

Supplementary Information *for*

Completely Annealing-Free Flexible Perovskite Quantum Dot Solar Cells Employing UV-Sintered Ga-Doped SnO₂ Electron Transport Layers

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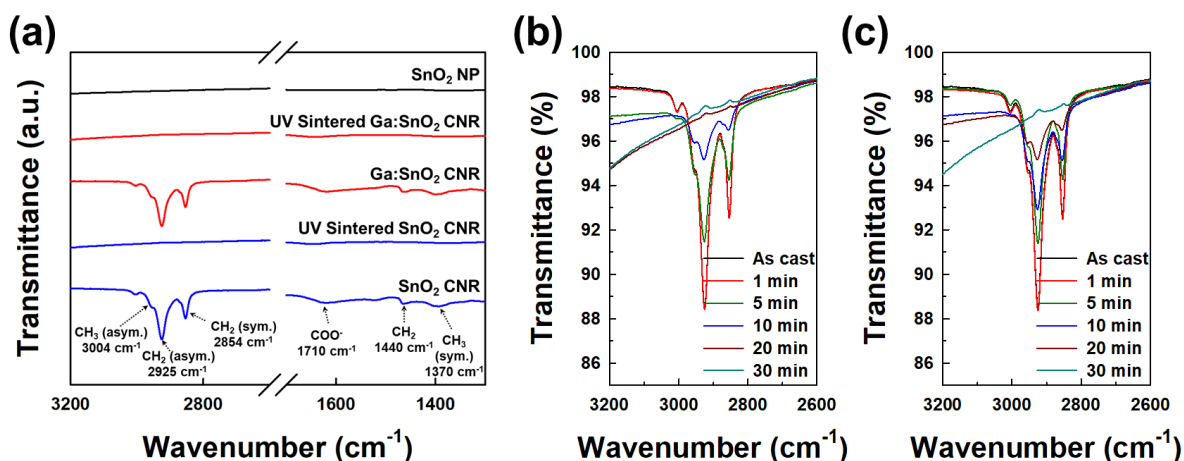
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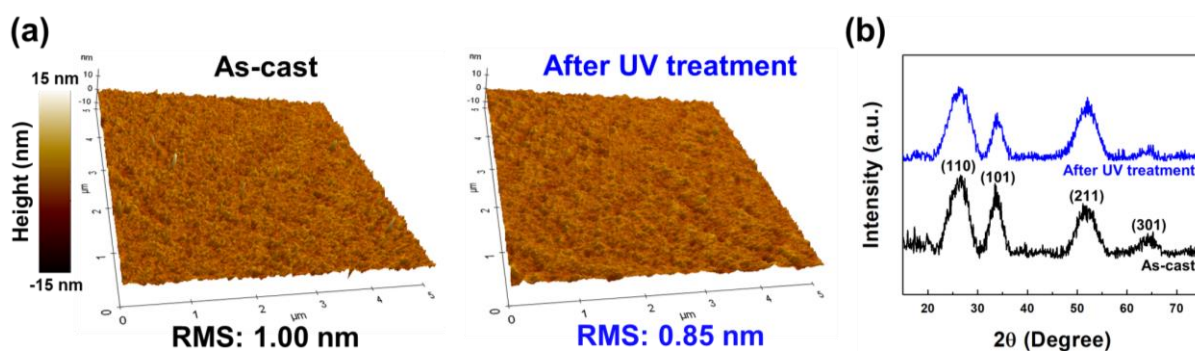
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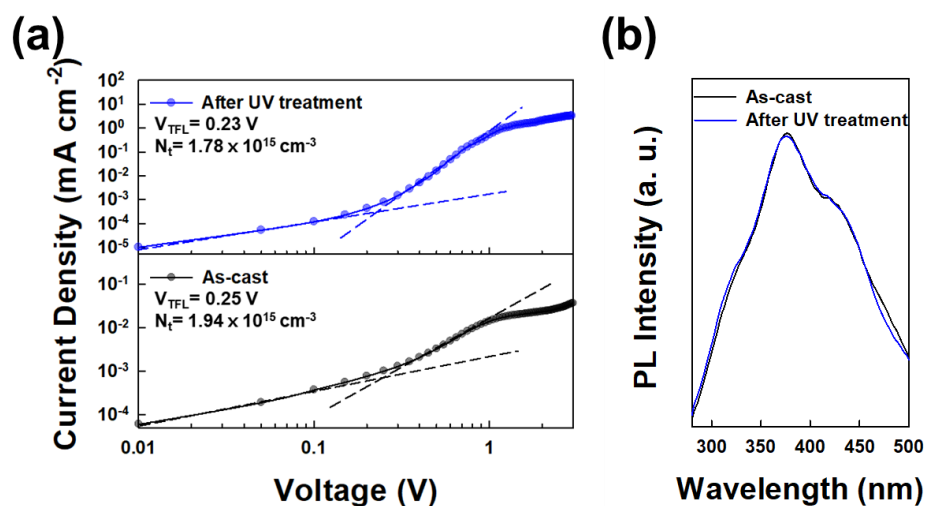
Supplementary Figures and Tables



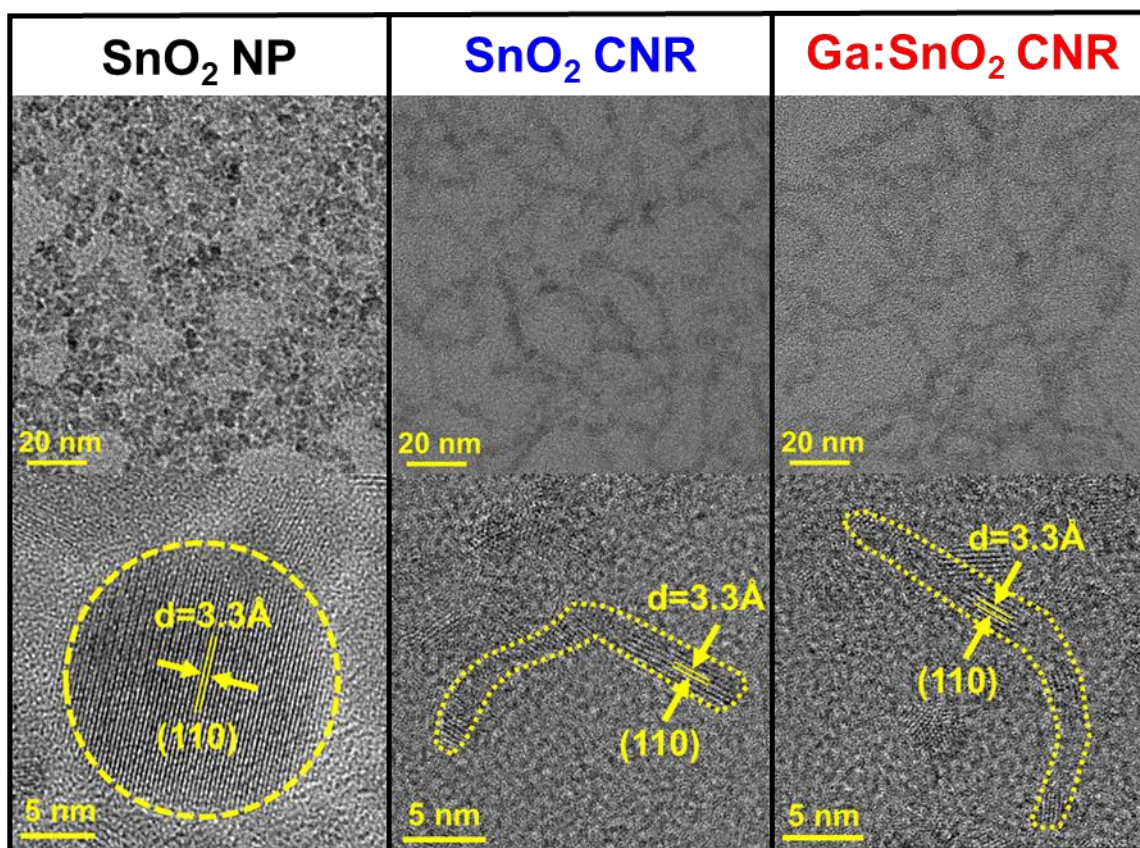
Supplementary Figure 1. (a) Attenuated total reflectance–Fourier transform infrared (ATR–FTIR) spectra of SnO₂ nanoparticles (SnO₂ NP) tin oxide (SnO₂) curved nanorods (SnO₂ CNR) and Ga:SnO₂ CNR films before and after ultraviolet (UV) sintering process. UV-sintered SnO₂ CNR films do not exhibit strong peaks at 2925 and 2854 cm⁻¹, which is attributed to the asymmetric and symmetric CH₂ stretching vibration of the oleic acid (OA) and oleylamine (OAm). ATR-FTIR transmission spectra obtained at (b) 500 W and (c) 250 W power levels under varying UV irradiation times of the SnO₂ CNR film.



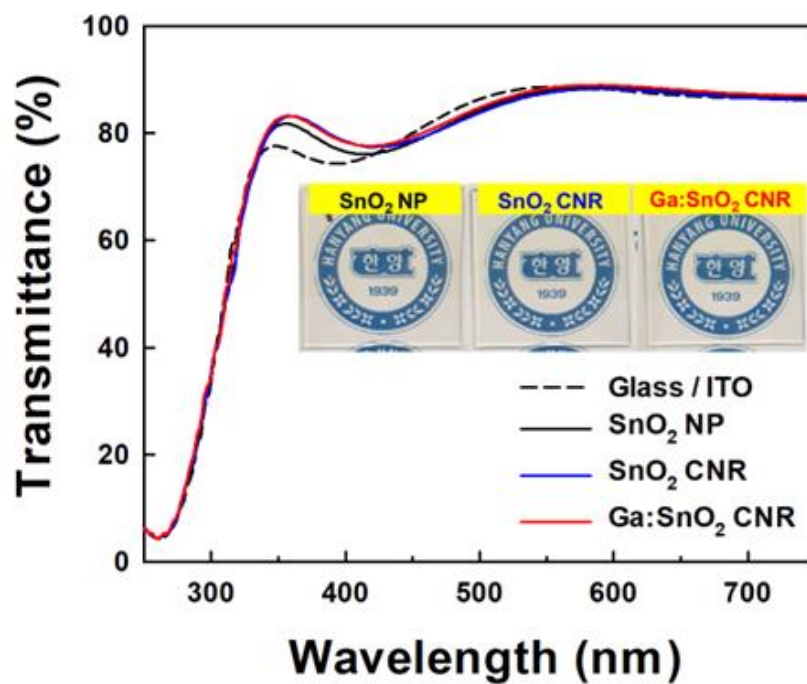
Supplementary Figure 2. (a) Atomic force microscopy topography images illustrating SnO₂ CNR films before and after UV irradiation. (b) XRD comparison between as-cast SnO₂ CNR (black) and SnO₂ CNR after UV irradiation (blue).



