Supplementary Information

Title: **Encapsulating perovskite solar cells to withstand damp heat and thermal cycling**

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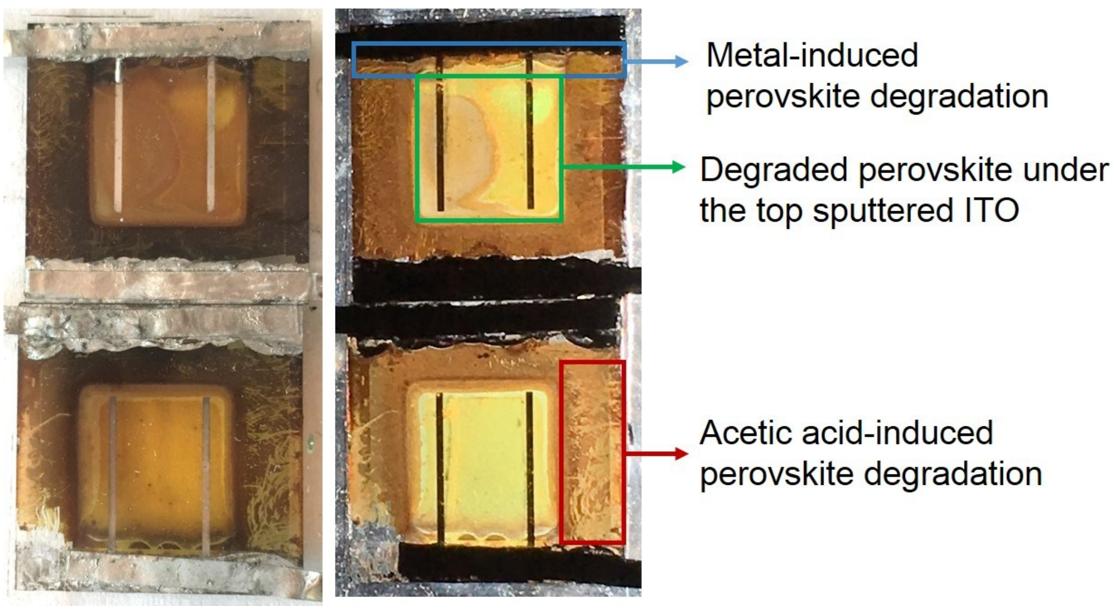

Figure S1: Encapsulated PSCs in the 1st generation package with an ethylene vinyl acetate encapsulant after 1000 hours of 85°C-85%RH taken in a room light (left) and taken under a solar lamp (right). The active area depicted by the rectangular top sputtered ITO turned from original brown to yellow, which signifies the perovskite degraded to PbI_2 (green box). The perovskite area adjacent to the metal ribbon degraded due to metal induced degradation (blue box). Yellow lines outside the sputtered ITO are also PbI_2, indicating degradation of perovskite which is likely induced by acetic acid released from the EVA in damp heat conditions (red box). Notice that features taken under a solar lamp are much clearer than ones taken under a room light.

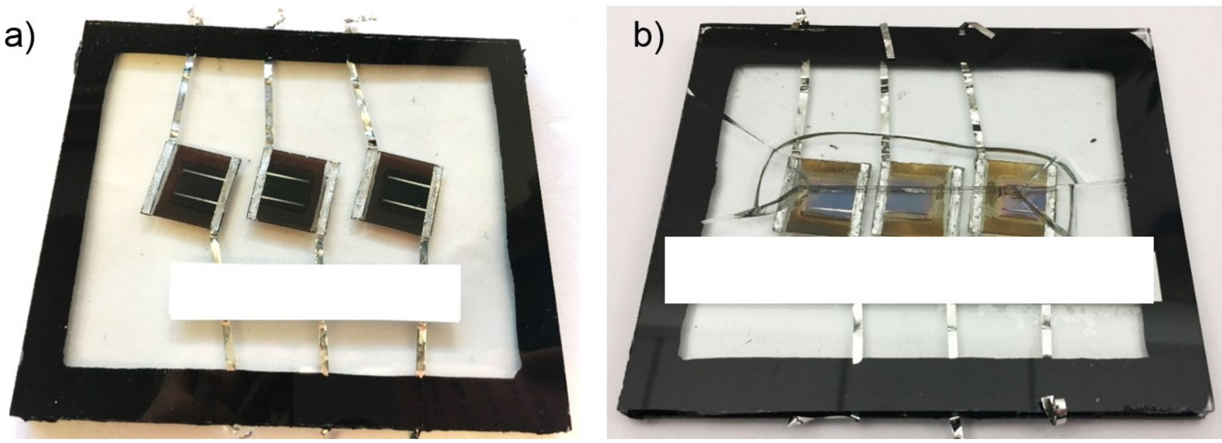

Figure S2: 1st generation packaged PSCs in ethylene vinyl acetate encapsulant. a) The solar cells in this package were all tilted to the right after the lamination process. The solar cells likely moved while the encapsulant was still in the molten state before the encapsulant was completely cured at 140°C. b) Built-in pressure after lamination due to uneven pressing pressure caused both glass sheets to crack. This was observed either right after lamination or a few hours after.

