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Supporting information

Room-temperature synthesized SnO_2 electron transport layers for efficient perovskite solar cells

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Experimental section

Materials

FAI and MABr (Lumtec, Taiwan), PbI_2 (TCI), $PbBr_2$ and Spiro were purchased from Xi'an Polymer Light Technology Corp. $SnCl_4$ was purchased from Aladdin. Except the chemicals mentioned above, all other chemicals used were purchased from Sigma-Aldrich or Alfa Aesar. All the chemicals were used as received.

Synthesis of SnO_2 nanoparticles

The anhydrous $SnCl_4$ solution was diluted to proper concentration (0.05 M) by ice/deionized water. The precursor solution was kept under 25 °C for 0 min, 50 min, 100 min, and 150 min, respectively. After proper hydrolysis time, we used IPA or BA as precipitant. We added IPA into $SnCl_4$ solution by volume ratio of $SnCl_4$ solution:IPA=1:2. As for the BA precipitant, ethanol was added with the volume ratio of 2:1:1 ($SnCl_4$ solution: ethanol: BA). We centrifuged the precipitation and washed only by IPA or BA for 3 times. The SnO_2 solid was then dispersed in absolute ethyl alcohol (25 mg/mL).

Preparation of the perovskite precursor

The perovskite precursor was prepared by dissolving 548.6 mg PbI_2, 77.07 mg $PbBr_2$, 190.06 mg FAI and 21.84 mg MABr solid into 800 µL DMF/DMSO mixed solution (4/1 by volume). Finally, 30 µL CsI and 15 µL KI solution (both pre-dissolved as a 2 M stock solution in DMSO respectively) were added.

Preparation of Spiro-OMeTAD solution

The Spiro-OMeTAD solution was prepared by dissolving 73 mg spiro into 1 mL Chlorobenzene (CBZ) and followed by adding 30 µL 4-tert-butylpyridine (tBP) and 18 µL Li-TFSI (pre-dissolved as a 520 mg/mL solution in acetonitrile) and 29 µL FK209 (pre-dissolved as a 300 mg/mL solution in acetonitrile).

Device fabrication

FTO/glass and ITO/PET substrates were etched by a femtosecond laser machine. Next, the substrates were ultrasonic cleaned in the order of detergent, deionized water and ethanol for 15 min respectively. After ultrasonic cleaning, they were dried by air flow and sliced into 2×1.25 cm^2 followed by the treatment of UVO for 15 min. The SnO_2 ETL was achieved by spin coating the SnO_2 NPs 3 times at 3000 rpm for 30 s. Then they were kept in a dry cupboard at room temperature for several hours to let the solvent volatilize completely. The perovskite film was deposited on SnO_2 substrates (without or with UVO treatment) by spun a 25 μL perovskite precursor at 6000 rpm with 1000 rpm for 30 s and 100 μL ethyl acetate was dropped at the last 5th second. Then perovskite films were then annealed at 120 ℃ for 50 min. After cooling to room temperature, 25 μL spiro solution was spun on the perovskite film by 3000 rpm for 30 s. At last, 60 nm of gold was deposited by vacuum evaporation as the back electrode.

Characterizations

The surface morphologies and microstructures of SnO_2 and perovskite films and the cross-sectional structure of the PSCs were investigated by the scanning electron microscopy (SEM, Hitachi S-4800). The SnO_2 NPs morphologies and lattice fringes were observed by transmission electron microscope (TEM, JEM-2100F). The SnO_2 NPs were dried in air under room temperature to collect SnO_2 powder and characterized by an X-ray diffractometer (XRD, D8 Advance). The UV-Vis transmittance test was characterized by an UV-Vis spectrometer (SolidSpec-3700, SHIMADZU). The photocurrent density-voltage curve of PSCs was measured by a solar simulator (Oriel 94023A, 300W) and a Keithley 2400 source meter. We used a standard Si solar cell (Oriel, VLSI standards) to calibrate the intensity of 100 mW/cm^2. All the PSCs were tested under AM 1.5G sun light (100 mW/cm^2) with a mask of 0.16 cm^2 under 10 mV/s scan rate. PL and TRPL were measured under conditions that laser enters from sodium calcium glass/SnO_2 ETLs/perovskite (FLS 980, EdinburghInstruments). Surface element analysis of SnO_2 film on the sodium calcium glass was conducted by XPS (ESCALAB 250Xi/ESCALAB 250Xi, Thermo Fisher Scientific).

