

Supplementary Information

High Efficiency Solution-Processed Thin-Film Cu(In,Ga)(Se,S)₂ Solar Cells

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Figure S1 to S6

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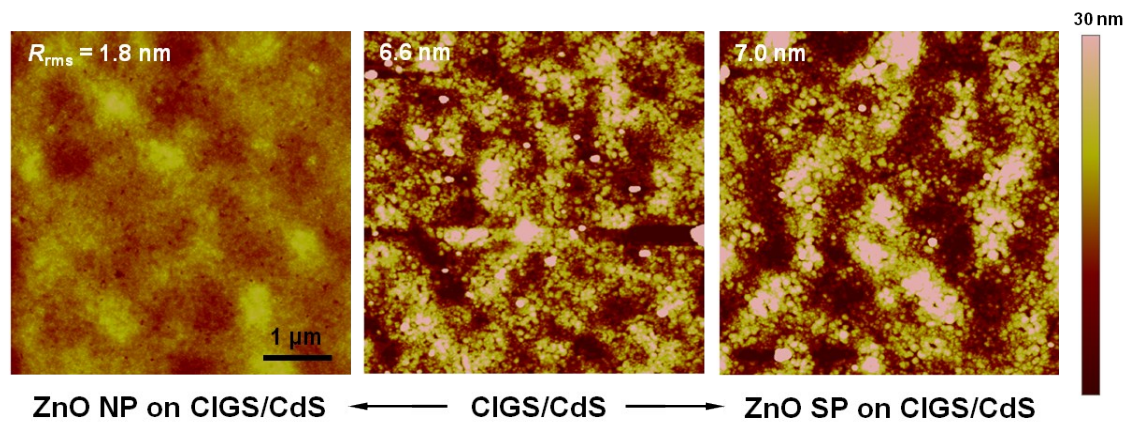


Figure S1. Tapping mode AFM topographic images of glass/CIGS/CdS film (middle) and ZnO NPs (left) or ZnO SP (right) film on top of glass/CIGS/CdS film. The scanning area is $5 \times 5 \mu\text{m}$ and the scale bar is $1 \mu\text{m}$ for all three figures. The R_{rms} value for each image is also indicated.

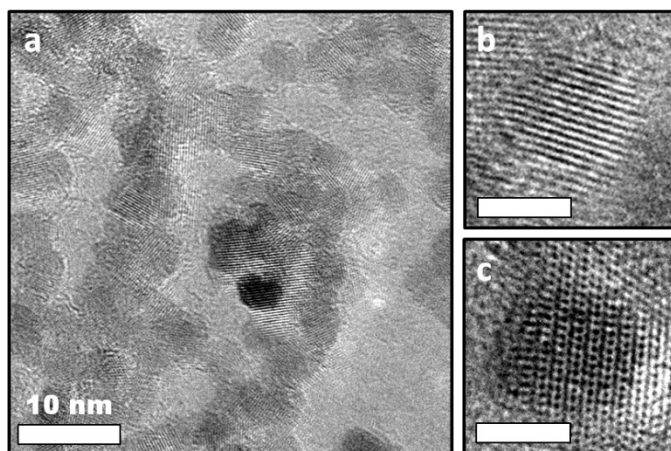


Figure S2. High resolution TEM images of ZnO NPs, indicating high crystallinity of individual nanoparticle. The scale bars of (a) and (b-c) are 10 nm and 3 nm, respectively.

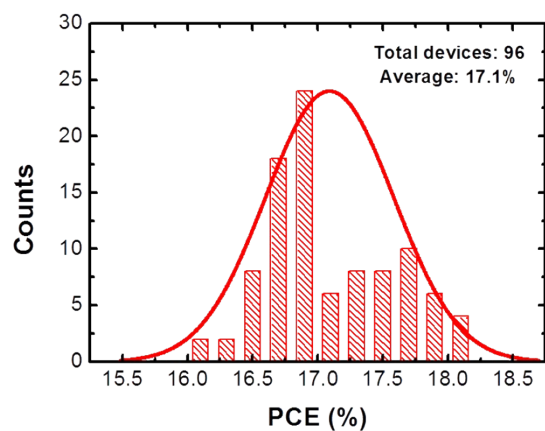


Figure S3. Histogram of power conversion efficiency (PCE) of 96 devices from multiple batches for CIGS solar cells with composition grading CIGS layer and ZnO NPs as window layer. The average PCE is 17.1%.

