.5 s as the temperature decreases from 293 to 175 K. The other observation is that while the initial short circuit photocurrent is independent of temperature, the magnitude of the loss of photocurrent resulting from the relaxation process increases as the temperature is decreased. In order to study the kinetics of the relaxation process, half-times for the decay were obtained and plotted in Figure 2b. It is apparent that the relaxation rate of decay follows Arrhenius behavior over the temperature range investigated, with an activation energy of 0.12 ± 0.02 eV.

To further investigate the effect of relaxation process(es) underlying the JV hysteresis, we undertook additional chronoamperometry measurements as for Figure 2, but holding
the cells at a range of initial voltages ("prebias" voltages) prior to switching to short-circuit under irradiation, for fullerene top cathode cells either held at room temperature or 175 K. The results at room temperature are shown in Figure 3a, with the corresponding time expansion in Figure 3b. It is apparent that while for forward prebiases, the relaxation results in a decay of the observed photocurrent; for reverse prebiases, the relaxation results in an increase in observed photocurrent. In all cases, the steady state currents tend toward the same value. We also note the kinetics of the relaxation process differ with prebias, and in some cases show clearly biphasic, and behavior of opposite signs, clearly indicating that at least two different processes on different time scales cause this relaxation. Qualitatively similar behavior is observed at 175 K, although on slower time scales, as shown in Figure 3c. It is instructive to compare these data against analogous room temperature data for a conventional bottom cathode cell comprising of ITO/TiO₂ compact layer/MAPI/Spiro-OMeTAD/Au as shown in Figure 3d. It is apparent that the relaxation data collected for this conventional MAPI at room temperature is strikingly similar to the data collected for the fullerene top cathode cell measured at 175 K.

Since prebiasing clearly affects the state of the cell and its current/voltage behavior, we attempted to "freeze" this conditioning in the cell by biasing the cell in the dark while cooling it down from room temperature to liquid nitrogen temperatures (77 K). Figure 4 shows that when no bias, or a reverse bias, is applied and the cell is cooled down, the JV performance of the cell is poor, whereas when the cells are cooled down under a forward bias of 1.2 V the cells show superior, stable JV performance even after this forward bias has been removed. The smaller amount of hysteresis in these 77 K data is believed to come from the process causing hysteresis being slowed down at 77 K to a time scale significantly slower than the scan time. From this observation we conclude that, at room temperature with no external bias in the dark, these cells are not in a state that is optimal for JV performance. However, under illumination or when a forward external bias is applied the cell equilibrates to a condition, whereby it gives an increased photovoltaic performance. By cooling the cell while under forward bias, we are able to essentially "lock in" this favorable condition, or more specifically extend the time it is in this condition to beyond the experiment time scale, resulting in improved performance at 77 K.

We have shown that the relaxation processes that cause JV hysteresis in many MAPI perovskite solar cells are still present even in fullerene top cathode cells which show no apparent hysteresis in JV scans at room temperature. Hysteresis behavior is observed in these fullerene top contact cells at lower temperatures, shown to be due to the time scale of the relaxation process causing the hysteresis to slow down to the same time scale as the scan speed. Significant hysteresis in the JV scan is only observed if the time scale of the relaxation process causing the hysteresis is similar to the time scale of the JV scan. Such apparent relaxation processes may at least in part be associated with capacitive charging/discharging currents, as has been discussed previously. For fullerene top cathode devices, it was seen at room temperature that this relaxation process has a decay half time from a forward bias condition to short circuit of 0.6 s, which is faster than the total scan time (~20 s) scan speeds of 0.125 V/s. At lowered temperatures of 175 K, the relaxation decay half time of 15.5 s is similar to typical scan times (~20 s), resulting in the observation of substantial hysteresis in the JV scan. At 77 K it appears that the relaxation process is slower than the scan speed employed, again resulting in little hysteresis behavior. Indeed extrapolation of the Arrhenius plot in Figure 2b would result in a half time of ~1700 s, well beyond the scan time. As such, it is apparent that room temperature JV scans, while crucial to determining practical device operational efficiency, are of only limited effectiveness in determining the presence of the underlying processes which can cause JV hysteresis.