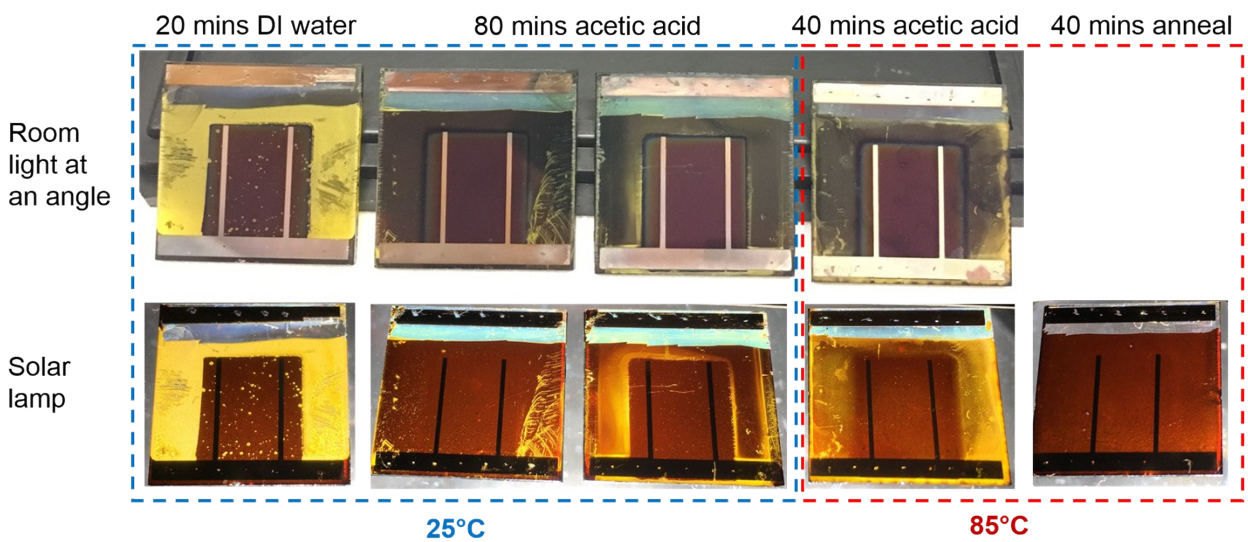

Figure S3: Picture of PSCs with a few drops of DI water and acetic acid (25°C and 85°C) in ambient condition with different degradation time scale as specified on top. A picture of a control solar cell aged at 85°C for the same time as the ones with acetic acid drops is also included in the bottom right for comparison. The top row pictures were taken under room light, while the bottom row pictures were taken under a solar lamp.

Table S1: Figures of merit after 8 minutes at 150°C lamination normalized to initial performance for the 2nd generation package averaged among 22 solar cells with standard deviation.

	Normalized After/Before encapsulation
J_{sc}	1.02±0.04
V_{oc}	0.94±0.04
FF	1.00±0.07
PCE	0.96±0.07

Note: Method for coming up with the normalized values:

$$Normalized \frac{After}{Before} encapsulation = \left(\frac{1}{N}\right) \times \sum_{i=1}^{N} \frac{V_{final}}{V_{initial}}$$

N: number of solar cells

V: each figure of merit – Jsc, Voc, FF, and PCE

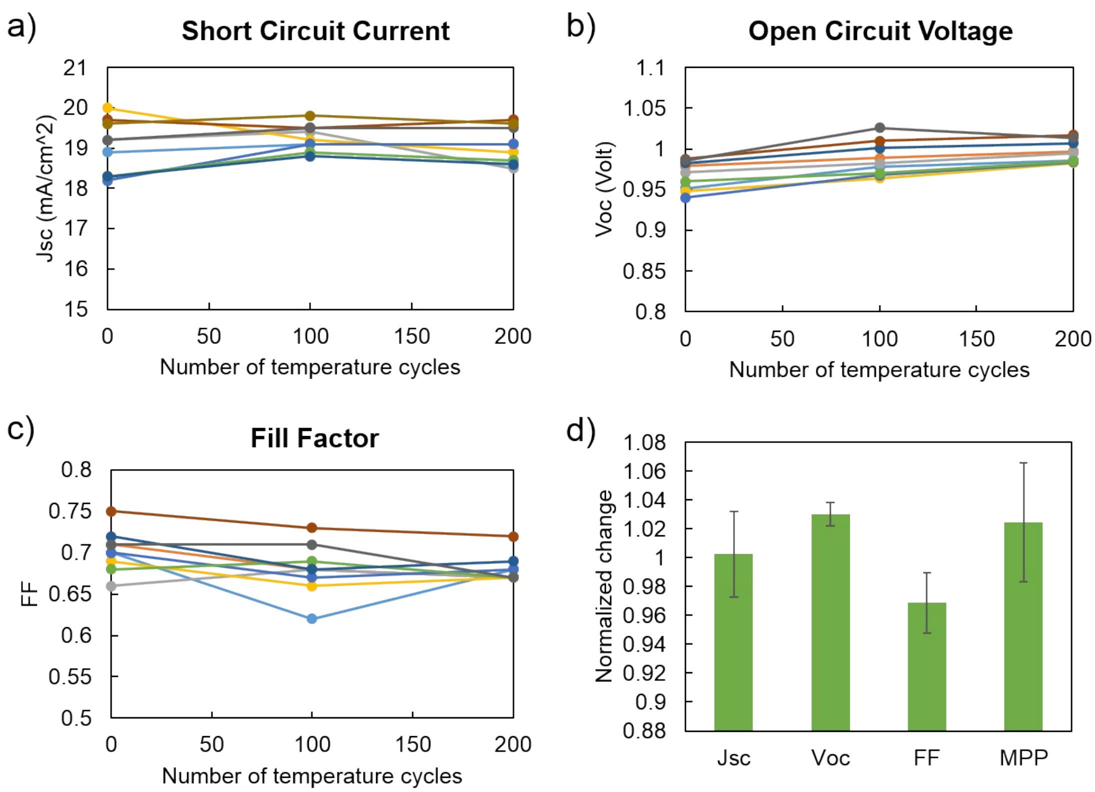

Figure S4: Performance a) short circuit current b) open circuit voltage c) fill factor of nine solar cells in three 2nd generation packages with the ENLIGHT polyolefin throughout the thermal cycling test between -40°C and 85°C. d) Figures of merit after 200 temperature cycles normalized to the initial values.

Table S2: Figures of merit of the 2nd generation package PSCs in the ENLIGHT polyolefin after storing at 25°C for 1000 hours normalized to initial performance with standard deviation for seven solar cells.

	Normalized After/Before
J_{sc}	1.04±0.02
V_{oc}	1.003±0.01
FF	0.98±0.02
PCE	1.05±0.03

