

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 area of the tested solar cells is 0.13 cm² (see "Methods" section in main text).
- Method used to determine the device area ☒ Yes ☐ No The device area is defined by the overlap between the pre-patterned ITO and back metal electrode, where the metal electrode is thermally evaporated.

2. Current-voltage characterization

- Current density-voltage (J-V) plots in both forward and backward direction ☒ Yes ☐ No Supplementary Figs. 22, 25 and 27.
- Voltage scan conditions ☒ Yes ☐ No The J-V measurements were conducted with sweep mode with reverse (from 1.23 V to -0.02 V) and forward (from -0.02 V to 1.23 V) scan with a scan rate of 10 mV s⁻¹ (see "Methods" section in main text).
For instance: scan direction, speed, dwell times
- Test environment ☒ Yes ☐ No All J-V measurements were conducted in N₂-filled glovebox at room temperature (see "Methods" section in main text).
For instance: characterization temperature, in air or in glove box
- Protocol for preconditioning of the device before its characterization ☒ Yes ☐ No No preconditioning protocol was used.
- Stability of the J-V characteristic ☒ Yes ☐ No The steady-outputs were measured with time evolution of the maximum power point in Figs. 2E and 3B.
Verified with time evolution of the maximum power point or with the photocurrent at maximum power point; see ref. 7 for details.

3. Hysteresis or any other unusual behaviour

- Description of the unusual behaviour observed during the characterization ☒ Yes ☐ No No unusual behaviour was observed during the characterization.
- Related experimental data ☒ Yes ☐ No Supplementary Figs. 22, 25 and 27.

4. Efficiency

- External quantum efficiency (EQE) or incident photons to current efficiency (IPCE) ☒ Yes ☐ No Fig. 2D.
- A comparison between the integrated response under the standard reference spectrum and the response measure under the simulator ☒ Yes ☐ No The J_{sc} obtained from J-V measurement is consistent with the J_{sc} integrated from EQE spectrum. (Fig. 2C, 2D).
- For tandem solar cells, the bias illumination and bias voltage used for each subcell ☐ Yes ☒ No Not relevant.

5. Calibration

- Light source and reference cell or sensor used for the characterization ☒ Yes ☐ No Simulated AM 1.5 G irradiation was from solar simulator (EnliTech, SS-F5, Taiwan). A silicon solar cell (with a KG-2 filter) was used as reference cell (see "Methods" section in main text).

Confirmation that the reference cell was calibrated and certified	☒ Yes ☐ No	The reference cell was calibrated by National Renewable Energy Laboratory (more see "Methods" section in main text).
Calculation of spectral mismatch between the reference cell and the devices under test	☐ Yes ☒ No	The test light source for the device measurement matches well with the one-sun light spectrum and reference cell. The spectral mismatch factor is 1 for the devices
6. Mask/aperture		
Size of the mask/aperture used during testing	☒ Yes ☐ No	The size of the mask used for J-V measurements is 0.104 cm ² (See "Methods" section in main text).
Variation of the measured short-circuit current density with the mask/aperture area	☐ Yes ☒ No	All devices has been measured with identical masks
7. Performance certification		
Identity of the independent certification laboratory that confirmed the photovoltaic performance	☒ Yes ☐ No	Certified by the National Institute of Metrology (NIM, China).
A copy of any certificate(s) <i>Provide in Supplementary Information</i>	☒ Yes ☐ No	Certificate is provided in Supplementary Fig. 26.
8. Statistics		
Number of solar cells tested	☒ Yes ☐ No	30 solar cells for each device configurations were tested and statistic for efficiency distribution demonstration (Fig. 2F and Supplementary Fig. 28).
Statistical analysis of the device performance	☒ Yes ☐ No	Fig. 2F and Supplementary Fig. 28.
9. Long-term stability analysis		
Type of analysis, bias conditions and environmental conditions <i>For instance: illumination type, temperature, atmosphere humidity, encapsulation method, preconditioning temperature</i>	☒ Yes ☐ No	Long-term stability for the cells was measured and analyzed at different conditions including shelf stability in humid air and MPP tracking at elevated temperature in N ₂ -filled glovebox (detailed conditions are described in main text).