It is interesting to note that at 293 K, Figure 1 indicates that the stabilized photocurrent in our fullerene top cathode MAPI cells is ~20 mA/cm². Figure 3a shows that following a positive prebias, the photocurrent is initially J_sc = 25 mA/cm² but then rapidly decays with a ~ 0.6 s half-time to a steady state value of 20 mA/cm². At lower temperatures the magnitude of this decay is greater, falling from an initial value of 25 mA/cm² to 16 mA/cm² in the case of a cell at 175 K. This raises the possibility that if cells could be stabilized under the conditions achieved by forward bias, then it may be possible to extract significantly higher photocurrents, and therefore potentially higher device efficiencies. In this regard, it is noted that "freezing" the cells under forward bias conditions, as shown in Figure 4 at 77 K, results in a significant enhancement in short circuit photocurrent and device efficiency.

From Figure 3a, it is apparent that fullerene top cathode MAPI cells reach equilibrium on a much faster time scale than that seen with other perovskite PV architectures and contacts. The value obtained for the activation energy in Figure 3b of the cells is 0.12 eV.
0.12 eV is significantly lower than that previously reported for MAPI devices with a bottom cathode architecture and for a mixed halide (I and Br) perovskite solar cell contacted with Spiro-OMeTAD and compact TiO2, which showed significant hysteresis at room temperature. The lower activation energy measured herein may be related to our observation of faster relaxation kinetics. This change in activation energy suggests that this particular cell architecture, and in particular the inclusion of the PEDOT:PSS and PC60BM interlayers, has accelerated the time scale of the process(es) causing the hysteresis effect. This may be related to PC60BM passivation effects discussed previously. However, it has also recently been shown that the value of activation energy for organic—inorganic lead halide perovskite can be a function of light intensity and measurement temperature range. We also note that our chronoamperometry studies provide clear evidence for biphasic relaxation kinetics, suggesting that at least two processes may be contributing to overall JV hysteresis. Detailed analysis of this biphasic behavior is beyond the scope of this paper, but may be related to the observation of different activation energies for the processes underlying JV hysteresis determined from different studies. In any case, while there is extensive evidence that the observation of JV hysteresis is associated with relaxation processes with the MAPI light absorber induced by applied voltages, it is apparent that the time scale of these relaxation processes can be strongly dependent upon the details of solar cell device architecture and/or contact materials.

**ASSOCIATED CONTENT**

*Supporting Information*

Details of fabrication methods for fabrication and measurement techniques used within this study can be found within the Supporting Information, as well as JV and cell performance data referred to within the text. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.jpcl.5b01381.

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**Figure 3.** (a) Current density of a fullerene top cathode MAPI solar cell plotted as a function of time when under different prebiasing conditions in the dark for 3 min (gray shaded area) and then switching to short circuit current conditions while simultaneously illuminating the cell under 1 sun intensity at 293 K. (b) Same as panel a, but expanded to only see the 10 s around when the light is turned on. (c) Same as panel a, however, with the cell held at 175 K. (d) same as panel a, but with a bottom cathode MAPI cell contacted with TiO2 and Spiro-OMeTAD.

**Figure 4.** JV curves taken of a MAPI fullerene top cathode solar cell at 77 K as a function of different biasing conditions while cooling from room temperature down to 77 K. Data shown for both sweep directions at a scan speed of 0.125 V/s.
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Notes
The authors declare no competing financial interest.

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Supporting Information for

“Observable Hysteresis at Low Temperature in ‘Hysteresis Free’ Organic-Inorganic Lead Halide Perovskite Solar Cells”

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Experimental

OPV-Hybrid Perovskite solar cell manufacture

These cells were manufactured following a previously reported procedure. In short and ITO coated glass substrate was coated with a PEDOT:PSS layer (P VP AL 4083, Heraeus) followed by a curing step at 150°C. Next a perovskite precursor solution was made by mixing a stoichiometric ratio of PbI$_2$ and methylammonium iodide was dissolved in a mix of DMSO and GBL (7:3) and stirred for 10 minutes. This perovskite precursor solution was coated using a spin coating procedure using two speeds where toluene was dripped onto the surface during the second step and then dried at 100°C post deposition. Then a PC$_{60}$BM (Solenne) layer was deposited by spin coating of a 20mg/ml solution in chlorobenzene at 1000rpm for 1 minute. Finally a LiF layer (0.7nm) and Ag layer (100nm) were sequentially evaporated onto the cell leaving an active area of 0.045cm$^2$.

