

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	It can be found in Methods Section
	☐ No	
Method used to determine the device area	☒ Yes	Methods can be found in the Method Section
	☐ No	

2. Current-voltage characterization

Current density-voltage (J-V) plots in both forward and backward direction	☒ Yes	It can be found in Fig. 5a, Supplementary Fig. 26
	☐ No	
Voltage scan conditions <i>For instance: scan direction, speed, dwell times</i>	☒ Yes	It can be found methods section: Characterisation of the photovoltaic devices.
	☐ No	
Test environment <i>For instance: characterization temperature, in air or in glove box</i>	☒ Yes	Text environment can be found in section, we have used RT for device testing. Details are given in Methods section and in each figure legends.
	☐ No	
Protocol for preconditioning of the device before its characterization	☒ Yes	No preconditioning protocol was used.
	☐ No	
Stability of the J-V characteristic <i>Verified with time evolution of the maximum power point or with the photocurrent at maximum power point; see ref. 7 for details.</i>	☒ Yes	We provide short-term (600 seconds) maximum power point tracking data in Fig. 4c. In addition, we performed long-term up to 600 hours (Fig.5b) and 200 hours at room temperature (Fig.5c) at maximum power point tracking under 1 sun illumination with encapsulated cells in ambient conditions.
	☐ No	

3. Hysteresis or any other unusual behaviour

Description of the unusual behaviour observed during the characterization	☒ Yes	In our case, we didn't observed unusual behavior. However, we have provided all forward and reverse scan J-V data for checking hysteresis behaviour, Fig. 5a, Supplementary Fig. 26.
	☐ No	
Related experimental data	☒ Yes	We provide hysteresis scans. All other J-V plots were recorded in reverse scan unless not mentioned.
	☐ No	

4. Efficiency

External quantum efficiency (EQE) or incident photons to current efficiency (IPCE)	☒ Yes	We provide EQE spectra in Figure 3e which was measured by a spectral response measurement system (CEP-25BX, JASCO JAPAN), which was equipped with a light source XE (500W), Halogen (400 W). Prior to the use of the light, the spectral response and the light intensity were calibrated using a Si-photodiode (Model: S1337-101BQ) and InGaAs photodiode (model: G12180-050A) for 300-1100 nm and 1100-1400 nm calibration respectively. All measurements were carried out in ambient environment at ~25 °C and ~30-35 % relative humidity in the dark chamber.
	☐ No	
A comparison between the integrated response under the standard reference spectrum and the response measure under the simulator	☒ Yes	The integrated short-circuit current from the EQE spectrum matches the short-circuit current from the J-V scan in reverse mode with negligible error, Fig. 3e.
	☐ No	
For tandem solar cells, the bias illumination and bias voltage used for each subcell	☐ Yes	Not applicable
	☒ No	

5. Calibration

Light source and reference cell or sensor used for the characterization

☒ Yes
☐ No

The cells were illuminated using a solar simulator at AM 1.5 G for 10 s, for which the light intensity was adjusted to 1 sun intensity (100 mW cm⁻²) through the use of an NREL-calibrated Si solar cell with a KG-5 filter.

Confirmation that the reference cell was calibrated and certified

☒ Yes
☐ No

The reference cell was recently calibrated with a KG-5 filtered silicon cell from McScience Engineers under standard protocol.

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

☒ Yes
☐ No

A spectral mismatch calculation was performed based on the spectral irradiance of the solar simulator, the EQE of the reference silicon solar cell and EQE spectra of our cells. The mismatch factor was ~0.9935. Given the very small deviation from unity the measured JSC was not corrected by the factor 1/M.

6. Mask/aperture

Size of the mask/aperture used during testing

☒ Yes
☐ No

An aperture metal masks of 0.09 cm² (for small area) , 1 cm² (for large area) and 18.08 cm² (for perovskite solar module) were used for J-V measurements.

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

☒ Yes
☐ No

We didn't observed a significant variation in short-circuit current.

7. Performance certification

Identity of the independent certification laboratory that confirmed the photovoltaic performance

☐ Yes
☒ No

We are not claiming our efficiency

A copy of any certificate(s)

Provide in Supplementary Information

☐ Yes
☒ No

We are not claiming our efficiency

8. Statistics

Number of solar cells tested

☒ Yes
☐ No

We have fabricated total >300 devices of respective composition. Statistical data of respective samples is given in Figure 4a for 20 devices in each type.

Statistical analysis of the device performance

☒ Yes
☐ No

We have provided statistical data in Figure 4a, 6e, Source data file 16b, Source data Table 1. Supplementary Table-14-16.

9. Long-term stability analysis

Type of analysis, bias conditions and environmental conditions

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

☒ Yes
☐ No

Maximum power point tracking was carried out at respective bias condition under 1 sun illumination which was calculated from initial J-V plot, Fig. 5c. Measurements was performed at room temperature of the encapsulated devices. However, we have not monitored any device temperature during actual J-V measurements under illumination for 200 hours. More details can be found in "device stability test" section.