### 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 | The area of test solar cells is 0.08920±0.0006 cm². (Supplementary Figure 26) | No |
| Method used to determine the device area | Yes | The device area is determined by the aperture area of metal mask, which was certified by accredited institute of Newport Laboratory. | No |
| 2. Current-voltage characterization |   |   |   |
| Current density-voltage (J-V) plots in both forward and backward direction | Yes | We give the J-V plots measured under both forward and backward directions in figure 3b. | No |
| Voltage scan conditions | Yes | The J-V curves were measured under forward scan (-0.1 V to 0.7 V) or reverse scan (0.7 V to -0.1 V) by a fixed step voltage of 10 mV and delay time of 50 ms. (Characterization) | No |
| Test environment | Yes | Photovoltaic properties were measured in air at room temperature near 25 celsius degree with encapsulation. (Characterization) | No |
| Protocol for preconditioning of the device before its characterization | Yes | No preconditioning was used | No |
| Stability of the J-V characteristic | Yes | The stabilized output and maximum power point tracking were conduced. (Figure 3e, 3f) | No |
| 3. Hysteresis or any other unusual behaviour |   |   |   |
| Description of the unusual behaviour observed during the characterization | Yes | We observed hysteresis that the efficiency measured at backward direction was higher than that at forward direction, which has been studied by many research groups. (Figure 3b) | No |
| Related experimental data | Yes | Figure 3b, Supplementary Table 2 | No |
| 4. Efficiency |   |   |   |
| External quantum efficiency (EQE) or incident photons to current efficiency (IPCE) | Yes | Figure 3c | No |
| A comparison between the integrated response under the standard reference spectrum and the response measure under the simulator | Yes | The integrated Jsc from IPCE is consistent with the Jsc from J-V curve. (Figure 3b, 3c) | No |
| For tandem solar cells, the bias illumination and bias voltage used for each subcell | Yes | No tandem cells were made in this manuscript | No |
| 5. Calibration |   |   |   |
| Light source and reference cell or sensor used for the characterization | Yes | Wacom Denso, WXS-1555-10, 100 mW cm⁻² (Characterization) | No |
Confirmation that the reference cell was calibrated and certified

Yes  No

We used a reference cell, which was calibrated by the Calibration, Standards and Measurement Team at the Research Center for Photovoltaics in AIST, Japan. (Characterization)

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

Yes  No

The spectral mismatch is less than 3%. (Characterization)

6. Mask/aperture

Size of the mask/aperture used during testing

Yes  No

0.08920±0.0006 cm², (Supplementary figure 26)

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

Yes  No

We used the same mask for all the photovoltaic measurements of devices.

7. Performance certification

Identity of the independent certification laboratory that confirmed the photovoltaic performance

Yes  No

Newport Laboratory, USA

A copy of any certificate(s)

Yes  No

Supplementary figure 26,27,28

8. Statistics

Number of solar cells tested

Yes  No

We have tested 16 cells for each composition under 100 mW cm⁻², AM 1.5G illumination under forward bias scan. A statistical box chart was included in figure 3d.

Statistical analysis of the device performance

Yes  No

A statistical box chart was included in figure 3d.

9. Long-term stability analysis

Type of analysis, bias conditions and environmental conditions

Yes  No

We measured the long term stability of devices at the maximum power point under AM 1.5G light soaking with encapsulation. (Figure 3f, characterization)

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