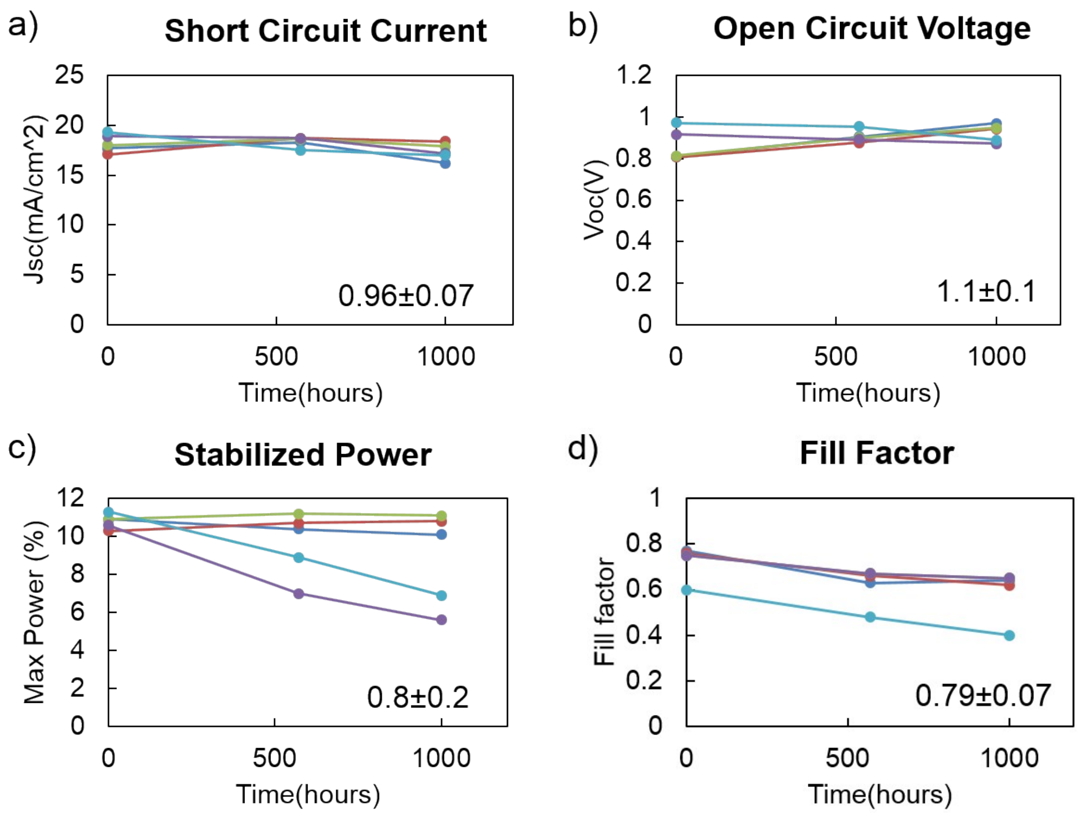

Figure S5: a) Short circuit current b) open circuit voltage c) maximum power stabilized performance d) fill factor of unencapsulated PSCs throughout aging at 85°C in an inert atmosphere. Numbers in the bottom right of each box represent average values after the 1000 hour test normalized to the initial performance.

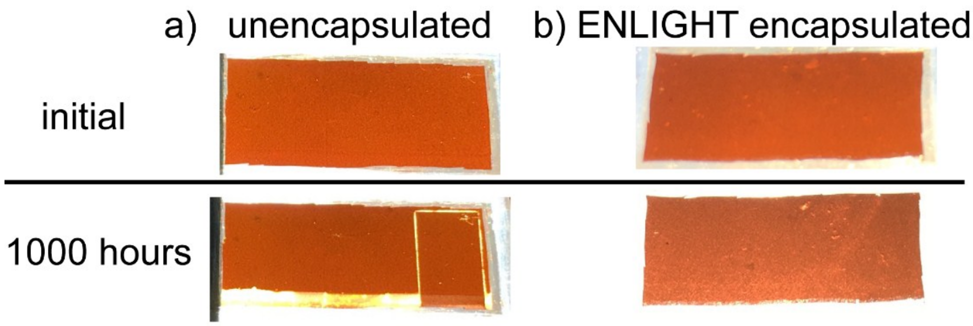

Figure S6: Pictures of a) unencapsulated b) 2nd generation ENLIGHT encapsulated PSCs, taken under the solar lamp, initially and after 1000 hours of aging at 85°C in inert atmosphere.

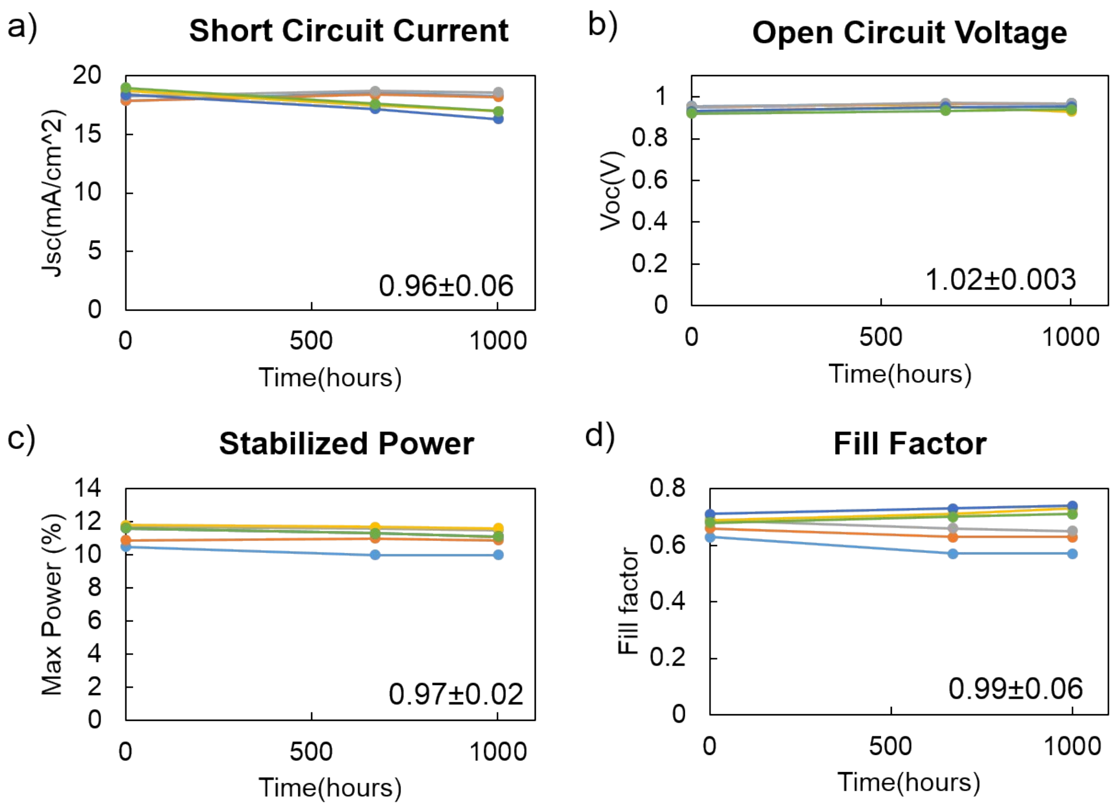

Figure S7: a) Short circuit current b) open circuit voltage c) maximum power stabilized performance d) fill factor of the 2nd generation package encapsulated PSCs with the ENLIGHT polyolefin as they went through aging at 85°C in an inert atmosphere. Numbers in the bottom right of each box represent average values after the 1000 hour test normalized to the initial performance.