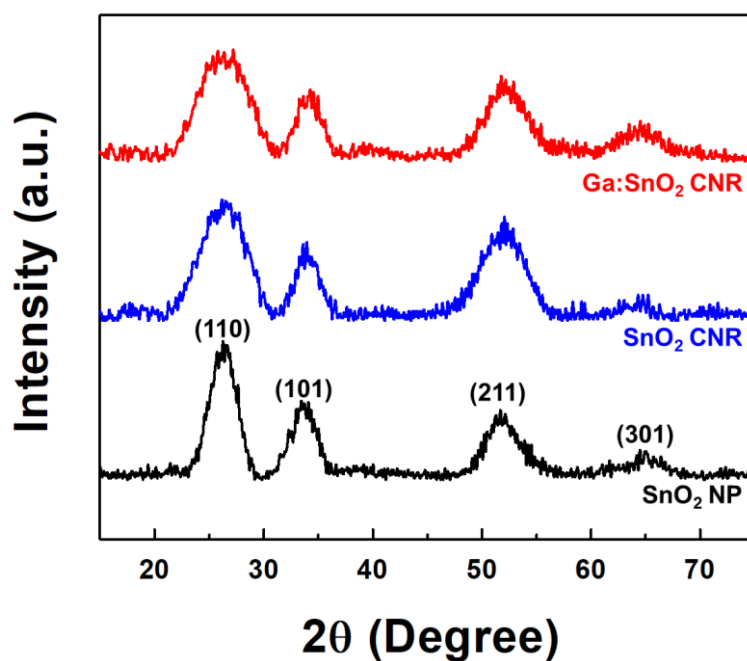
Supplementary Figure 3. (a) SCLC measurements comparison between as-cast SnO_2 CNR (black) and SnO_2 CNR after UV irradiation (blue) with V_{TFL} kink points. (b) PL spectra comparing SnO_2 CNR before and after UV irradiation.



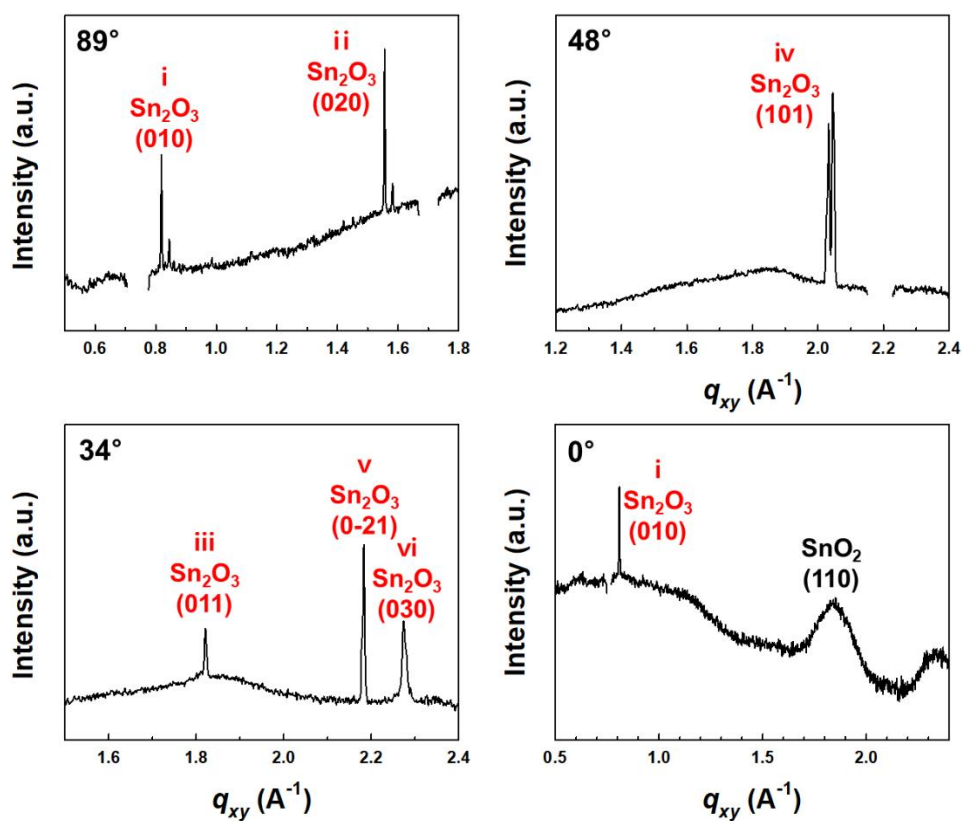
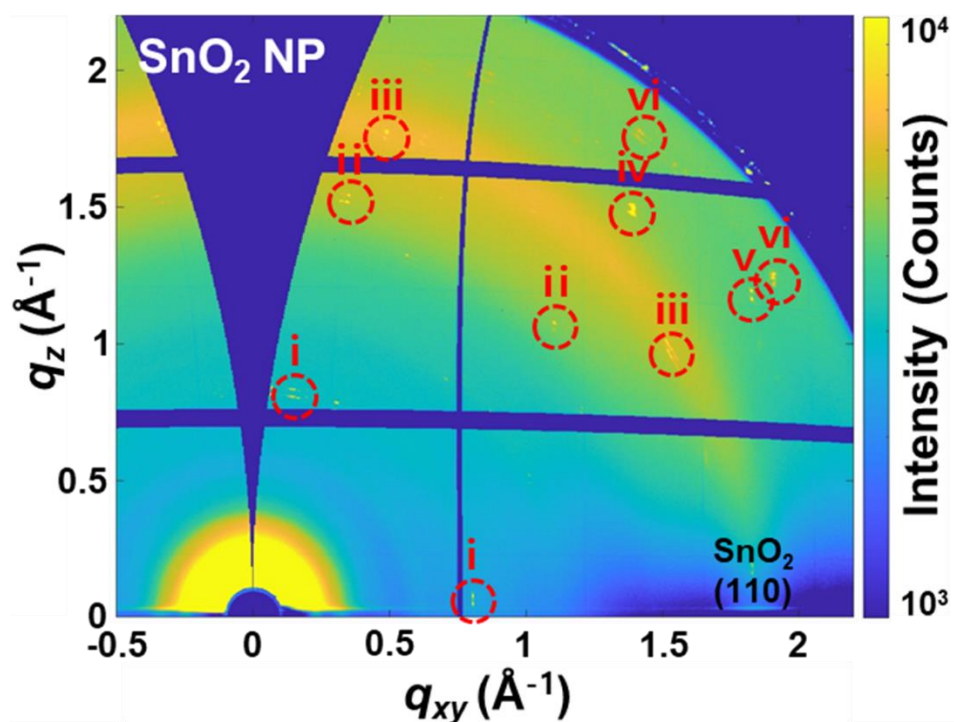
Supplementary Figure 4. High-resolution transmission electron microscopy (HR-TEM) images of SnO_2 nanocrystals.



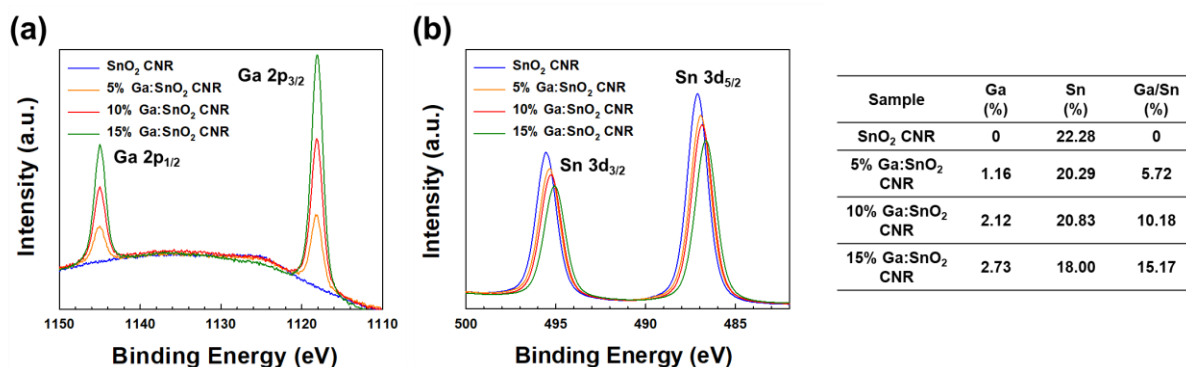
Supplementary Figure 5. Transmittance spectra and photograph images of SnO₂ nanocrystals (SnO₂ NP), SnO₂ CNR, and Ga:SnO₂ CNR films on Glass/ITO.



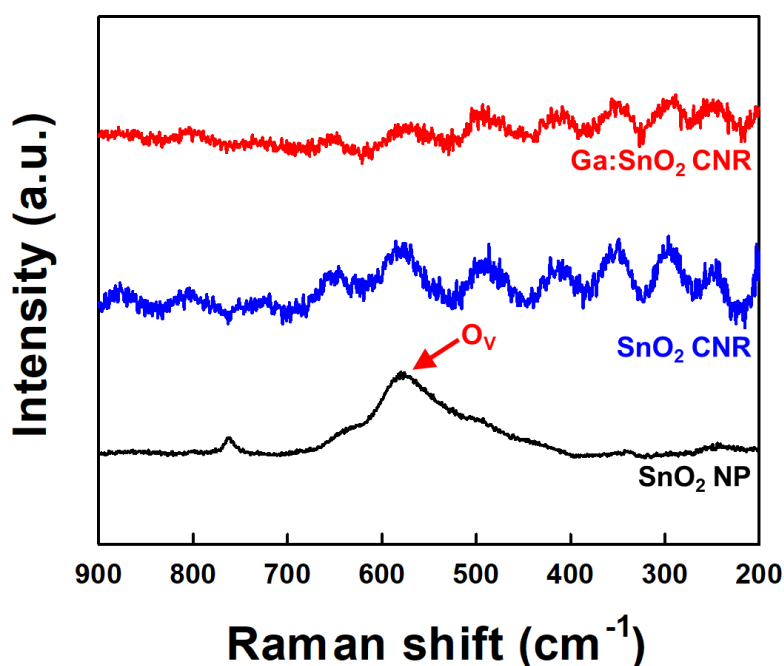
Supplementary Figure 6. XRD comparison for various SnO₂ thin films; SnO₂ NP (black), SnO₂ CNR (blue), and SnO₂ CNR (red).