Planar hetrojunction Compact TiO$_2$ and Spiro-OMeTAD perovskite cell In instances where a compact TiO$_2$ layer was used, a commercially available precursor solution (Solaronix BL/SC) was spin-coated onto the substrate at 5,000 rpm for 30 seconds, followed by a 2 minute sinter at 550°C. Once cooled a perovskite solution was deposited in the same method for the OPV-hybrid perovskite cell. A solution of 8% wt. 2,2',7,7'-tetrakis[N,N-di(4-methoxyphenyl)amino]-9,9'-spirobifluorene (spiro-OMeTAD, Borun Chemical) in chlorobenzene was next spin-coated onto the perovskite films. The spiro-OMeTAD solution contained additives including 19mM bis(trifluoromethane)sulfonimide lithium salt (Li-TFSI), 7mM 4-tert-butylypyridine (tBP). V$_2$O$_5$
powder (99.99%, Aldrich) was also added to the spiro-OMeTAD solution in the quantity of 2.5%wt with respect to the spiro-OMeTAD powder. Finally a 50nm Au contact was evaporated onto the cell under vacuum leaving an active area of 0.045cm$^2$.

**OPV Cells** Cleaned ITO glass substrates were treated with an oxygen plasma at 100 W for 7 min before a 35-nm-thick PEDOT:PSS layer was deposited on to the substrates and then annealed at 150 °C for 20 min. For the PCDTBT:PC$_{60}$BM devices PCDTBT and PC$_{60}$BM were codissolved in anhydrous chlorobenzene with a total solution concentration of 25 mg ml$^{-1}$ and a weight ratio of 1:2. Solutions were stirred in N$_2$ glovebox at 55 °C for more than 24 h followed by filtering through a 0.2-µm filter. Active layer film thickness is ~85-nm thick for the devices fabricated. All devices were completed by evaporation of 0.7 nm of LiF and 100 nm of Ag. The active area size is defined as 0.045 cm$^2$.

**Measurements**

**Cryostatic measurements** For temperature measurements the cells were mounted within an Oxford Instruments OptistatDN-V2 cryostat. A vacuum was applied to the cryostat’s chamber before filling a reservoir within the cryostat with liquid nitrogen. Temperature was then controlled using a Oxford Instruments Thermal Controller which varied the temperature by adjusting the flow of liquid nitrogen and power supplied to a heater internally. Samples were allowed to equilibrate for 20 minutes at each temperature before a measurement was taken, this was deemed sufficient enough time for the temperature reading to become accurate and stable.
**Current-Voltage (JV) Measurements** Initial $JV$ characteristics were measured using a Xenon lamp at AM1.5 solar illumination (Oriel Instruments) calibrated to a silicon reference cell with a Keithley 2,400 source meter. Calibration was performed with a silicon photodiode before measurements. Further JV measurements, including those measured in the cryostat, were measured under 1 sun equivalent white light illumination provided by a ring of 11 white LEDs, calibrated to the device performance as measured under AM1.5.

**Current Turn on Measurements** Current turn-on measurements were performed under 1 sun equivalent illumination as described above. Current and voltage measurements and the applied voltage were provided from a NI PCI6251 DAQ card with NI SCC68 connector block. Switching of the applied voltage and light bias was done with fast MOSFETs.
Table S1. Photovoltaic performance of methyl ammonium lead iodide OPV-hybrid perovskite solar cells obtained from current-voltage sweeps at room temperature (293K) made at different scan rates and sweep directions along with the degree of hysteresis (DoH) obtained from Equation S1.

<table>
<thead>
<tr>
<th>Sweep Direction</th>
<th>Scan Rate (V/s)</th>
<th>Voc (V)</th>
<th>Jsc (mA/cm²)</th>
<th>Eff (%)</th>
<th>FF (%)</th>
<th>Degree Of Hysteresis</th>
</tr>
</thead>
<tbody>
<tr>
<td>FB-RB</td>
<td>0.125</td>
<td>0.83</td>
<td>-19.53</td>
<td>10.87</td>
<td>0.67</td>
<td>0.013</td>
</tr>
<tr>
<td>RB-FB</td>
<td>0.125</td>
<td>0.82</td>
<td>-19.27</td>
<td>10.52</td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td>FB-RB</td>
<td>0.333</td>
<td>0.83</td>
<td>-19.59</td>
<td>10.81</td>
<td>0.67</td>
<td>0.017</td>
</tr>
<tr>
<td>RB-FB</td>
<td>0.333</td>
<td>0.83</td>
<td>-19.26</td>
<td>10.35</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>FB-RB</td>
<td>0.476</td>
<td>0.83</td>
<td>-19.66</td>
<td>10.76</td>
<td>0.66</td>
<td>0.020</td>
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<tr>
<td>RB-FB</td>
<td>0.476</td>
<td>0.83</td>
<td>-19.27</td>
<td>10.36</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>FB-RB</td>
<td>2.38</td>
<td>0.83</td>
<td>-19.90</td>
<td>10.85</td>
<td>0.66</td>
<td>0.041</td>
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<tr>
<td>RB-FB</td>
<td>2.38</td>
<td>0.83</td>
<td>-19.11</td>
<td>9.97</td>
<td>0.63</td>
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<tr>
<td>FB-RB</td>
<td>4.76</td>
<td>0.82</td>
<td>-20.12</td>
<td>11.00</td>
<td>0.66</td>
<td>0.062</td>
</tr>
<tr>
<td>RB-FB</td>
<td>4.76</td>
<td>0.83</td>
<td>-18.94</td>
<td>9.67</td>
<td>0.62</td>
<td></td>
</tr>
</tbody>
</table>
Equation S1.