Table S1 Photovoltaic characteristics of the PSCs based on Sn-100 NPs formed ETLs with/without the UVO treatments

	J-V Sweep direction	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	PCE (%)	R_s (Ω cm^2)	R_{sh} (kΩ cm^2)	Hysteresis index
UVO	RS	1.122	21.62	0.72	17.47	5.6	0.67	0.124
0 min	FS	1.118	21.73	0.63	15.31	7.8	16.95	
UVO	RS	1.117	21.95	0.71	17.41	6.3	35.11	0.019
5 min	FS	1.140	22.03	0.68	17.08	7.0	2.35	
UVO	RS	1.117	21.86	0.72	17.58	4.7	1.20	0.021
10 min	FS	1.134	21.99	0.69	17.21	5.1	14.46	
UVO	RS	1.122	21.87	0.72	17.68	4.8	2.06	0.026
15 min	FS	1.133	22.01	0.69	17.21	5.5	2.38	

$$Hysteresis\ index = \frac{PCE(RS) - PCE(FS)}{PCE(RS)}$$

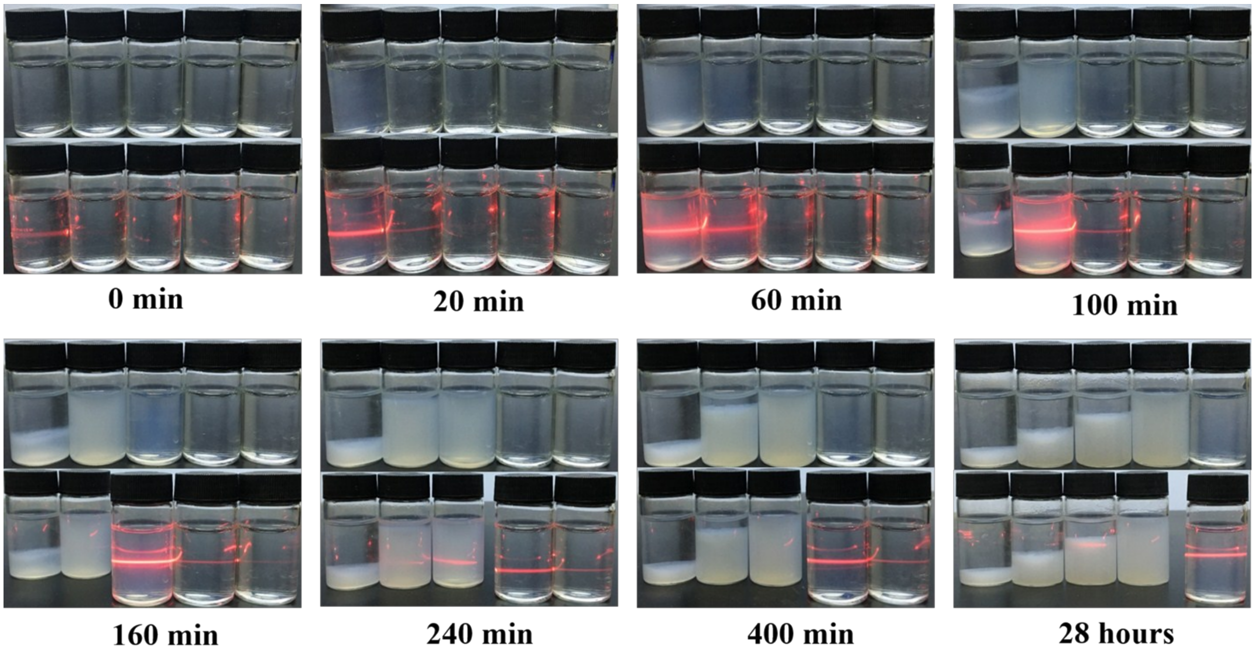

Fig. S1 Photos of $SnCl_4$ aqueous solutions with the concentration of 0.01 M, 0.03 M, 0.05 M, 0.075 M, and 0.1 M from left to right, respectively. All of them were kept at room temperature for different times.