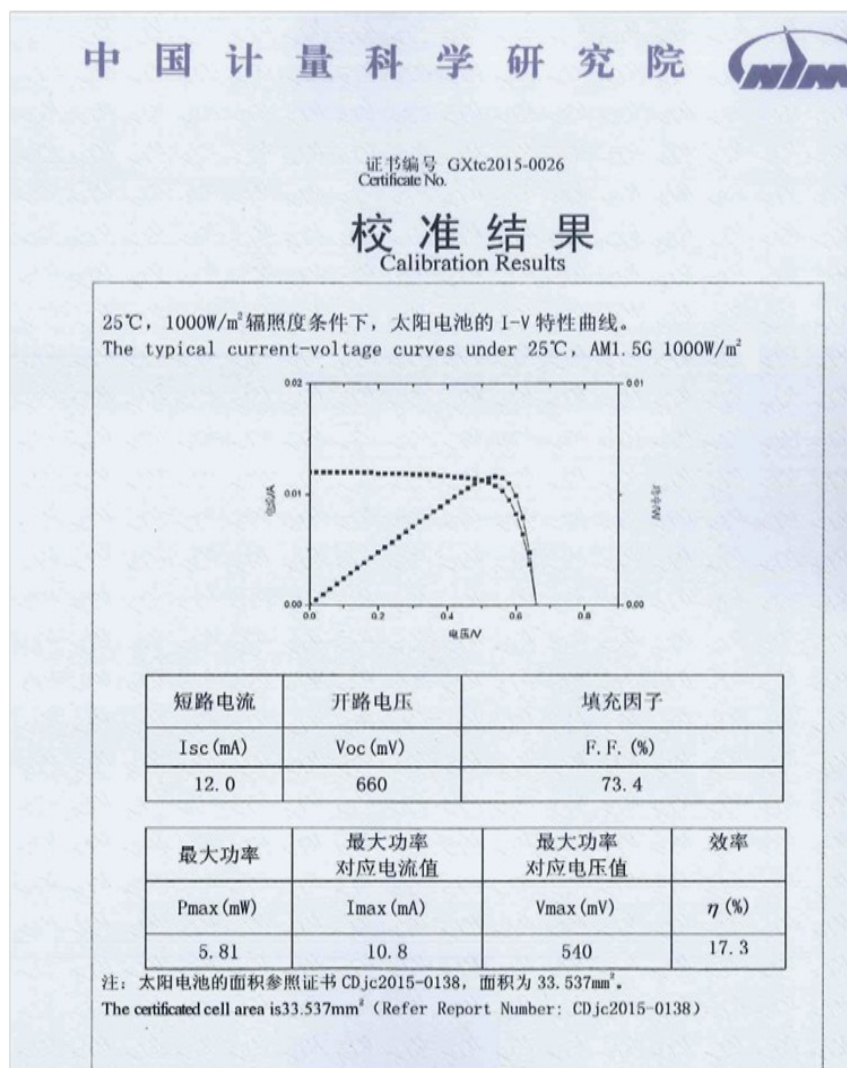


Figure S4. Independent certification from National Institute of Metrology of China (NIM). The J - V characteristics was measured under 1 sun AM 1.5G solar illumination (1000 W/m²) in ambient air and 25 °C. The V_{oc} and FF are measured to be 660 mV and 73.4%, respectively, and the J_{sc} can be calculated to be 35.78 mA/cm² based on I_{sc} (= 12.0 mA) and device area (= 33.537 mm²). The overall PCE of this CIGS solar cell was confirmed to be 17.3%.

ZnO Type	Thickness (nm)	V_{oc} (%)	J_{sc} (mA/cm ²)	FF (%)	η_{PCE} (%)
ZnO SP	10	0.59	30.87	68.1	12.4
	25	0.61	30.38	70.7	13.1
	50	0.61	28.42	72.8	12.6
ZnO NP	10	0.59	32.07	70.24	13.3
	15	0.62	32.67	71.56	14.8
	20	0.63	32.93	72.19	15.2
	25	0.64	33.37	72.52	15.6
	50	0.62	32.98	68.98	14.3

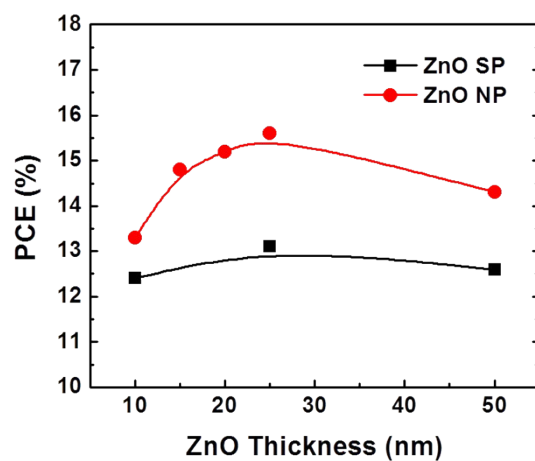


Figure S5. Thickness dependence of ZnO SP (black squares) and ZnO NP (red circles) as window layer on the CIGS device performance.

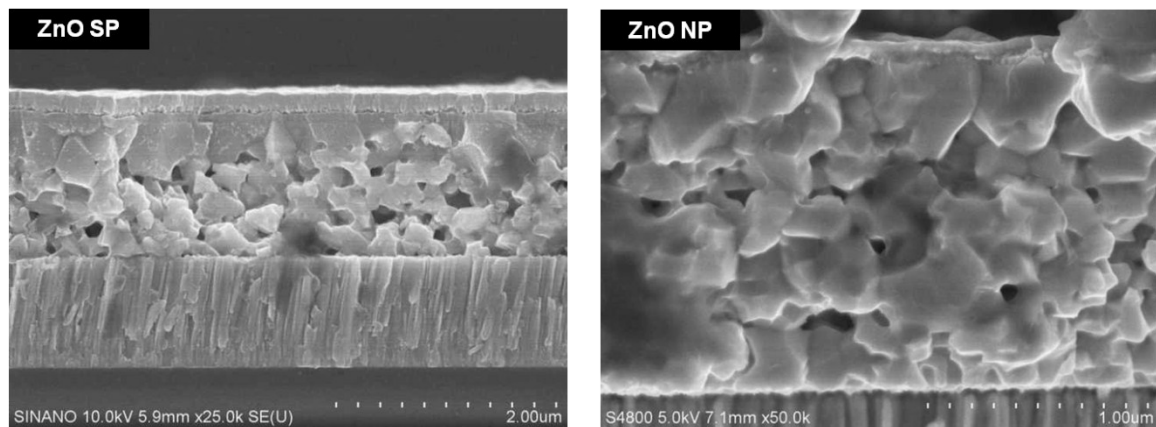


Figure S6. SEM cross-sectional images of ZnO SP (left) and ZnO NP (right) on top of CIGS/CdS layers. The scale bar is 2 μm and 1 μm for ZnO SP and ZnO NP images, respectively.