

Solar Cells Reporting Summary

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► Experimental design

Please check: are the following details reported in the manuscript?

1. Dimensions

Area of the tested solar cells

☒ Yes
☐ No

The active area of small-size perovskite solar cells is 0.09 cm². The designated area of perovskite modules on 25 cm² substrate is 22.4 cm². The information can be found in the Photovoltaic characterization part in Method.

Method used to determine the device area

☒ Yes
☐ No

The small-size perovskite solar cells were measured using a metal mask with the aperture area of 0.09 cm². The designated area of 22.4 cm² for modules was defined by a corresponding metal mask. The information can be found in the Photovoltaic characterization part in Method.

2. Current-voltage characterization

Current density-voltage (J-V) plots in both forward and backward direction

☒ Yes
☐ No

The J-V curves were scanned in the reverse direction unless specified otherwise. The J-V curves for the hysteresis study are obtained from scans in both forward and backward directions. The information can be found in the Photovoltaic characterization part in Method and the plots are showed in Supplementary Information (Supplementary Figure 18 for solar modules and Supplementary Table 3 for solar cells).

Voltage scan conditions

For instance: scan direction, speed, dwell times

☒ Yes
☐ No

All the J-V curves are measured under reverse scan with a scan rate of 0.25V/s unless otherwise specified. The information can be found in the Photovoltaic characterization part in Method.

Test environment

For instance: characterization temperature, in air or in glove box

☒ Yes
☐ No

The J-V curves were measured in ambient air at ~25 °C and a relative humidity of ~40–60%. The information can be found in the Photovoltaic characterization part in Method.

Protocol for preconditioning of the device before its characterization

☒ Yes
☐ No

No preconditioning protocol was used before the characterization. The information is stated in the Photovoltaic characterization part in Method.

Stability of the J-V characteristic

Verified with time evolution of the maximum power point or with the photocurrent at maximum power point; see [ref. 7](#) for details.

☒ Yes
☐ No

Stabilized photocurrent output by holding the voltage at the maximum power point (6.0 V) for perovskite solar module (Supplementary Figure 18). The stability test information can be found in the Stability testing part in Method.

3. Hysteresis or any other unusual behaviour

Description of the unusual behaviour observed during the characterization

☒ Yes
☐ No

Small J–V hysteresis was observed in the case of the solar cells (Supplementary Table 3) and solar modules (Supplementary Figure 18). The hysteresis study is discussed in the device performance discussion part.

Related experimental data

☒ Yes
☐ No

We show the stabilized photocurrent output and J-V plots under different directions in Supplementary Figure 18.

4. Efficiency

External quantum efficiency (EQE) or incident photons to current efficiency (IPCE)

☒ Yes
☐ No

The EQE of small size device is shown in Figure 3b.

A comparison between the integrated response under the standard reference spectrum and the response measure under the simulator

☒ Yes
☐ No

The integrated current densities from the EQE curves are approximately the same as the measured J_{sc} values. This is stated in the device performance discussion part.

For tandem solar cells, the bias illumination and bias voltage used for each subcell

☐ Yes
☒ No

There is no tandem cells in this work.

5. Calibration

Light source and reference cell or sensor used for the characterization

☒ Yes
☐ No

Xenon-lamp (USHIO, UXL-150SO) based solar simulator (Oriel Sol 1A) was used for J-V characterizations. The solar simulator illumination intensity was calibrated using a KG3 reference Si-cell (Enlitech). The information can be found in the Photovoltaic characterization part in Method.

Confirmation that the reference cell was calibrated and certified

☒ Yes
☐ No

The solar simulator illumination intensity was calibrated using a KG3 reference Si-cell (Enlitech). The information can be found in the Photovoltaic characterization part in Method.

Calculation of spectral mismatch between the reference cell and the devices under test

☒ Yes
☐ No

No spectral mismatch calculation was performed.

6. Mask/aperture

Size of the mask/aperture used during testing

☒ Yes
☐ No

The small size PSCs were measured using a metal mask with the aperture area of 0.09cm². The designated area of 22.4 cm² for modules was defined by a corresponding metal mask. The information can be found in the Photovoltaic characterization part in Method.

Variation of the measured short-circuit current density with the mask/aperture area

☒ Yes
☐ No

The information can be found in the Supplementary Figure 6 and 10 in Supplementary Information.

7. Performance certification

Identity of the independent certification laboratory that confirmed the photovoltaic performance

☐ Yes
☒ No

We sent our modules to National Institute of Advanced Industrial Science and Technology (AIST) for J-V characterization according to their standard protocol (IEC60904-3 Ed. 3). The information can be found in Supplementary Figure 15.

A copy of any certificate(s)
Provide in Supplementary Information

☐ Yes
☒ No

AIST provided J-V results according to their standard protocol (IEC60904-3 Ed. 3). The information can be found in Supplementary Figure 15. Note that the Supplementary Figure 15 is not a certificate.

8. Statistics

Number of solar cells tested

☒ Yes
☐ No

Statistical analysis of the photovoltaic parameters for 12 small size devices (Supplementary Figure 6 and 10) and 15 module devices (Supplementary Figure 17 and Supplementary Table 7) are provided and in Supplementary Information.

Statistical analysis of the device performance

☒ Yes
☐ No

Statistical analysis of the photovoltaic parameters for small size devices (Supplementary Figure 6 and 10) and module devices (Supplementary Figure 17 and Supplementary Table 7) are provided and in Supplementary Information.

9. Long-term stability analysis

Type of analysis, bias conditions and environmental conditions

☒ Yes
☐ No

See the Stability testing in Method part.

For instance: illumination type, temperature, atmosphere humidity, encapsulation method, preconditioning temperature