

Solar Cells Reporting Summary

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► Experimental design

Please check the following details are reported in the manuscript, and provide a brief description or explanation where applicable.

1. Dimensions

Area of the tested solar cells

☒ Yes
☐ No

0.1 cm² for single junction and 1.0 cm² for tandems (Methods)

Explain why this information is not reported/not relevant.

Method used to determine the device area

☒ Yes
☐ No

The device areas were defined by masks with different aperture areas (Methods)

Explain why this information is not reported/not relevant.

2. Current-voltage characterization

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

☒ Yes
☐ No

J-V curves were obtained from scans in both forward and backward direction. The J-V curves can be found in Fig. 4 and supplementary information.

Voltage scan conditions

☒ Yes
☐ No

All J-V measurements were conducted at a scan rate of 10 mV/s with the delay time of 10 ms

Explain why this information is not reported/not relevant.

Test environment

☒ Yes
☐ No

Our devices were characterized at room temperature (ca. 25 Celsius degree) in air

Explain why this information is not reported/not relevant.

Protocol for preconditioning of the device before its characterization

☒ Yes
☐ No

No preconditioning protocol was used in the characterization. The information is stated in "device characterization" part in "Methods"

Explain why this information is not reported/not relevant.

Stability of the J-V characteristic

☒ Yes
☐ No

Stabilized photocurrent output by holding the voltage at the maximum power point (Supplementary Figs. 36, 53, 56)

Explain why this information is not reported/not relevant.

3. Hysteresis or any other unusual behaviour

Description of the unusual behaviour observed during the characterization

☒ Yes
☐ No

No J-V hysteresis or any other unusual behaviour was observed and the related comments were mentioned in manuscript.

Explain why this information is not reported/not relevant.

Related experimental data

☒ Yes
☐ No

We show the J-V curves under different directions in Fig. 4 and supplementary information.

Explain why this information is not reported/not relevant.

4. Efficiency

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

☒ Yes
☐ No

The EQE spectrum can be found in supplementary Figs. 37, 40, 44, 45 and 54.

Explain why this information is not reported/not relevant.

A comparison between the integrated response under the standard reference spectrum and the response measure under the simulator	☒ Yes ☐ No	The integrated JSC from EQE spectrum are agreed well (less than 5% mismatch) with the J-V measurements. The comparison is represented in supplementary Figs. 37, 40, 44, 45 and 54. <i>Explain why this information is not reported/not relevant.</i>
For tandem solar cells, the bias illumination and bias voltage used for each subcell	☒ Yes ☐ No	"Device characterization" part in "Methods" <i>Explain why this information is not reported/not relevant.</i>
5. Calibration		
Light source and reference cell or sensor used for the characterization	☒ Yes ☐ No	A solar simulator (EMS-35AAA, Ushio Spax Inc.) based on the Ushio Xe short arc lamp 500 was used to simulate sunlight irradiation of 1 sun (AM1.5G; 100 mW cm ⁻²). The solar simulator illumination intensity was calibrated using a KG5 reference Si-cell (Enlitech). The information can be found in the "Device characterization" part in "Methods" <i>Explain why this information is not reported/not relevant.</i>
Confirmation that the reference cell was calibrated and certified	☒ Yes ☐ No	The information can be found in the "Device characterization" part in "Methods" <i>Explain why this information is not reported/not relevant.</i>
Calculation of spectral mismatch between the reference cell and the devices under test	☒ Yes ☐ No	Spectral mismatch factor of 1 was used for all J-V measurements <i>Explain why this information is not reported/not relevant.</i>
6. Mask/aperture		
Size of the mask/aperture used during testing	☒ Yes ☐ No	Single junction solar cells: 0.1 cm ² , 1.21 cm ² ; Tandem solar cells: 1.0 cm ² <i>Explain why this information is not reported/not relevant.</i>
Variation of the measured short-circuit current density with the mask/aperture area	☒ Yes ☐ No	J-V results in main text are reported with illumination mask. We note, the unmasked current is typically ~5% higher. <i>Explain why this information is not reported/not relevant.</i>
7. Performance certification		
Identity of the independent certification laboratory that confirmed the photovoltaic performance	☒ Yes ☐ No	We sent our device to Ningbo New Materials Testing and Evaluation Center (NBMTEC) for j-V characterization according to their standard protocol (IEC60891: 2021). The information can be found in Supplementary Fig. 55. <i>Explain why this information is not reported/not relevant.</i>
A copy of any certificate(s)	☒ Yes ☐ No	NBMTEC provided j-V results according to their standard protocol IEC60891: 2021). The information can be found in Supplementary Fig. 55. <i>Explain why this information is not reported/not relevant.</i>
8. Statistics		
Number of solar cells tested	☒ Yes ☐ No	22 devices are provided for statistical analysis of the photovoltaic parameters <i>Explain why this information is not reported/not relevant.</i>
Statistical analysis of the device performance	☒ Yes ☐ No	Supplementary Fig. 39 <i>Explain why this information is not reported/not relevant.</i>
9. Long-term stability analysis		
Type of analysis, bias conditions and environmental conditions	☒ Yes ☐ No	The unencapsulated tandems were aged using a xenon lamp with 100 mW cm ⁻² irradiance at the regular ambient conditions (40-60%RH, 25-35?) without preconditioning. The information of long-term stability test is presented in the manuscript and in the "Methods" section. <i>Explain why this information is not reported/not relevant.</i>