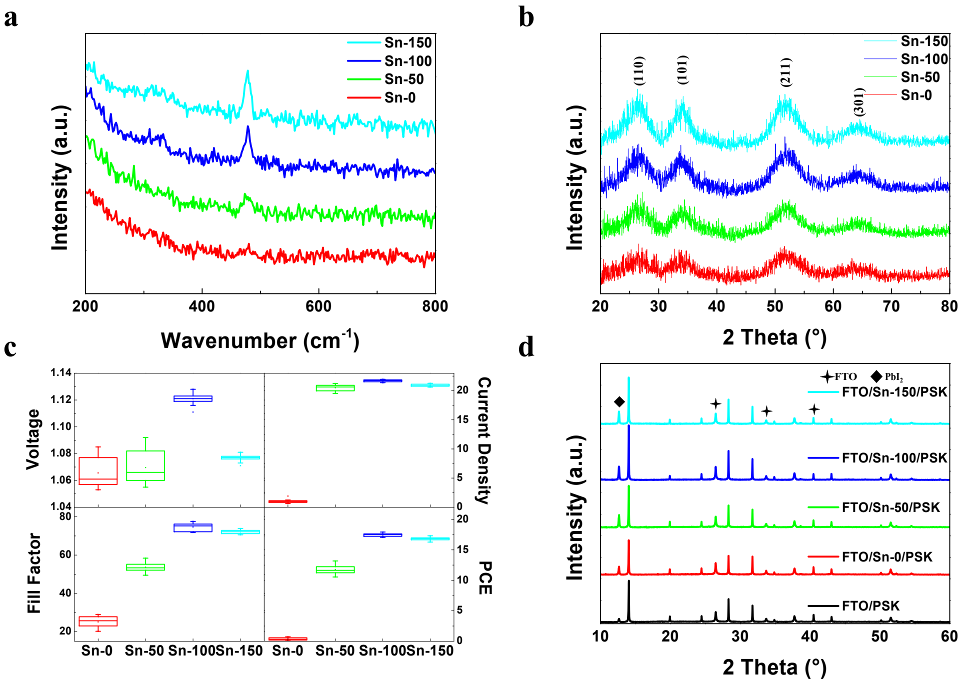

Fig. S2 (a) Raman spectra of the aqueous solution and (b) XRD spectra of SnO_2 powder for different reaction time. (c) The statistical photovoltaic characteristics data of the Sn-0, Sn-50, Sn-100, and Sn-150 samples each having 10 devices. (d) XRD for perovskite prepared on aforementioned SnO2 films.