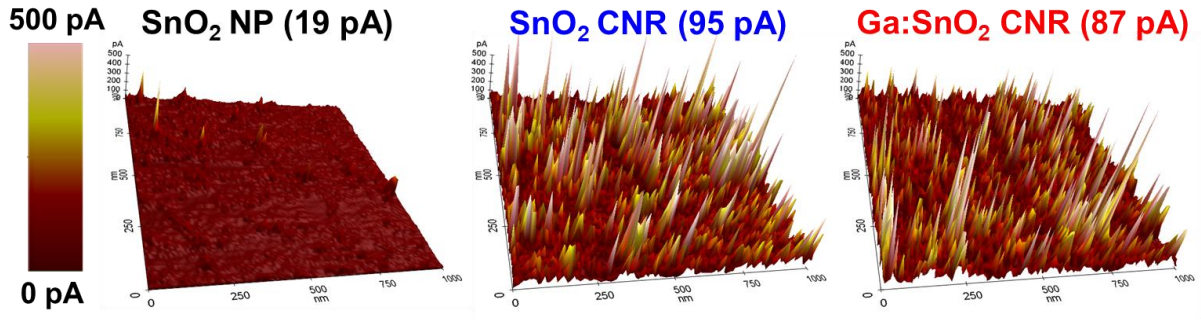
Supplementary Figure 7. Grazing-incidence wide-angle X-ray scattering (GIWAXS) patterns and 1D line profiling of SnO_2 NP film. 1D line profiling was performed at 89° , 48° , 34° , and 0° , respectively.



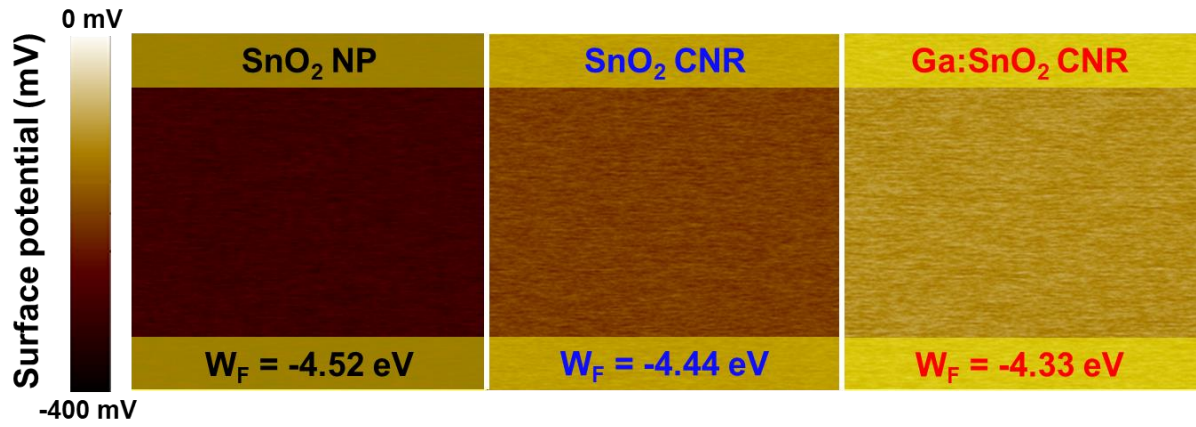
Supplementary Figure 8. Surface components of SnO₂ CNRs by Ga³⁺ doping concentration via X-ray photoelectron spectroscopy (XPS) measurement: (a) Ga 2p and (b) Sn 3d regions. We also tabulated the atomic compositions and atomic ratio (Ga/Sn) from XPS.



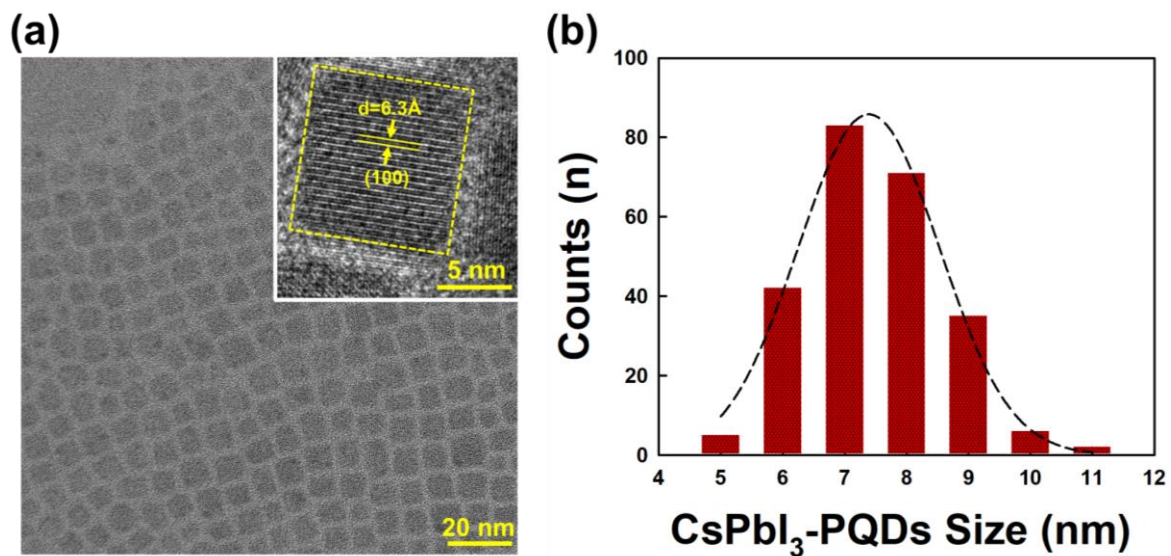
Supplementary Figure 9. Raman spectra for each SnO₂ sample. An oxygen vacancy (O_v) peak appeared at approximately 570 cm⁻¹ for SnO₂ NP, whereas it was difficult to identify a distinct peak for the synthesized SnO₂ CNRs.



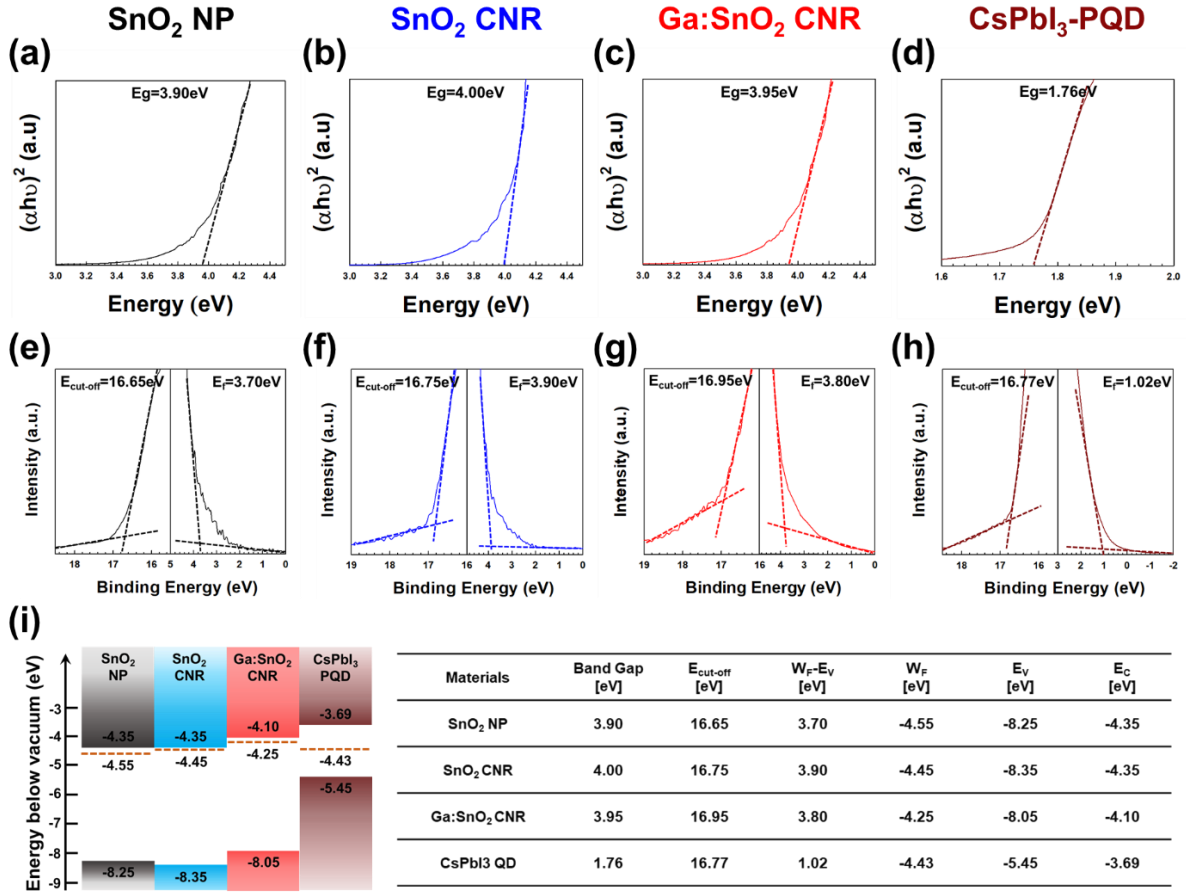
Supplementary Figure 10. Conductive AFM images of each SnO₂ film on ITO with the applied voltage (Positive voltage: 2 V).



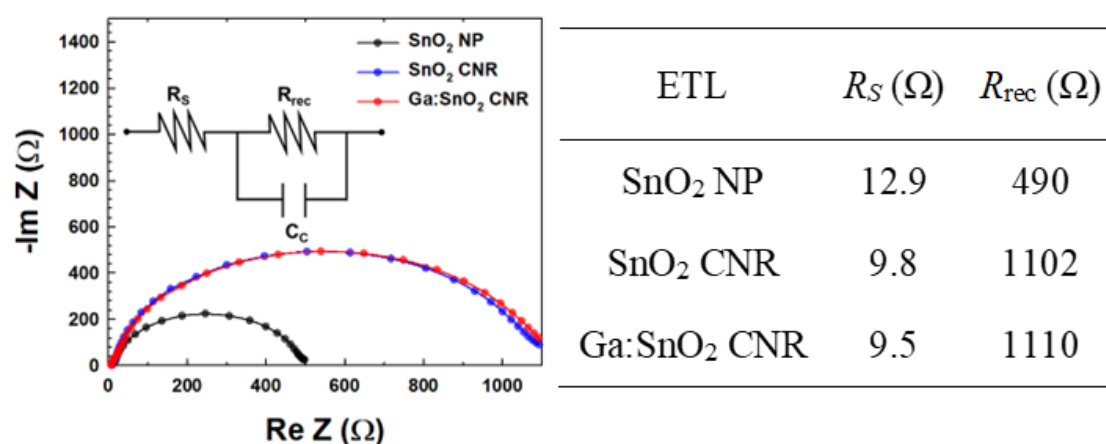
Supplementary Figure 11. Surface potential difference (V_{sp}) of each SnO₂ film were obtained from Kelvin probe force microscopy (KPFM) measurements. The V_{sp} is given as $V_{sp} = -(\Phi_t - \Phi_s)/e$, where Φ_t and Φ_s are work function of the conductive tip and sample, e is the elementary charge. To obtain the work function of each SnO₂ film, we used a highly oriented pyrolytic graphite (HOPG) as a reference. Assuming a HOPG work function of $\Phi_{HOPG} = 4.65$ eV,¹ a work function of SnO₂ films were evaluated by applying the equation: $\Phi_{SnO_2} = V_{sp}(SnO_2) - V_{sp}(HOPG) + \Phi_{HOPG}$. The size of the images is $5 \times 5 \mu m^2$.