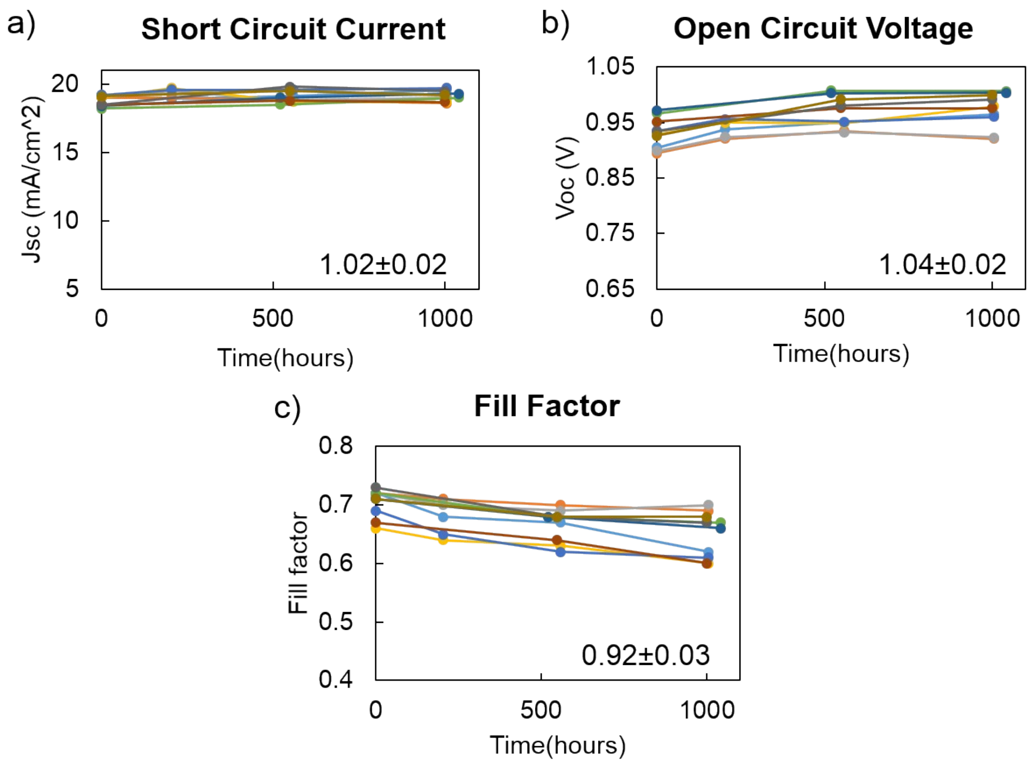

Figure S8: a) Short circuit current b) open circuit voltage c) fill factor of the 2nd generation package encapsulated PSCs with the ENLIGHT polyolefin as they were aged at 85°C-85%RH, "Damp heat" Numbers in the bottom right of each box represent average values after the 1000 hour test normalized to the initial performance.

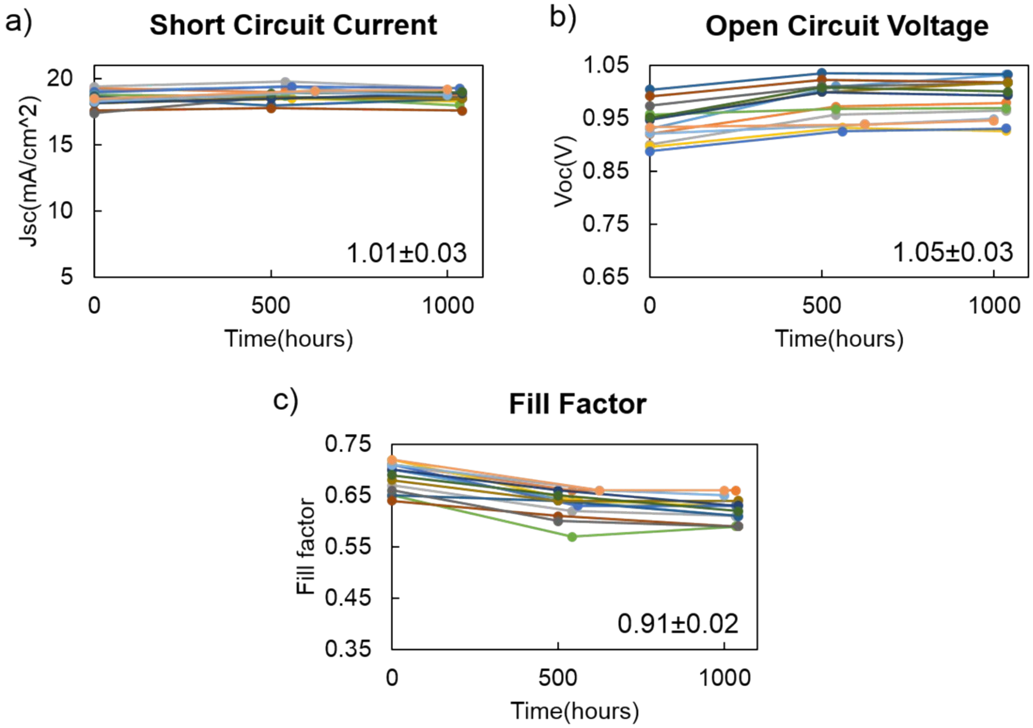

Figure S9: a) Short circuit current b) open circuit voltage c) fill factor of the 2nd generation package encapsulated PSCs with the ENLIGHT polyolefin as they were aged at 85°C-25%RH, "Dry heat." Numbers in the bottom right of each box represent average values after the 1000 hour test normalized to the initial performance.