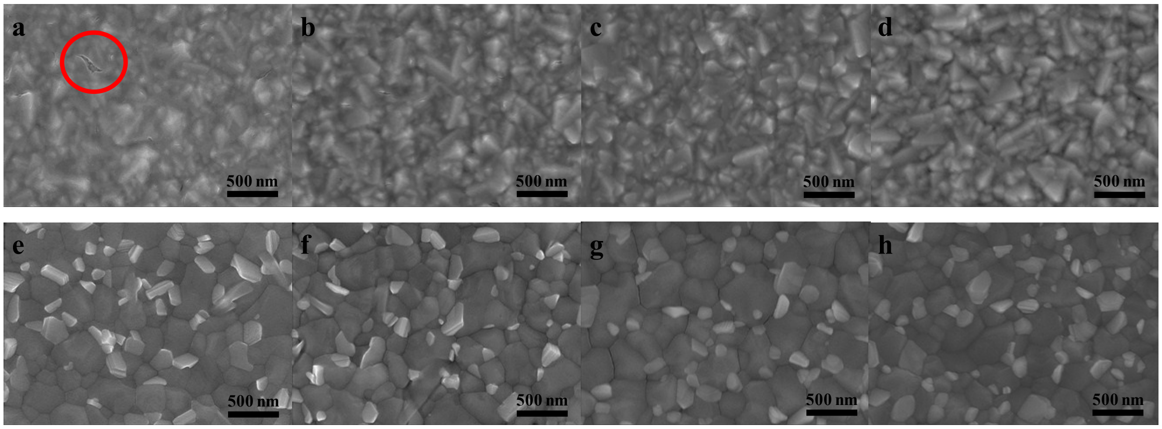

Fig. S3 SEM images of (a) Sn-0, (b) Sn-50, (c) Sn-100, (d) Sn-150 films and corresponding perovskite films deposited on those SnO_2 films.

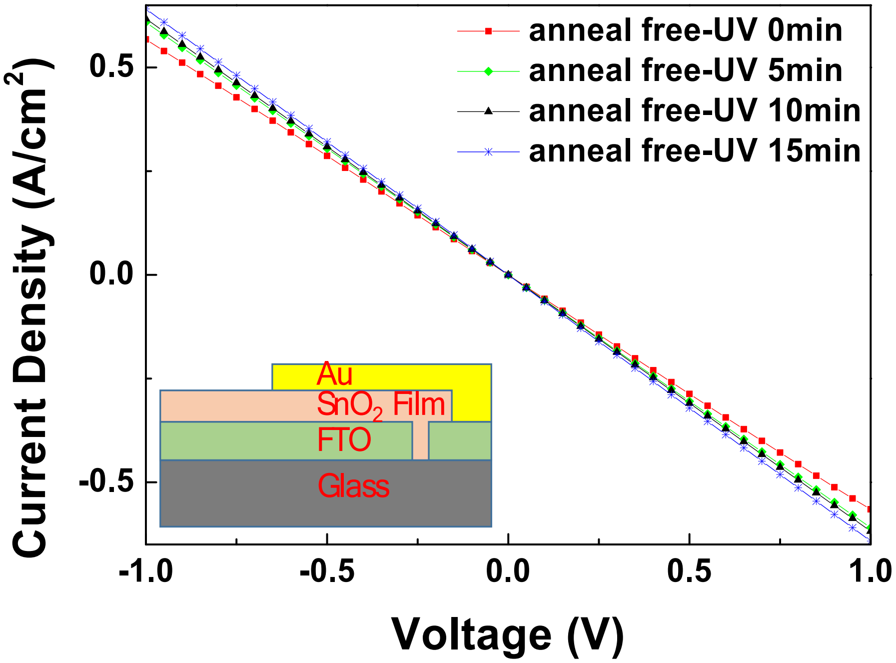

Fig. S4 The conductivity of the SnO_2 films treated by UVO with different times.