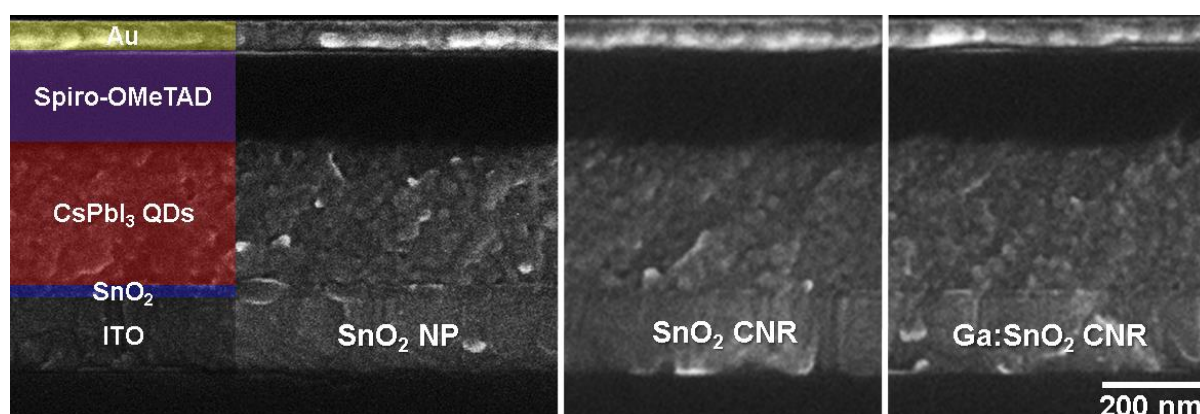
Supplementary Figure 12. (a) HR-TEM image of CsPbI₃-perovskite quantum dots (PQDs) used as the light absorption layer of the solar cells. (b) Histogram illustrating the size distribution of the synthesized CsPbI₃-PQDs, with an average particle size of 7.5 nm.



Supplementary Figure 13. Tauc plots and optical bandgap energies of SnO₂ NP, SnO₂ CNR, Ga:SnO₂ CNR, and CsPbI₃-PQD films (a-d) and linear extrapolations of ultraviolet photoelectron spectroscopy (UPS) spectra for each sample (e-h). (i) Energy level diagrams of each SnO₂ and CsPbI₃-PQD. It was calculated and tabulated as a result of the Tauc plot and UPS spectrum. (W_F : Fermi level, E_V : valence band edge, E_C : conduction band edge)

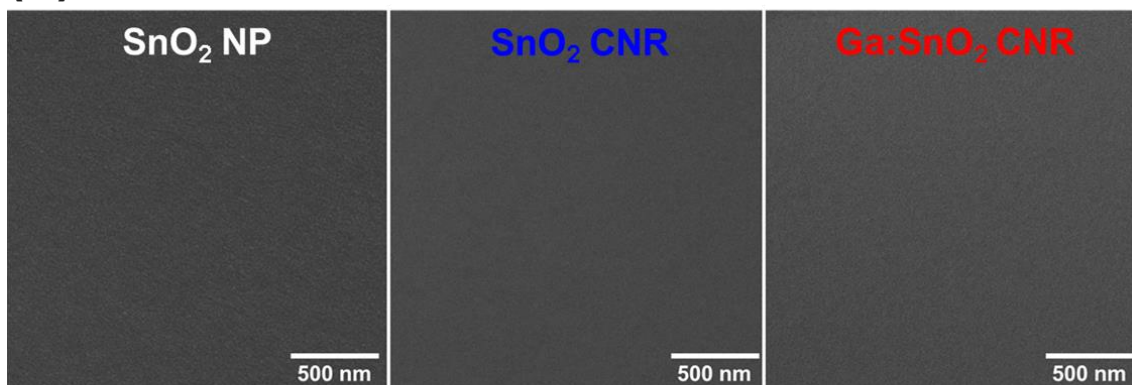


Supplementary Figure 14. EIS curves of each SnO₂-based device. The parameters extracted from the equivalent circuit were tabulated.

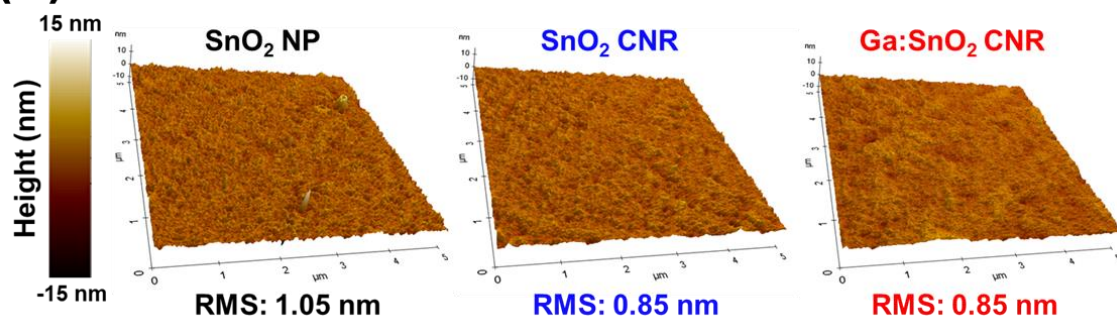


Supplementary Figure 15. Cross-sectional scanning electron microscopy (SEM) image of various SnO₂ electron transport layer (ETL)-based CsPbI₃-PQD solar cells.

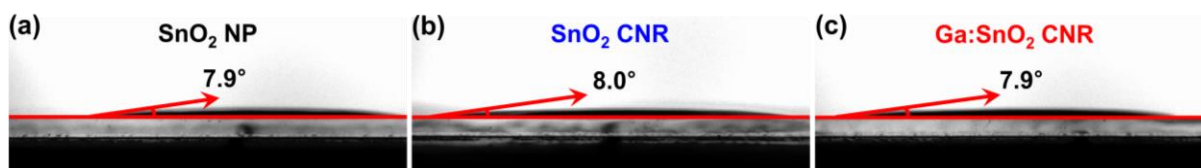
(a)



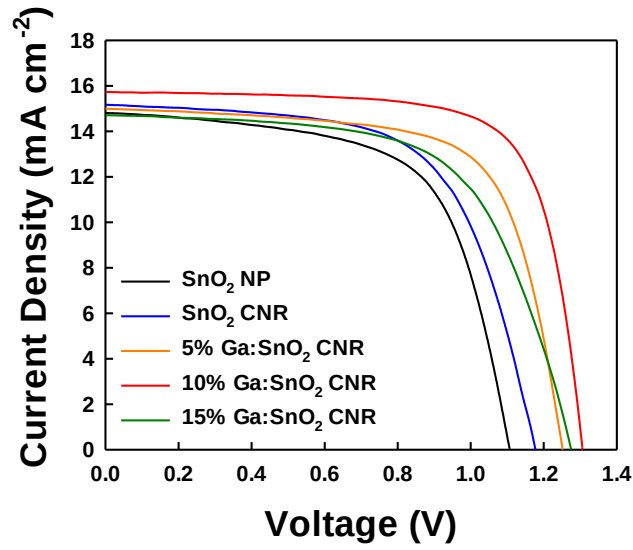
(b)



Supplementary Figure 16. (a) Planar-view SEM image and (b) Atomic force microscopy topography image of each SnO₂ ETL coated on a glass/ITO substrate.

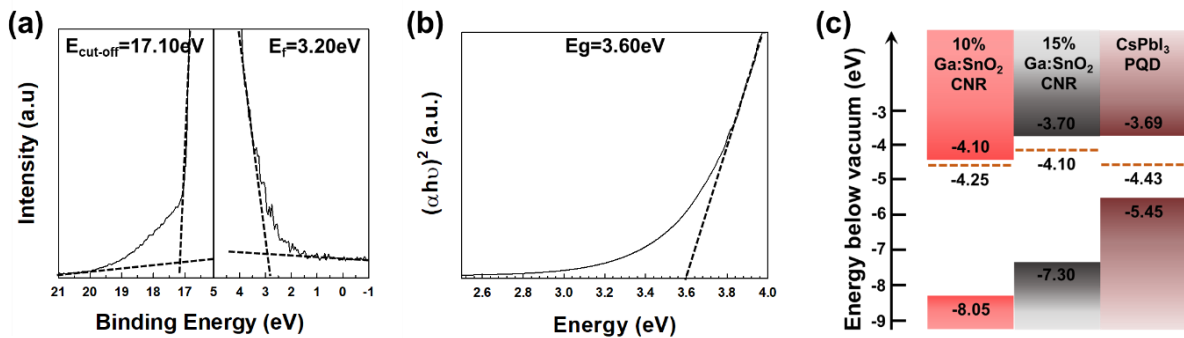


Supplementary Figure 17. Contact angles of the (a) SnO₂ NP, (b) SnO₂ CNR, and (c) Ga:SnO₂ CNR films.

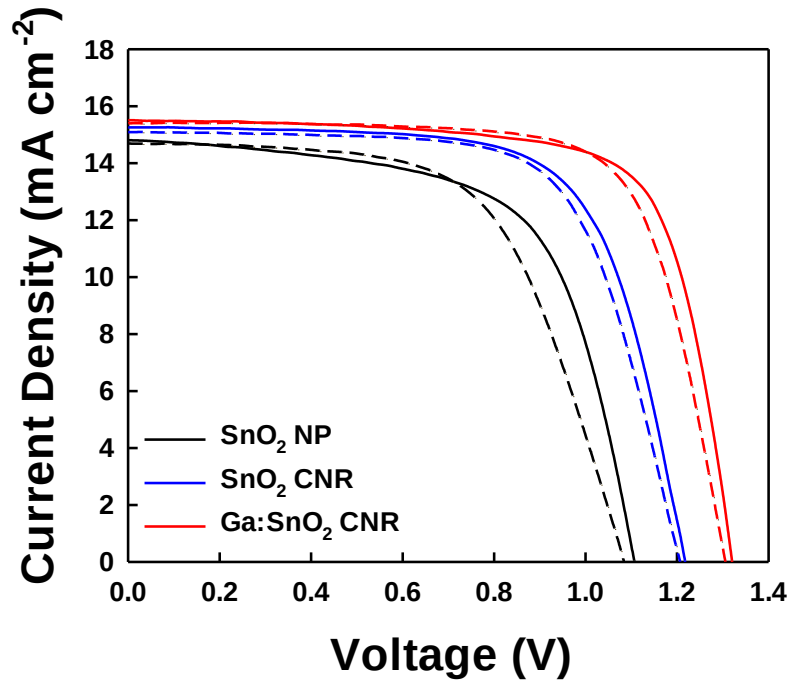


ETL	V _{oc} (V)	J _{sc} (mA cm ⁻²)	FF (%)	PCE (%)
SnO ₂ NP	1.107	14.82	63.33	10.39
SnO ₂ CNR	1.160	15.08	63.87	11.18
5% Ga:SnO ₂ CNR	1.251	14.99	68.65	12.88
10% Ga:SnO ₂ CNR	1.305	15.73	73.32	15.06
15% Ga:SnO ₂ CNR	1.272	14.72	62.41	11.68

Supplementary Figure 18. J - V curves and photovoltaic parameters of best-performing CsPbI₃-PQD solar cells with various SnO₂ ETLs under 1 sun conditions.