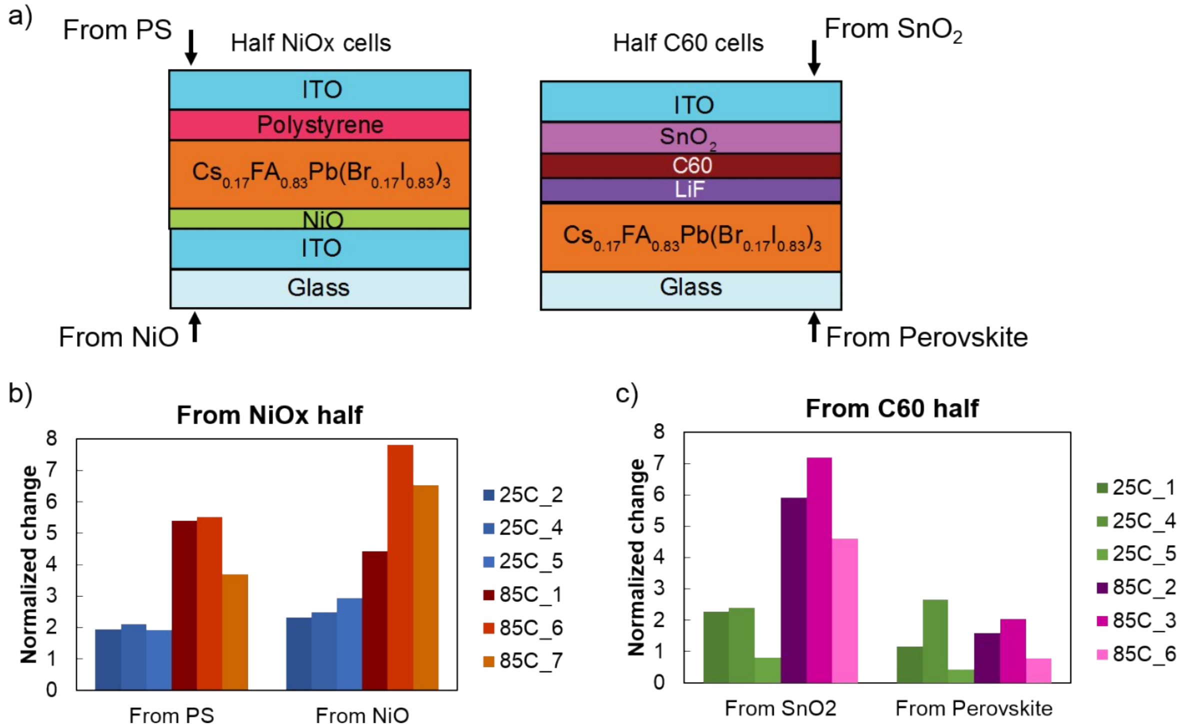

Figure S10: a) Arrow shows where the laser came in for the photoluminescence quantum efficiency (PLQE) measurement of the half NiOx cells and half C60 cells. Normalized PLQE after aging at 25°C and 85°C in inert atmosphere of b) NiOx half cells and c) C60 half cells to the initial values.

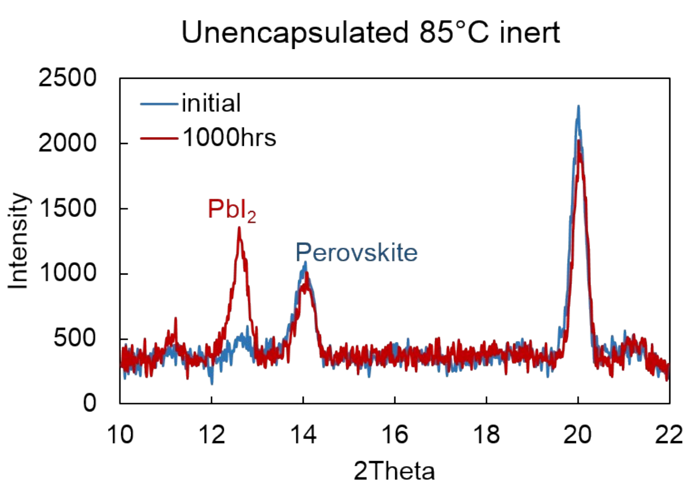

Figure S11: X-ray diffraction pattern of unencapsulated perovskite solar cells initial (blue) and after 1000 hours (red). Notice that PbI_2 increased relative to perovskite after 1000 hours.

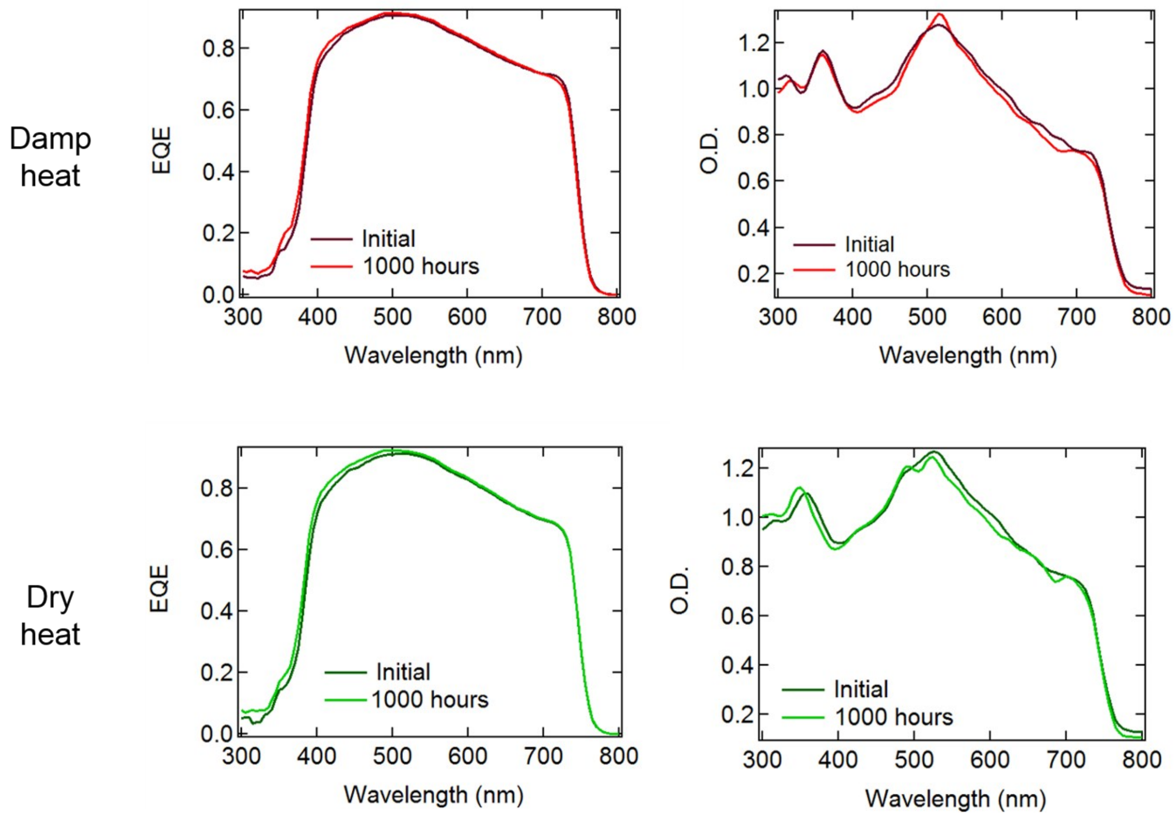

Figure S12: External quantum efficiency and absorption (O.D.) of 2nd generation encapsulated PSCs in the low elastic modulus polyolefin initially and after 1000 damp heat (top) and dry heat (bottom) tests.