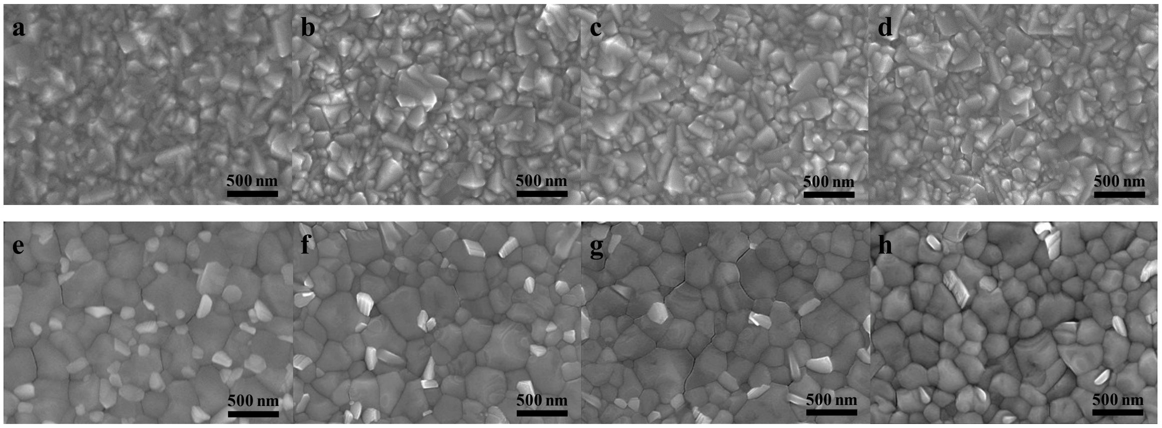

Fig. S5 Top SEM images of SnO_2 film with UVO treatment for (a) 0min, (b) 5 min, (c) 10min, (d) 15 min, (e-f) corresponding SEM images of perovskite film deposited on the aforementioned SnO_2 film.

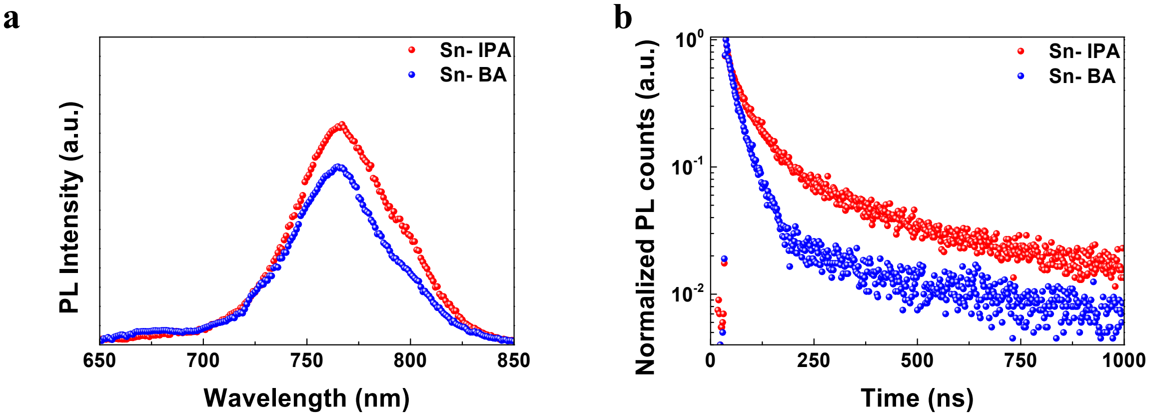

Fig. S6 (a) The PL and (b) the TRPL spectra of perovskite/Sn-IPA and perovskite/Sn-BA.

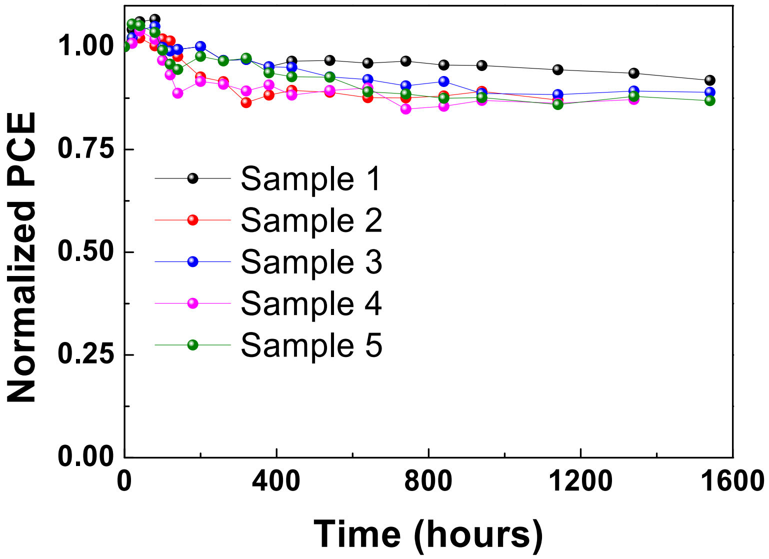

Fig. S7 Stability test of five Sn-BA devices.