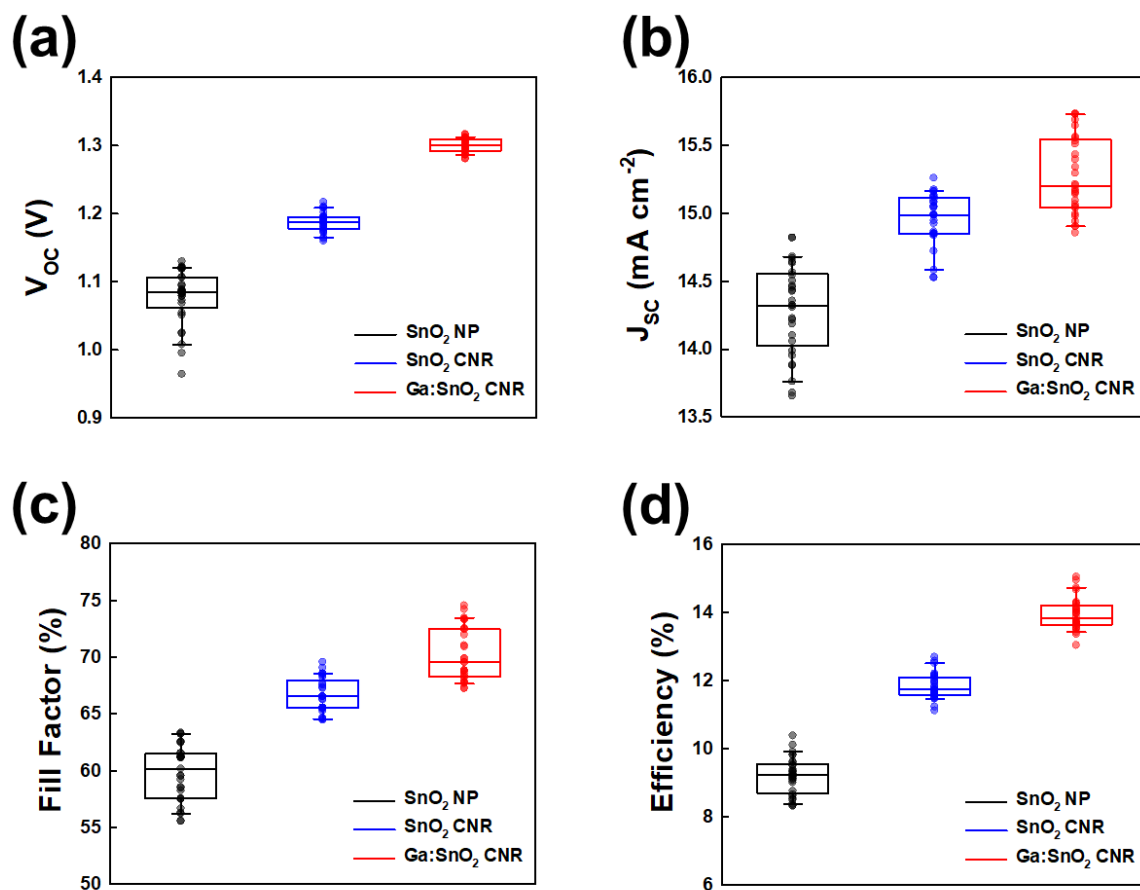
Supplementary Figure 19. (a) Linear extrapolations of UPS spectra for 15% Ga:SnO₂ CNR. (b) Tauc plots and optical bandgap energy of 15% Ga:SnO₂ CNR. (c) Energy level diagrams of 10% Ga:SnO₂ CNR, 15% Ga:SnO₂ CNR and CsPbI₃-PQD.



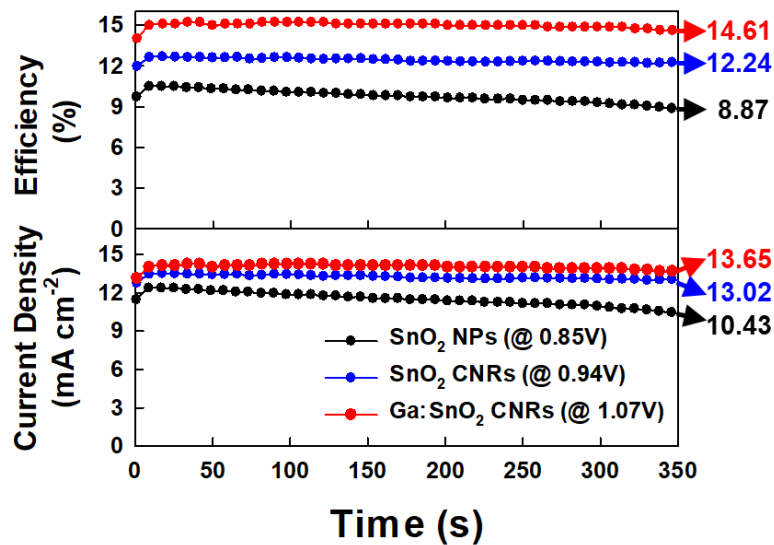
ETL	Scan	V _{oc} (V)	J _{sc} (mA cm ⁻²)	FF (%)	PCE (%)	HI* (%)
SnO ₂ NP	Reverse	1.107	14.82	63.33	10.39	6.45
SnO ₂ NP	Forward	1.083	14.67	61.13	9.72	
SnO ₂ CNR	Reverse	1.217	15.26	68.39	12.70	2.44
SnO ₂ CNR	Forward	1.208	15.10	67.97	12.39	
Ga: SnO ₂ CNR	Reverse	1.320	15.51	72.83	14.91	2.21
Ga: SnO ₂ CNR	Forward	1.306	15.41	72.44	14.58	

*HI (Hysteresis index) = (PCE_{Reverse} - PCE_{Forward}) / PCE_{Reverse} × 100%

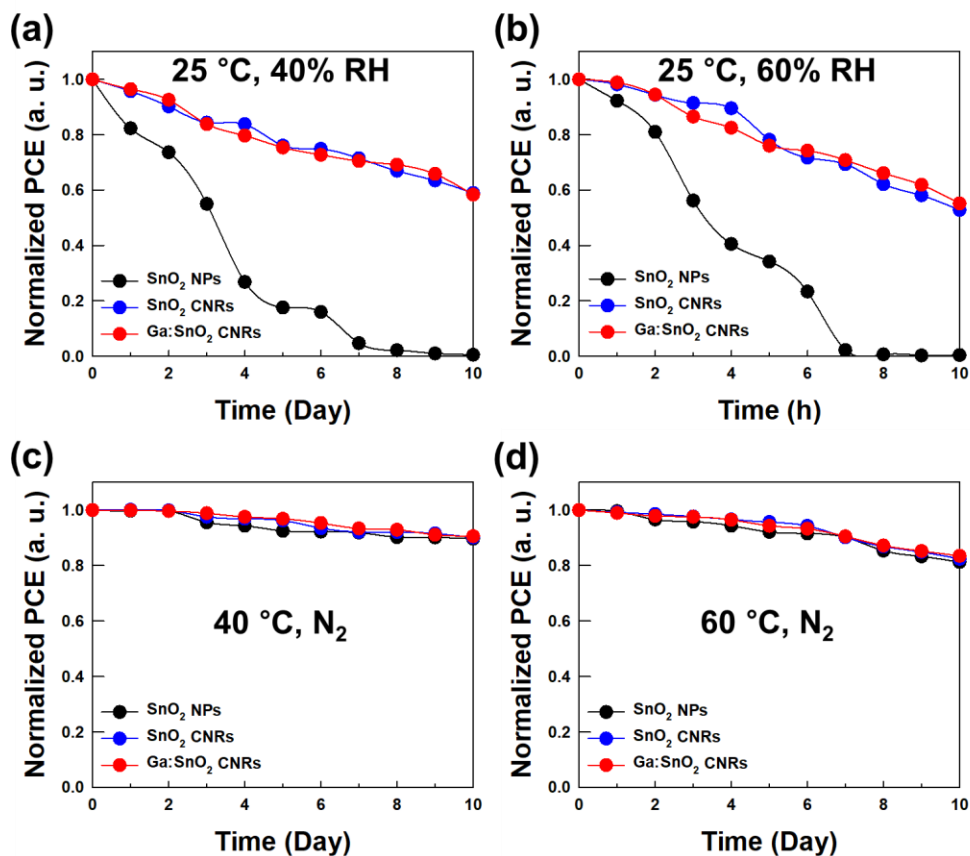
Supplementary Figure 20. Device hysteresis curves and summarized photovoltaic parameters of each SnO₂ ETL-based CsPbI₃-PQD solar cells obtained from J - V measurements with forward and reverse scan.