Extracting Solar Cell Performance from "stabilized" state

When we removed the solar cells from thermal stressing, we found that we needed to light soak them anywhere from 10 minutes to more than 3 hours while holding them at their maximum power point to reach their stabilized performance. The longer the solar cells were aged, the longer it took to stabilize them (Figure S13). During each maximum power point stabilization, the performance of the solar cells recovered through an increase in fill factor and V_{OC}, while the short circuit current remained constant as shown in the J-V curves in Figure S14 and representative figures of merit throughout 1000 hours damp and dry heat in Figure S15-16. The need for light soaking to recover the efficiency can be connected to the reversible light-induced halide vacancy migration effect as observed by others.[1–4] One must be cautious when monitoring PCE of PSCs after prolonged stability testing and ensure that the PSCs are stabilized properly in each data point. The detailed mechanism behind maximum power recovery is beyond the scope of this study and should be the subject of future study in the perovskite community.

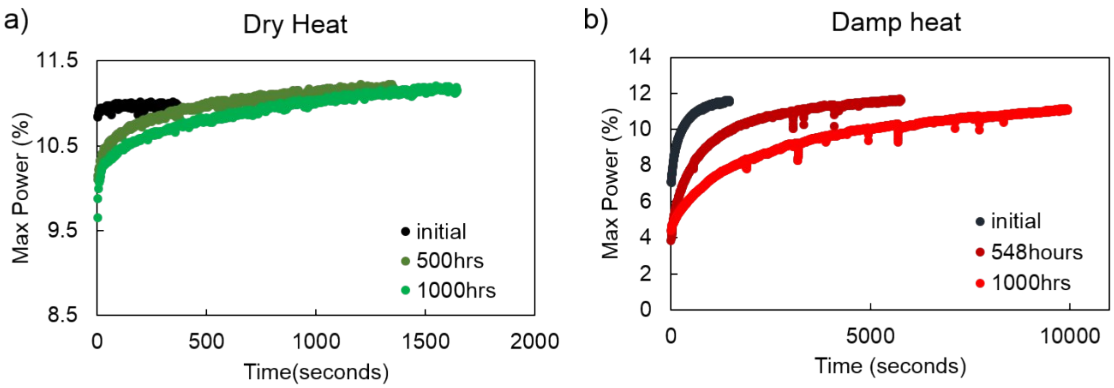

Figure S13: Representative power conversion efficiency stabilization of 2nd generation encapsulated PSCs in the ENLIGHT polyolefin initially, after 500 hours, and after 1000 hours in a) 85°C-25%RH, "Dry Heat" b) 85°C-85%RH, "Damp Heat".

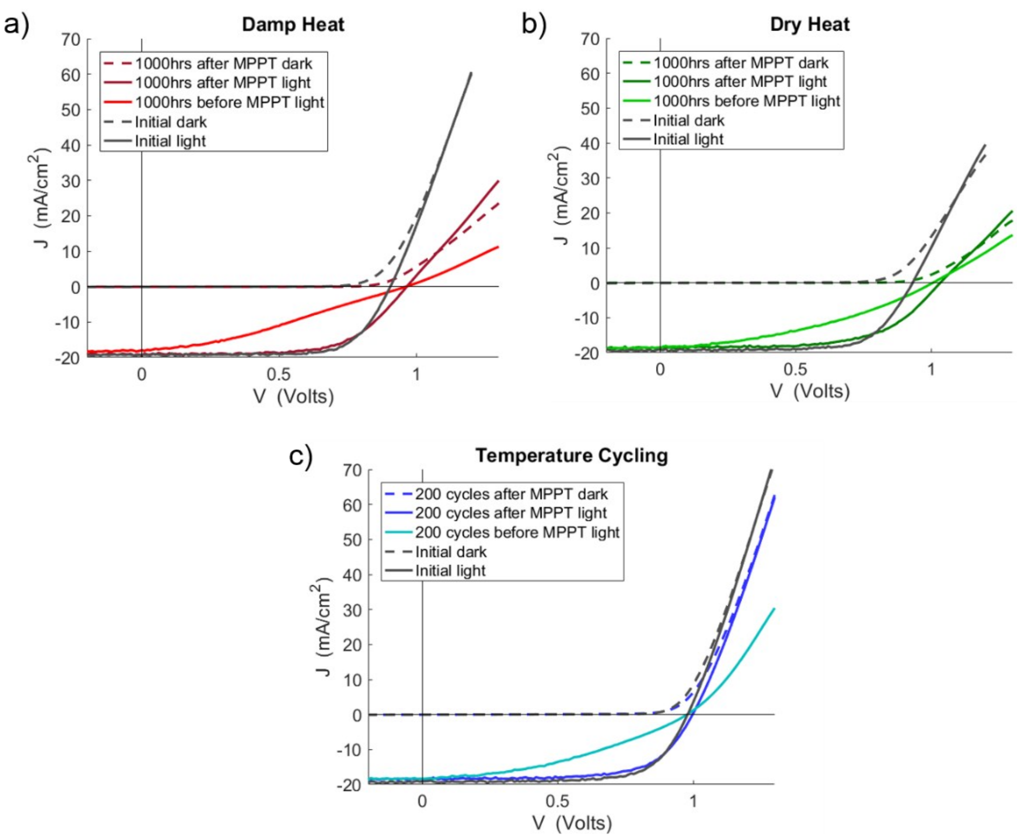

Figure S14: Representative current-voltage curve of 2nd generation encapsulated PSCs in the ENLIGHT polyolefin initially and after respective test in a) 85C-85%RH, "Damp Heat" b) 85C-25%RH, "Dry Heat" c) Temperature cycling. After either 1000 hour tests or the 200 temperature cycle test, the J-V curve was taken just after the PSCs were taken out from the chambers, "before MPPT", and after they achieved 200 second stability in maximum power point tracking, "after MPPT".

