

Scan-Rate Dependence of Hysteresis in Planar Perovskite Solar Cells: A Reproducibility Study

Anonymised manuscript for review. SYNTHETIC EXAMPLE PAPER for testing; all data are invented.

ABSTRACT

Current-voltage (J - V) hysteresis in perovskite solar cells is routinely reported, yet the scan conditions that produce it are rarely stated. Here we measure 60 planar $\text{CH}_3\text{NH}_3\text{PbI}_3$ devices at six scan rates between 10 and 500 mV s^{-1} , with and without a 60 s preconditioning step at open circuit. The power conversion efficiency (PCE) obtained from the reverse scan fell from 18.9 % to 16.5 % as the scan rate increased, while the forward scan peaked near 50 mV s^{-1} . A hysteresis index below 0.05 was reached only for slow, preconditioned scans. A stabilised power point at the maximum power voltage (V_{mpp}) agreed with the slow reverse scan within ± 0.4 % absolute. We report all devices, including the 9 that failed, and give the complete measurement protocol so that others can repeat it. The study does not claim a record efficiency; its value is the documented, repeatable procedure.

Keywords: perovskite solar cells; hysteresis; scan rate; reproducibility; stabilised power output

1. Introduction

Hysteresis between the forward and reverse J - V scans of perovskite solar cells has been linked to ion migration, trap filling and capacitive effects [1–3]. Reported efficiencies depend on the scan direction, the scan rate and the pre-bias history, so a single number is not comparable between laboratories [4]. We therefore ask a narrow question: *how large is the scan-rate dependence in devices made by one reproducible recipe?*

The PCE is defined by Equation (1),

$$PCE = \frac{J_{sc} V_{oc} FF}{P_{in}} \times 100 \% \quad (1)$$

where J_{sc} is the short-circuit current density, V_{oc} the open-circuit voltage, FF the fill factor and $P_{in} = 100 \text{ mW cm}^{-2}$ the incident power density. We quantify hysteresis with the index $HI = (PCE_{rev} - PCE_{fwd}) / PCE_{rev}$.

2. Methods

2.1 Device fabrication

Devices had the stack glass/ITO/SnO₂/CH₃NH₃PbI₃/Spiro-OMeTAD/Au (Figure 1). Substrates (15 × 15 mm²) were cleaned in three solvents and treated with UV-ozone for 15 min at 25 °C. The absorber was spin-coated at 4000 rpm for 30 s and annealed at 100 °C for 10 min. The layer thickness was 450 ± 20 nm (profilometer, $n = 12$). The active area was 0.09 cm², defined by a metal mask.

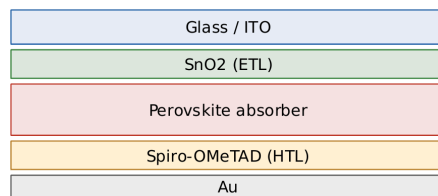


Figure 1. Device architecture used in this study (vector figure inserted as EMF to test fallback conversion).

2.2 Measurement protocol

Measurements followed these steps:

1. Illuminate the device for 60 s at open circuit (preconditioning; omitted for the “no preconditioning” group).
2. Scan from 1.2 V to 0 V (reverse), then from 0 V to 1.2 V (forward).
3. Repeat at scan rates of 10, 25, 50, 100, 250 and 500 mV s^{-1} .
4. Hold the device at V_{mpp} for 300 s and record the stabilised power output.

The diode behaviour used for the fits is given by Equation (2) and the aligned relations that follow:

$$J(V) = J_L - J_0 \left[\exp \left(\frac{qV}{nk_B T} \right) - 1 \right] \quad (2)$$

$$\begin{aligned} V_{oc} &= \frac{nk_B T}{q} \ln \left(\frac{J_L}{J_0} + 1 \right) \\ FF &= \frac{J_{mp} V_{mp}}{J_{sc} V_{oc}} \end{aligned} \quad (3)$$

Charge collected during a scan can be estimated from $Q = \int_0^{V_{max}} C(V) dV$, and the mean of N devices with standard deviation is $\bar{x} = \frac{1}{N} \sum_{i=1}^N x_i$, $\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})^2}$.

3. Results and discussion

3.1 Effect of scan direction

Figure 2 shows representative curves. The reverse scan gives $V_{oc} = 1.12$ V and $J_{sc} = 22.4$ mA cm⁻²; the forward scan gives 1.09 V and 22.3 mA cm⁻².

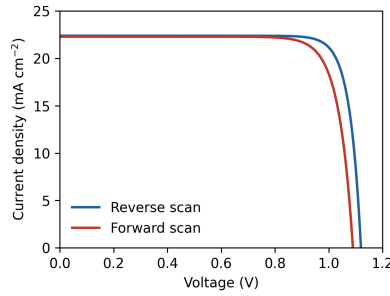


Figure 2. Representative J - V curves of one device measured at 50 mV s⁻¹ in reverse (blue) and forward (red) direction.

Table 1 summarises the champion and mean device parameters.

Table 1. Photovoltaic parameters of the champion and mean devices (reverse scan, 50 mV s⁻¹). Mean $\pm$ standard deviation for $N = 51$ working devices.