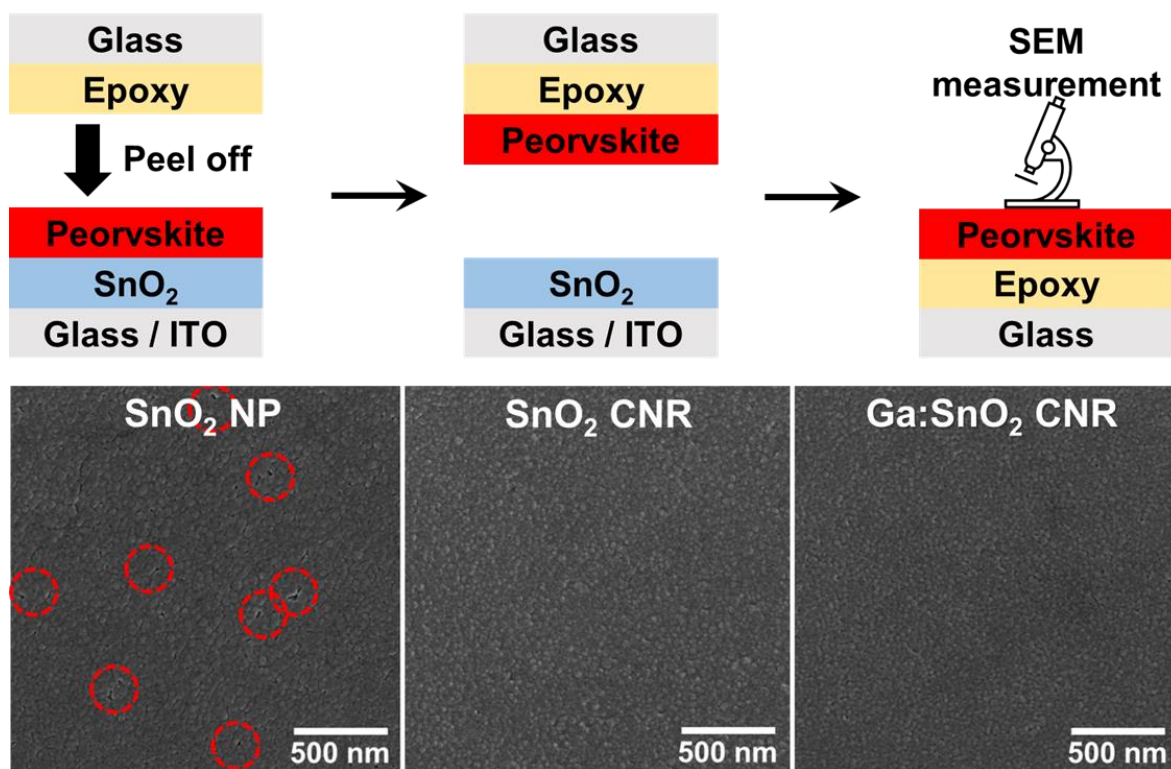
Supplementary Figure 21. Statistical box for the performance of each SnO₂ ETL-based CsPbI₃-PQD solar cell (30 devices). (a) V_{OC} , (b) J_{SC} , (c) FF , and (d) PCE . Photovoltaic parameters were obtained from reverse J - V scans.



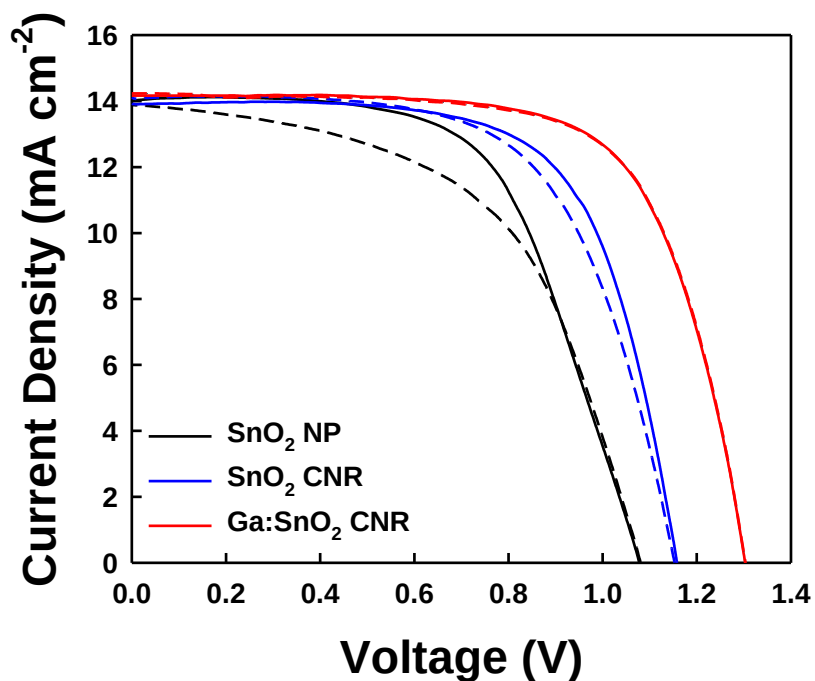
Supplementary Figure 22. Static *PCE* and current density measured as a function of time for each SnO₂-based device biased at voltage of each maximum power point.



Supplementary Figure 23. Normalized *PCE* obtained from stability tests at various conditions for each SnO₂-based device: (a) 25°C, 40% RH, (b) 25°C, 60% RH, (c) 40°C in a N₂ environment, and (d) 60°C in a N₂ environment.



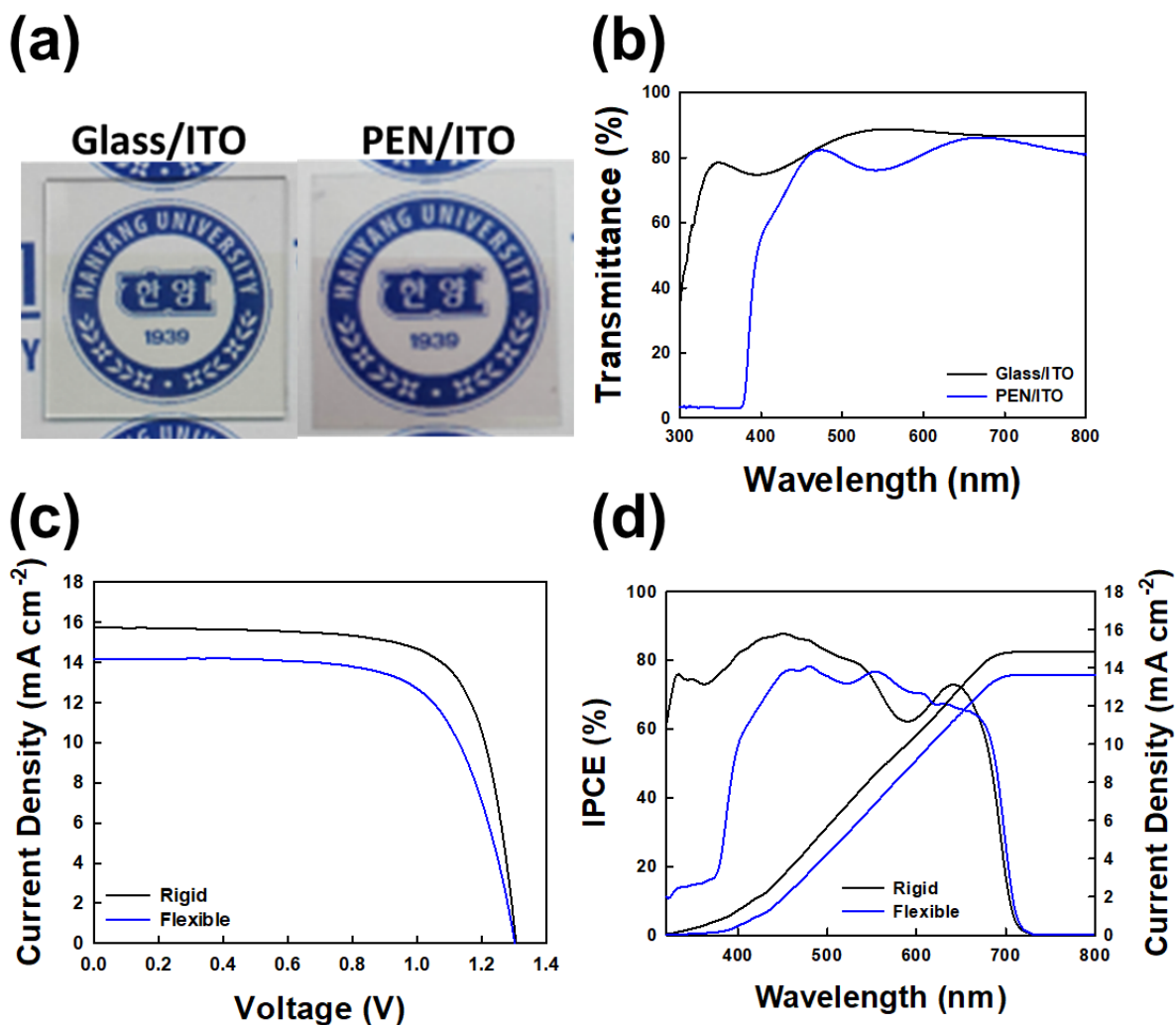
Supplementary Figure 24. Schematic of peel-off sample preparation and planar-view SEM image of peeled-off samples.



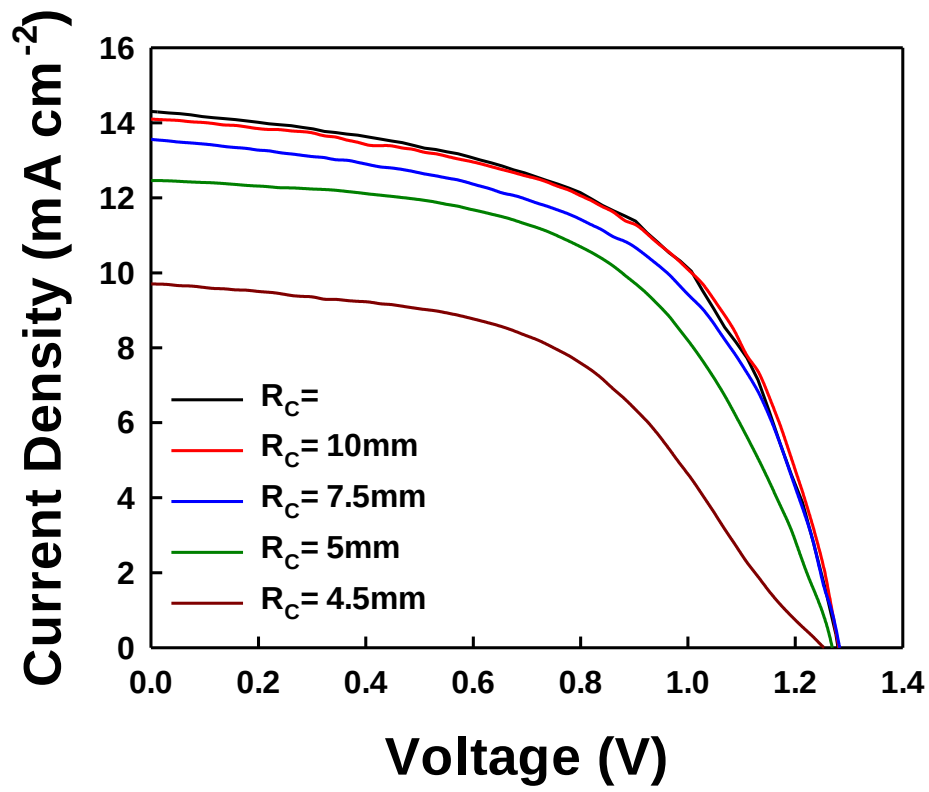
ETL	Scan	V _{oc} (V)	J _{sc} (mA cm ⁻²)	FF (%)	PCE (%)	HI* (%)
SnO ₂ NP	Reverse	1.076	13.93	61.36	9.20	11.41
SnO ₂ NP	Forward	1.079	13.89	54.34	8.15	
SnO ₂ CNR	Reverse	1.157	14.02	66.90	10.85	5.62
SnO ₂ CNR	Forward	1.152	14.12	62.97	10.24	
Ga: SnO ₂ CNR	Reverse	1.302	14.17	68.84	12.70	0.08
Ga: SnO ₂ CNR	Forward	1.303	14.24	68.40	12.69	

*HI (Hysteresis index) = $(PCE_{\text{Reverse}} - PCE_{\text{Forward}}) / PCE_{\text{Reverse}} \times 100\%$

Supplementary Figure 25. Device hysteresis curves and summarized photovoltaic parameters of each SnO₂ ETL-based flexible CsPbI₃-PQD solar cells obtained from $J-V$ measurements with forward and reverse scan.