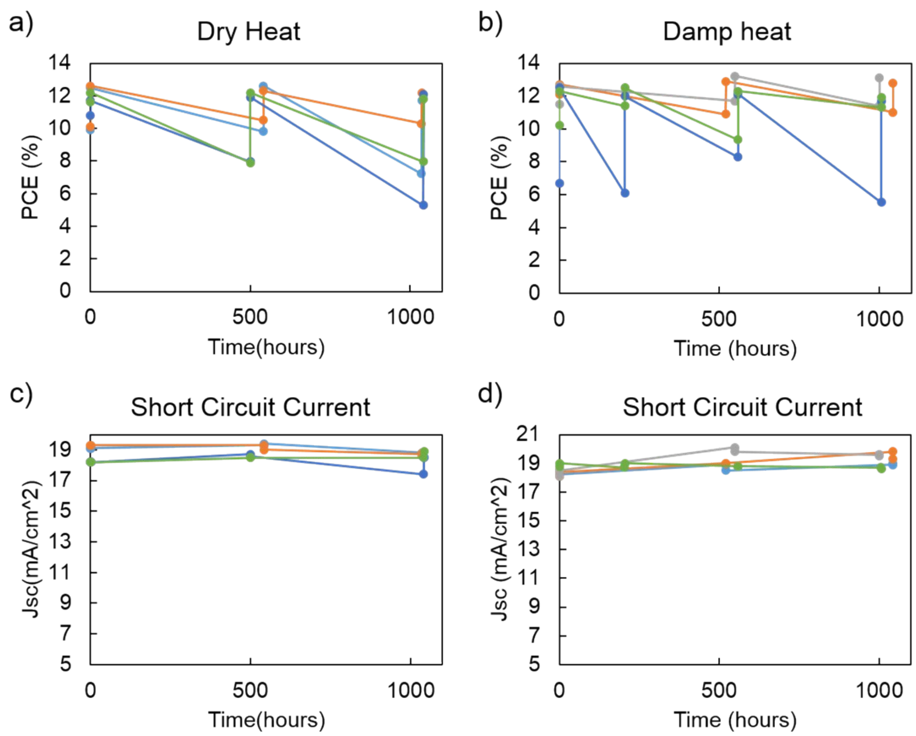

Figure S15: Power conversion efficiency and short circuit current of 2nd generation encapsulated PSCs in the ENLIGHT polyolefin as they went through a) and c) Dry heat, 85°C-25%RH b) and d) Damp heat, 85°C-85%RH. There are two data points at 0, ~500, and 1000hours, which represent before and after maximum power stabilization.

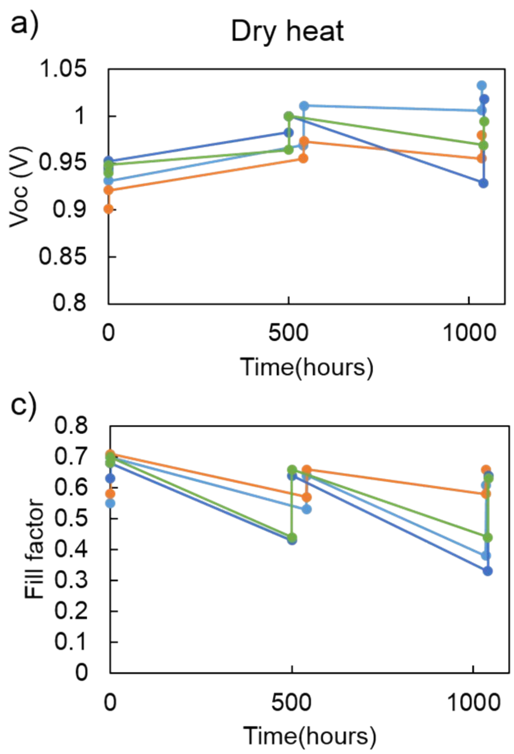

Figure S16: Open circuit voltage and fill factor of 2nd generation encapsulated PSCs in the ENLIGHT polyolefin as they went through a) and c) Dry heat, 85°C-25%RH b) and d) Damp heat, 85°C-85%RH. There are two data points at 0, ~500, and 1000hours, which represent values before and after maximum power stabilization.

Table S3: Measured current comparison from EQE and solar simulator of a representative encapsulated solar cell.

Measurements	Current (mA/cm^2)
Integrated EQE response	18.5
Jsc from solar simulator	18.4

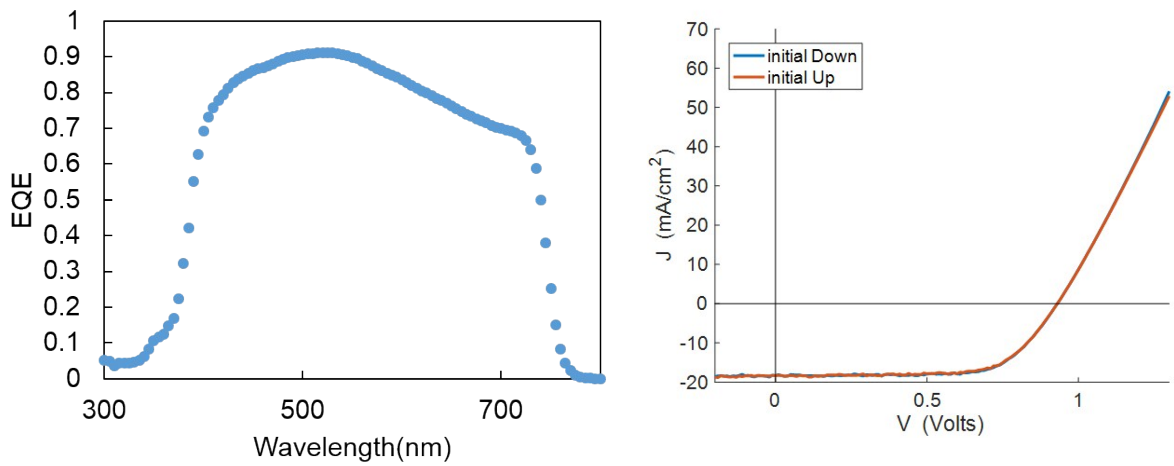

Figure S17: External quantum efficiency and J-V curve with both scan direction of a representative encapsulated solar cell.