\[
DoH = \frac{J_{sc}^{FB\rightarrow RB}}{J_{sc}^{RB\rightarrow FB}} - 1
\]

Where \( J_{sc}^{FB\rightarrow RB} \) is the efficiency obtained from a JV scan when scanning from forward bias to reverse bias and \( J_{sc}^{RB\rightarrow FB} \) is the efficiency obtained from a JV scan when scanning from reverse bias to forward bias.

**Table S2.** Photovoltaic performance of methyl ammonium lead iodide OPV-hybrid perovskite solar cells obtained from current-voltage sweeps at a 0.125 V/s scan rate at varying temperatures and sweep directions along with the degree of hysteresis (DoH) obtained from Equation S1.

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Sweep Direction</th>
<th>Voc (V)</th>
<th>Jsc (mA/cm²)</th>
<th>Eff (%)</th>
<th>FF (%)</th>
<th>Degree Of Hysteresis</th>
</tr>
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<tbody>
<tr>
<td>77</td>
<td>FB-RB</td>
<td>0.69</td>
<td>-14.14</td>
<td>1.99</td>
<td>0.20</td>
<td>0.115</td>
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<tr>
<td>77</td>
<td>RB-FB</td>
<td>0.68</td>
<td>-12.68</td>
<td>1.53</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>175</td>
<td>FB-RB</td>
<td>0.91</td>
<td>-19.70</td>
<td>7.91</td>
<td>0.44</td>
<td>0.659</td>
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<tr>
<td>175</td>
<td>RB-FB</td>
<td>0.90</td>
<td>-11.87</td>
<td>3.99</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>FB-RB</td>
<td>0.91</td>
<td>-20.22</td>
<td>8.23</td>
<td>0.45</td>
<td>0.410</td>
</tr>
<tr>
<td>200</td>
<td>RB-FB</td>
<td>0.90</td>
<td>-14.34</td>
<td>5.43</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>225</td>
<td>FB-RB</td>
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<td>-19.15</td>
<td>9.34</td>
<td>0.55</td>
<td>0.116</td>
</tr>
<tr>
<td>225</td>
<td>RB-FB</td>
<td>0.88</td>
<td>-17.17</td>
<td>7.77</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>FB-RB</td>
<td>0.86</td>
<td>-19.22</td>
<td>9.56</td>
<td>0.58</td>
<td>0.038</td>
</tr>
<tr>
<td>250</td>
<td>RB-FB</td>
<td>0.86</td>
<td>-18.52</td>
<td>9.13</td>
<td>0.57</td>
<td></td>
</tr>
<tr>
<td>293</td>
<td>FB-RB</td>
<td>0.83</td>
<td>-19.53</td>
<td>10.87</td>
<td>0.67</td>
<td>0.013</td>
</tr>
<tr>
<td>293</td>
<td>RB-FB</td>
<td>0.82</td>
<td>-19.27</td>
<td>10.52</td>
<td>0.66</td>
<td></td>
</tr>
</tbody>
</table>
Figure S1. JV curves obtained for a planar TiO$_2$ compact layer bottom cathode cell at room temperature (293K) when scanning at a sweep speed of 0.125V/s in a direction from FB-RB (solid line) and RB-FB (dashed line) under 1 sun illumination. With a schematics of the cell architecture shown in the inset.
Figure S2. JV curves obtained under 1 sun illumination for a fullerene top cathode cell in a sweep direction from FB-RB (solid line) and RB-FB (dashed line) differing scanning speeds from 0.125-4.75 V/s.
Figure S3. JV curves of a PCDTBT PCBM bulk hetrojunction OPV solar cell at temperatures ranging between 175-293K at scanning directions from FB-RB and RB-FB at scan speeds of 0.125 V/s under 1 sun illumination.