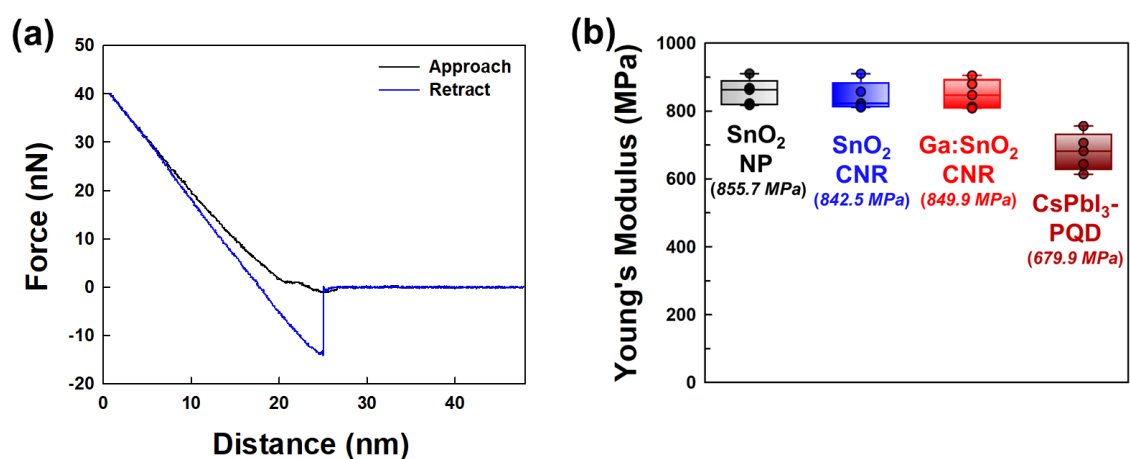


Supplementary Figure 26. (a) Photographic images of rigid Glass/ITO and flexible Polyethylene naphthalate (PEN)/ITO substrates, (b) transmittance spectra of the substrates measured via UV-Vis spectroscopy, and (c) and (d) J - V characteristics and IPCE spectra of Ga:SnO₂ ETL-based CsPbI₃-PQD solar cells using rigid/flexible substrates.

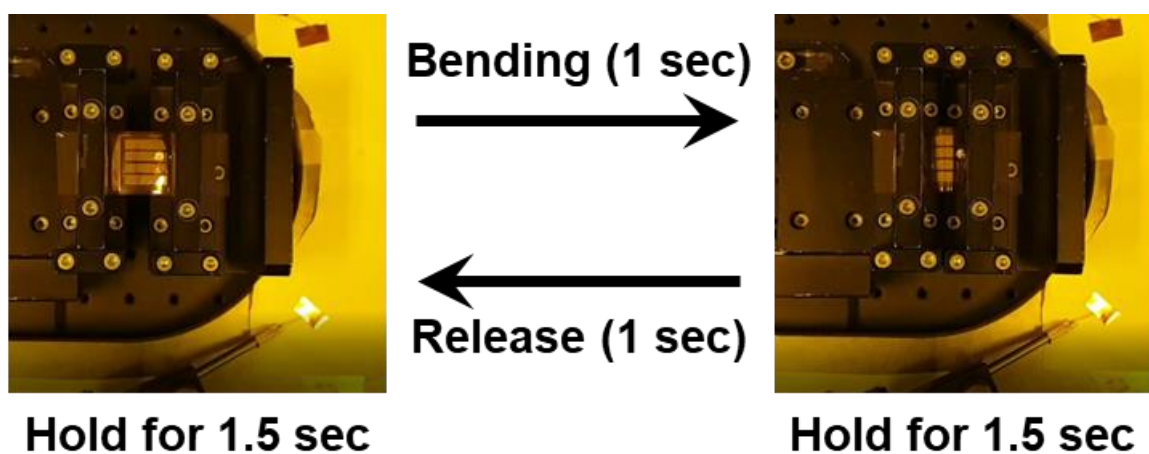


R_C (mm)	V_{oc} (V)	J_{sc} (mA cm $^{-2}$)	FF (%)	PCE (%)
∞	1.283	14.31	55.91	10.27
10	1.282	14.13	56.37	10.21
7.5	1.279	13.56	55.59	9.64
5	1.266	12.47	55.65	8.78
4.5	1.254	9.72	49.84	6.07

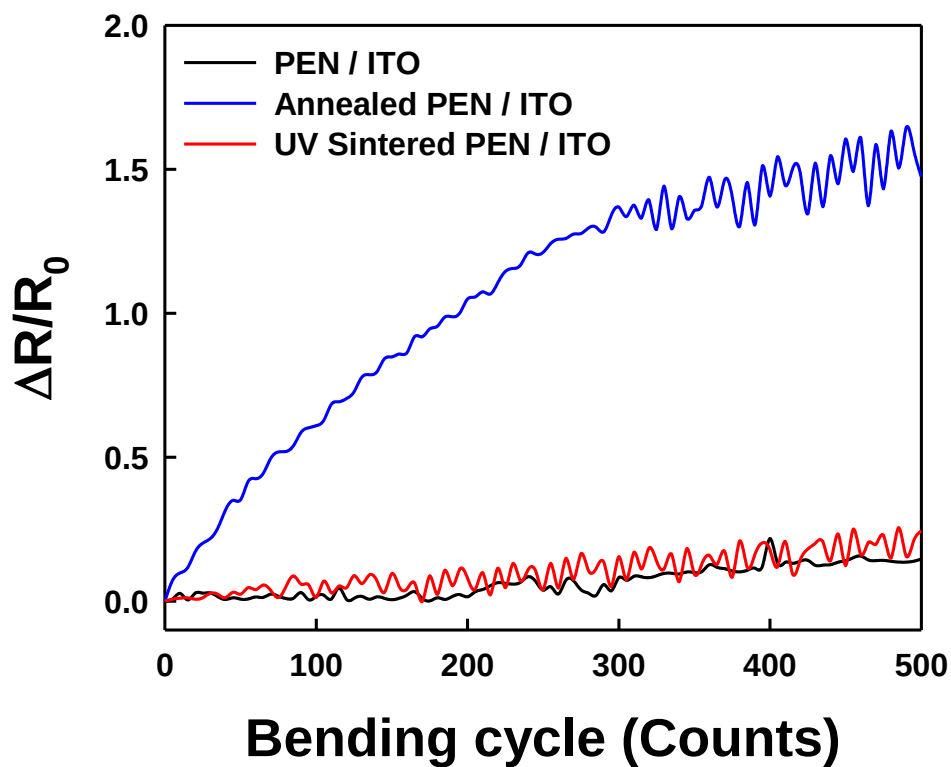
Supplementary Figure 27. $J-V$ curves and photovoltaic parameters of Ga:SnO₂ CNR ETL-based flexible CsPbI₃-PQD solar cells after different radius of curvature (R_C) conditions.



Supplementary Figure 28. (a) Typical force curves obtained for AFM. Utilizing a Derjaguin–Müller–Toporov (DMT) model for fitting these force curves enables the calculation of Young's modulus values. (b) Young's modulus values of SnO₂ NP, SnO₂ CNR, Ga: SnO₂ CNR, and CsPbI₃-PQD films were calculated from five individual regions. The average values of Young's modulus are also presented.

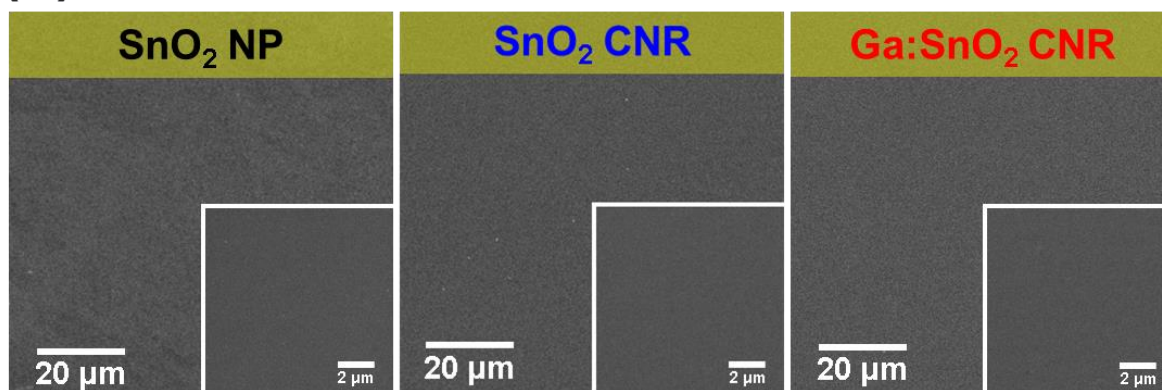


Supplementary Figure 29. Photographs and setting conditions of a cyclic bending robot tester that evaluates the mechanical stability of flexible devices. To measure the *in-situ* relative resistance change ($\Delta R/R_0$) during bending tests, the gold electrodes of the devices and copper wires were soldered with indium.

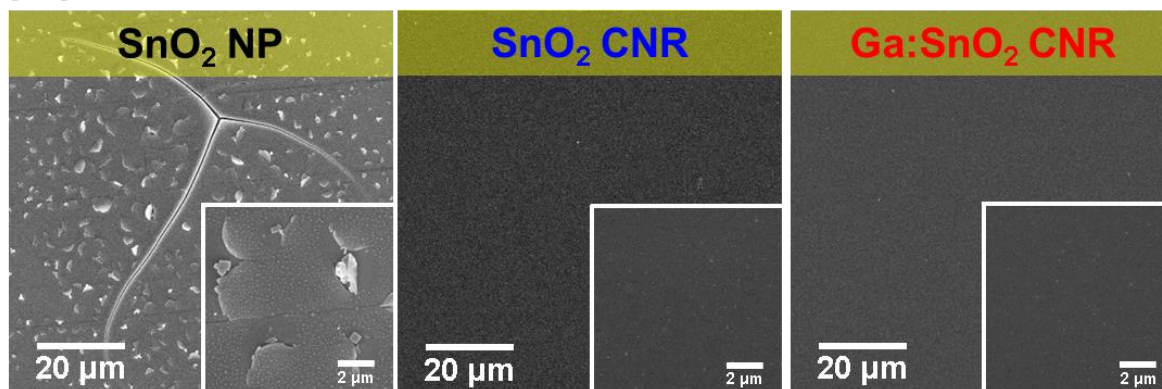


Supplementary Figure 30. *In-situ* relative resistance change ($\Delta R/R_0$) during bending test with a R_C of 7.5 mm for PEN/ITO after each process. The PEN/ITO films were analyzed after annealing at 150°C for 30 min, after UV-sintering process, respectively.