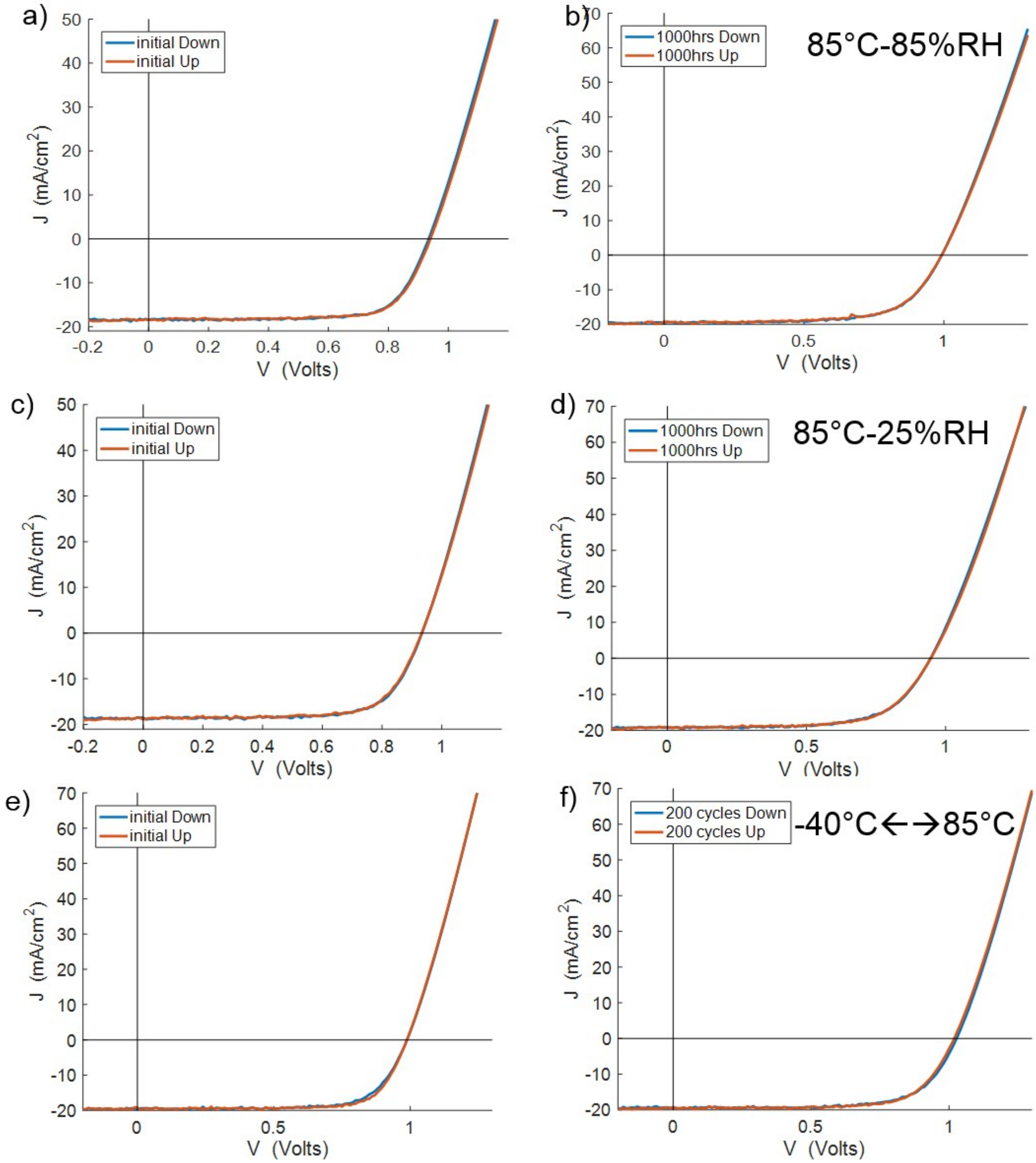

Figure S18: Representative J-V curve with both Down and Up sweep direction of encapsulated solar cells for 85°C-85%RH test a) initial b) after 1000 hours, 85°C-25%RH test c) initial d) after 1000 hours, and temperature cycling test between -40 to 85°C e)initial f) after 200 cycles. There is no hysteresis before and after lifetime testing.

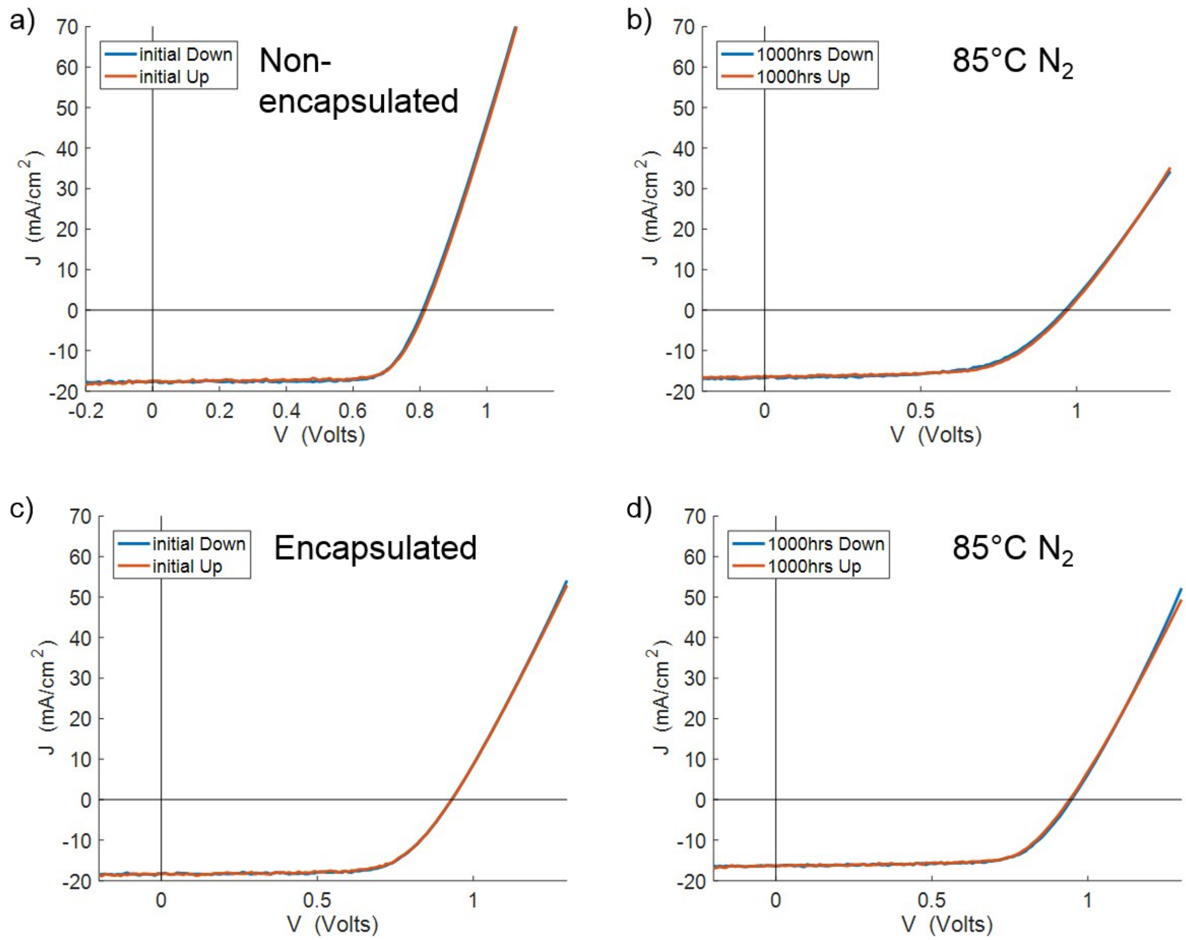

Figure S19: Representative J-V curve with both Down and Up sweep direction of unencapsulated solar cell a) initial b) after 1000hours and encapsulated solar cells c) initial d) after 1000hours.

Reference:

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