Parameter	Symbol	Unit	Champion	Mean $\pm$ SD
Open-circuit voltage	V_{oc}	V	1.12	1.10 ± 0.02
Short-circuit current density	J_{sc}	mA cm ⁻²	22.4	21.9 ± 0.5
Fill factor	FF	-	0.75	0.72 ± 0.03
Power conversion efficiency	PCE	%	18.4	17.4 ± 0.8
Series resistance	R_s	Ω cm ²	3.1	4.0 ± 0.9

3.2 Effect of scan rate

Figure 3 shows that the reverse-scan PCE decreased monotonically with scan rate (panel a), whereas the forward scan passed through a maximum. The hysteresis index is distributed around 0.09 (panel b).

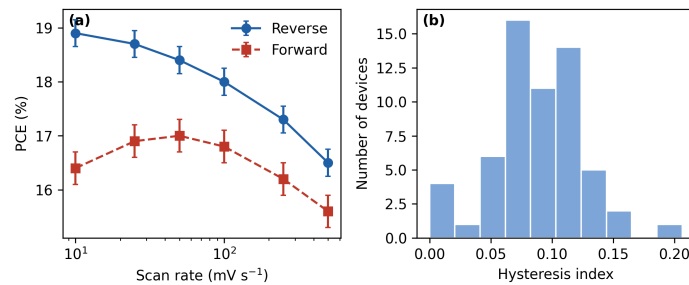


Figure 3. Scan-rate dependence. (a) PCE from reverse and forward scans versus scan rate (log scale). (b) Distribution of the hysteresis index for 60 devices.

Table 2 groups the results by preconditioning, with merged header cells and a footnote marker.

Table 2. PCE (%) and hysteresis index (HI) by scan rate and preconditioning. a Only 6 devices in this cell.

Scan rate (mV s ⁻¹)	No preconditioning			60 s preconditioning		
	PCE _{rev}	PCE _{fwd}	HI	PCE _{rev}	PCE _{fwd}	HI
10	18.6	16.0	0.14	18.9	17.9	0.05
50	18.1	16.7	0.08	18.4	17.5	0.05
500	16.2	15.1	0.07	16.5	15.6	0.05 ^a

The stabilised power output at V_{mpp} was 18.2 % after 300 s, consistent with the slow reverse scan.¹

Table 3 is deliberately wide to test horizontal scrolling on phones.

Table 3. Full per-batch statistics (wide table).

Batch	Devices	Failed	V_{oc} (V)	J_{sc} (mA cm ⁻²)	FF	PCE rev (%)	PCE fwd (%)	HI	Stabilised (%)	Humidity
A	15	2	1.11	22.0	0.73	17.8	16.4	0.08	17.6	32
B	15	3	1.09	21.7	0.71	16.8	15.5	0.08	16.7	38
C	15	1	1.11	22.2	0.73	18.0	16.9	0.06	17.9	30
D	15	3	1.08	21.5	0.70	16.3	15.0	0.08	16.1	41

3.3 Failed devices

Nine devices (15 %) were excluded because of shunts ($R_{sh} < 500 \Omega cm^2$) or because the Au contact delaminated. They are listed in the supplementary data so that the yield is not overstated. The trap density estimated by space-charge-limited current was about $2 \times 10^{15} cm^{-3}$ and the film thickness varied by ± 20 nm. A bold claim such as “no hysteresis” is therefore **not** supported; a modest statement is: hysteresis was *small* (HI < 0.05) only for slow, preconditioned scans.

A short excerpt of the analysis script:

```
hi = (pce_rev - pce_fwd) / pce_rev
print(f"mean HI = {hi.mean():.3f} +/- {hi.std(ddof=1):.3f}")
```

4. Conclusions

- The reverse-scan PCE depends on scan rate, falling from 18.9 % to 16.5 %.
- Hysteresis is small only for slow, preconditioned scans (HI < 0.05).
- Reporting scan rate, direction and pre-bias history is necessary for comparable efficiencies.

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Data availability

The raw J - V files for all 60 devices are available from the corresponding author on request. (Fictional statement.)

Competing interests

The authors declare no competing interests.

References

1. H. J. Snaith, A. Abate, J. M. Ball *et al.*, "Anomalous hysteresis in perovskite solar cells," *J. Phys. Chem. Lett.* **5**, 1511 (2014). doi:10.1021/jz500113x
2. W. Tress, N. Marinova, T. Moehl *et al.*, "Understanding the rate-dependent *J*-*V* hysteresis, slow time component, and aging in CH₃NH₃PbI₃ perovskite solar cells," *Energy Environ. Sci.* **8**, 995 (2015). doi:10.1039/C4EE03664F
3. E. L. Unger, E. T. Hoke, C. D. Bailie *et al.*, "Hysteresis and transient behavior in current-voltage measurements of hybrid-perovskite absorber solar cells," *Energy Environ. Sci.* **7**, 3690 (2014). doi:10.1039/C4EE02465F
4. E. Zimmermann, P. Ehrenreich, T. Pfadler *et al.*, "Erroneous efficiency reports harm organic solar cell research," *Nat. Photonics* **8**, 669 (2014). doi:10.1038/nphoton.2014.210

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1. Stabilised output was recorded for 11 of the 51 working devices only, because the others were consumed by later characterisation.↵