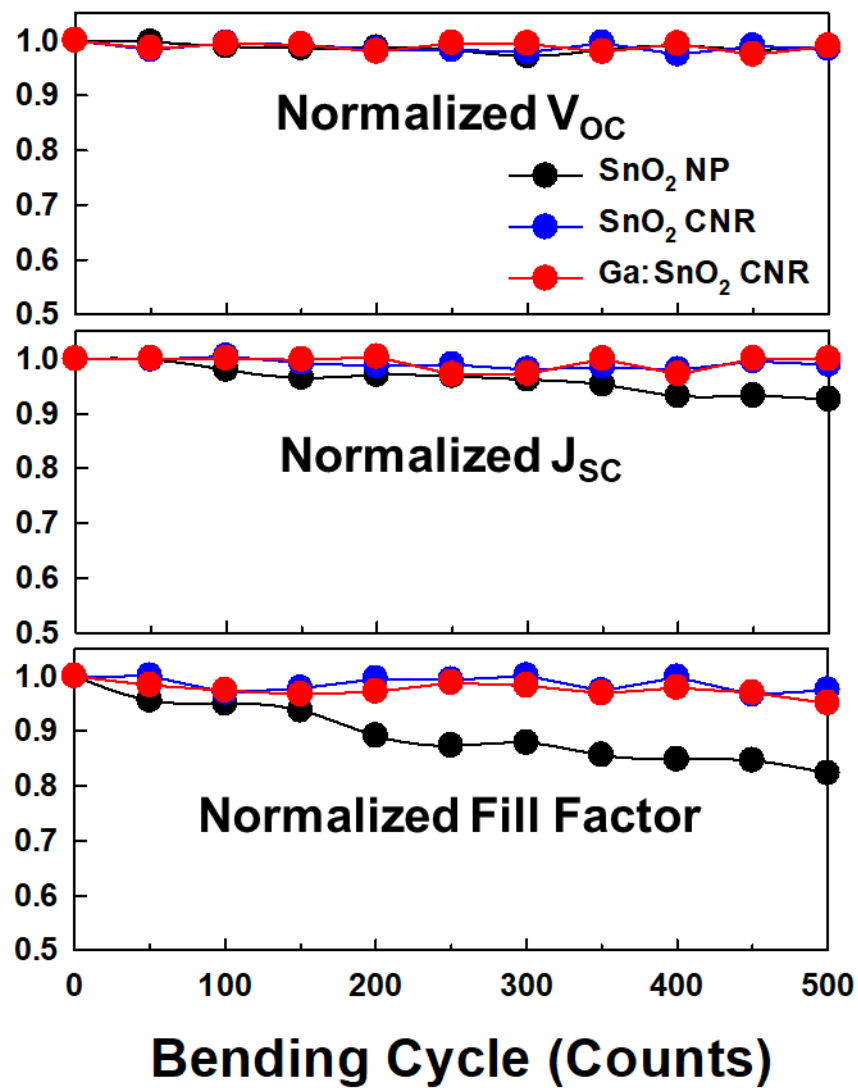
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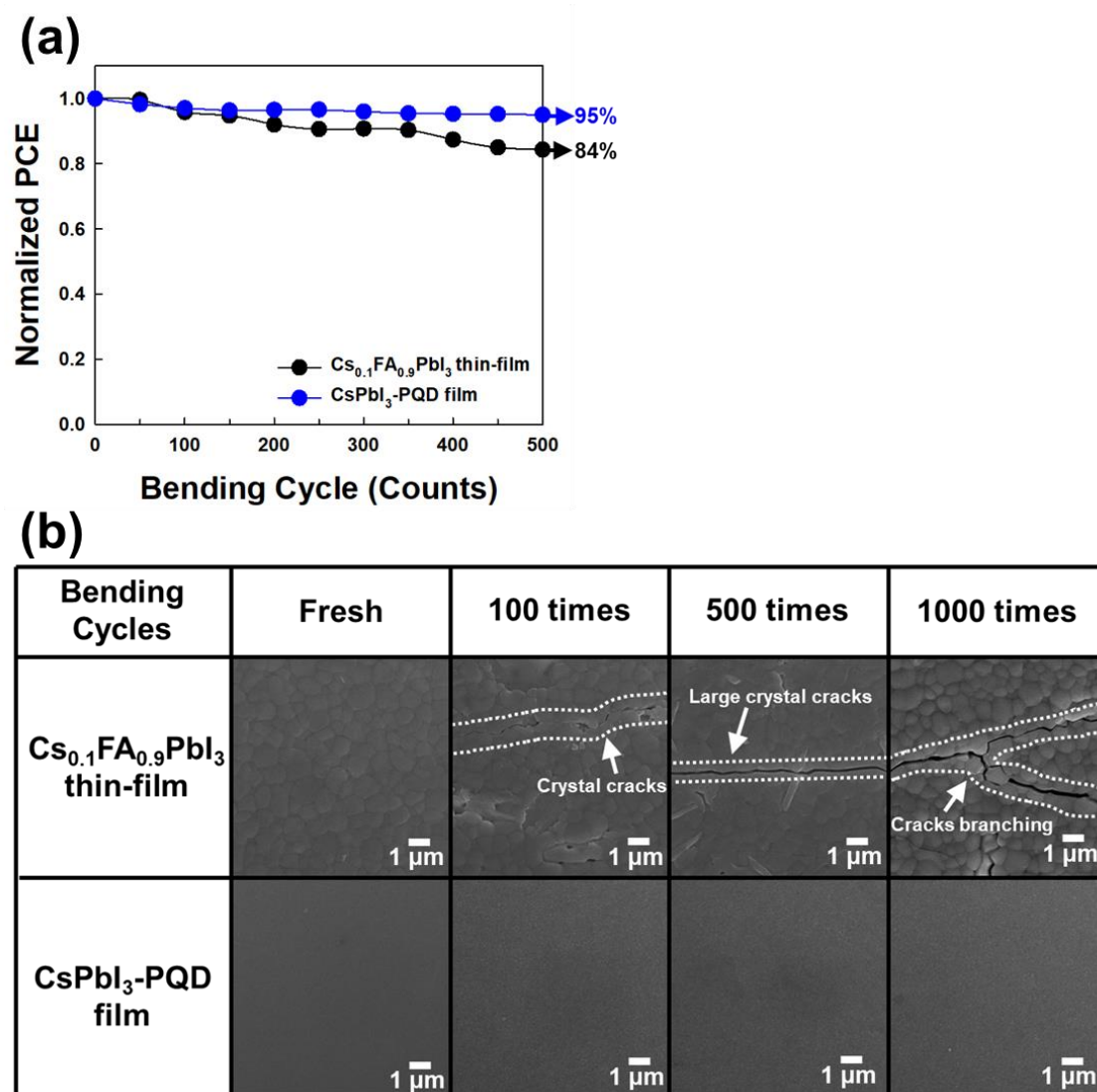
(b)



Supplementary Figure 31. Planar-view SEM images of each SnO₂ deposited on PEN/ITO substrate: (a) before bending test and (b) after 500 bending tests.



Supplementary Figure 32. Normalized photovoltaic parameters (V_{OC} , J_{SC} , Fill Factor) during bending tests of various SnO₂-based flexible CsPbI₃-PQD solar cells.



Supplementary Figure 33. (a) Normalized PCE of CsPbI_3 -PQD solar cell and perovskite thin-film solar cell as a function of bending cycles. (b) Planar-view SEM images of the CsPbI_3 -PQD film and mixed perovskite thin-film fabricated on PEN/ITO with mechanical bending.

Supplementary Table 1. Time constants calculated from time resolved photoluminescence (TRPL) spectra. Lifetime decay components were fitted using a bi-exponential decay model (Fit function = $A_1 e^{-t/\tau_1} + A_2 e^{-t/\tau_2}$).

Sample	τ_1 (ns)	A_1 (%)	τ_2 (ns)	A_2 (%)	τ_{ave} (ns)
CsPbI ₃ -PQD only	10.11	9.29	85.17	90.71	84.27
SnO ₂ NP / PQD	2.77	55.96	10.82	44.04	8.84
SnO ₂ CNR / PQD	2.32	72.36	7.68	27.64	5.31
Ga:SnO ₂ CNR / PQD	2.26	78.61	7.38	21.39	4.67

$$\tau_{\text{ave}} = \sum [(A_1 \tau_1^2 + A_2 \tau_2^2) / (A_1 \tau_1 + A_2 \tau_2)]$$

Device architecture	Flexibility	V _{oc} (V)	J _{sc} (mA cm ⁻²)	FF (%)	PCE (%)	Ref.
ITO/ZnMgO/PbS	Rigid	0.62	24.7	68	10.4	2
QD/PbS-EDT/Au	Flexible	0.62	24.5	62	9.4	
Ag NWs/AZO/PbS	Rigid	0.64	24.4	62	9.7	3
QD/PbS-EDT/Au	Flexible	0.64	24.6	63	9.9	
ITO/SnO ₂ /QD:PCBM/ CsPbI ₃ -PQD/PTB7/ MoO ₃ /Ag	Rigid	1.26	15.2	78	15.1	4
	Flexible	-	-	-	12.3	
ITO/Ga:SnO ₂ / CsPbI ₃ -PQD/ Spiro-OMeTAD/Au	Rigid	1.31	15.7	73.3	15.1	This work
	Flexible	1.30	14.2	68.8	12.7	

Supplementary Table 2. Summary of previously reported flexible quantum dot solar cell architectures and their photovoltaic parameters.

Supplementary References

1. Melitz, W. et al. Scanning tunneling spectroscopy and Kelvin probe force microscopy investigation of Fermi energy level pinning mechanism on InAs and InGaAs clean surfaces. *J. Appl. Phys.* **108**, 023711 (2010).
2. Zhang, X. L. et al. Highly Efficient Flexible Quantum Dot Solar Cells with Improved Electron Extraction Using MgZnO Nanocrystals. *ACS Nano* **11**, 8478-8487 (2017).
3. Zhang, X. L. et al. Extremely lightweight and ultra-flexible infrared light-converting quantum dot solar cells with high power-per-weight output using a solution-processed bending durable silver nanowire-based electrode. *Energy Environ. Sci.* **11**, 354-364 (2018).
4. Hu, L. et al. Flexible and efficient perovskite quantum dot solar cells via hybrid interfacial architecture. *Nature Communications* **12**, 466 (2021).