Supporting information

Materials

SnO_2 precursor (Alfa Aesar, 15% in H_2O colloidal dispersion) was purchased from Alfa Aesar. PbI_2 was purchased from Advance Election Technology Co., Ltd. FAI, (99.5%), $PbBr_2$, 99.5%, octyl ammonium iodide (OAI, 99.5%), cesium Iodide (CsI, 99.9%) and 2,2′,7,7′-Tetrakis[N,N-di(4-methoxyphenyl)amino]-9,9′-spirobifluorene (Spiro-OMeTAD, 99.5%) were purchased from Xi'an Yuri Solar Co., Ltd. Isopropanol (IPA, 99.5%), N,N-dimethylformamide (DMF, 99.8%), dimethyl sulfoxide (DMSO), chlorobenzene (CB, 99.8%), 4-tert-butylpyridine (TBP, 99.9%), bis(trifluoromethane)sulfonimide lithium salt (Li-TSFI, 99.95%) and acetonitrile (ACN, 99.95%) were purchased from Sigma Aldrich. All materials were used directly without any purification.

Perovskite precursor solution

Wide-bandgap $FA_{0.8}Cs_{0.2}Pb(I_{0.6}Br_{0.4})_3$ perovskite 1.1 mol/L was prepared from four precursors (CsI, FAI, PbI_2 and $PbBr_2$) dissolved in mixed solvents of DMF and DMSO with a volume ratio of 4:1. The molar ratios FAI/CsI/ PbI_2/$PbBr_2$ was 0.8:0.2:0.4:0.6. The precursor solution was stirred at 60 °C for overnight and then filtered through 0.22 μm PTFE membrane before use.

Fabrication of single-junction wide-bandgap PSCs

Patterned indium tin oxide (ITO) glass with a sheet resistance of 15 Ω/sq underwent a cleaning process involving ultrasonic treatment in detergent, deionized water, acetone, and isopropanol, followed by UV-ozone treatment for 25 min. Subsequently, a SnO_2 dispersion was spin-coated onto the ITO glass at 3000 r/min for 30 s and annealed at 150 °C in air for 30 min. The substrates were then subjected to another 25-min UV-ozone treatment and transferred into a N_2 glovebox. The perovskite film was prepared using a two-step spin-coating procedure. In the first step, the perovskite precursor solution was spin-coated onto the substrates at 2000 r/min for 10 s with an acceleration of 200 rmp/s. The second step involved spin-coating at 6000 r/min for 40 s with an acceleration of 2000 rmp/s, with the addition of 200 μL of anti-solvent onto the substrate at 20 seconds before the end. The substrates were then transferred onto a hotplate and heated at 80 °C for 15 min. Following cooling, a hole-transporting layer (HTL) solution was spin-coated onto the perovskite layer at 3000 r/min for 30 s. For the fabrication of opaque cells, a 100 nm layer of silver (Ag) was evaporated onto the HTL layer under vacuum (10^{-4} Pa). For the fabrication of semi-transparent cells, a 200 nm layer of ITO was sputtered with slow rate onto the HTL layer using a magnetron sputtering system.

Fabrication of OSCs

OSCs were fabricated with a device structure of ITO/PEDOT:PSS/PM6:L8-BO/PDINN/Ag. The active layer was dissolved in CB at a concentration of 16.5 mg/mL, and the ratio of the donor and acceptor is 1:1.2. The ITO glass was sequentially cleaned with detergent, deionized water, and ethanol and then dried at 70 °C in a baking oven. After 15 min UV treatment for the ITO substrate, a thin-layer PEDOT:PSS was deposited through spin-coating at 3000 r/min for 30 s on ITO-coated glass. Then, the active layer was coated through a doctor blade (BD Coater H100, Hunan NanoUp Electronics Technology Co., Ltd.) with a coating velocity of 20 mm/s and a blade-substrate gap of 550 μm. The temperature of the bottom plate of doctor-blade equipment is the same as room temperature, approximately 25 °C. The wet film was then transferred to a vacuum chamber with a pressure of 1 Pa. After pumping for 2 min, the film was annealed at 100 °C for 10 min in a nitrogen-filled glovebox. Next, PDINN/methanol solution (1.0 mg/mL) was spin-cast on the active layer at 5000 r/min for 30 s. The silver (~100 nm) was deposited on the active layers by thermal evaporation.

Characterization

The XRD patterns of the perovskite thin films were obtained on X-ray diffraction (XRD, Rigaku D, MAX 2500, Japan). The scanning electron microscopy images were acquired using a field-emission scanning electron microscope (FEI Helios Nanolab 600i SEM, America). The UV-vis spectrophotometer (Puxi, T9, China) was used to characterize the tramsmittance of perovskite and organic films. Steady-state PL spectra were measured by FLS1000 (Edinburgh Inc.) spectrometer. Current density-voltage (*J*−*V*) characteristics of the devices were measured from −0.1 V to 1.2 V by a digital Source Meter (Keithley, model 2400). The devices were illuminated by a Xenon-lamp-based solar simulator (SAN-EI, XES-40S3, AM 1.5G), calibrated by a standard silicon solar cell with a light intensity of 1 Sun.

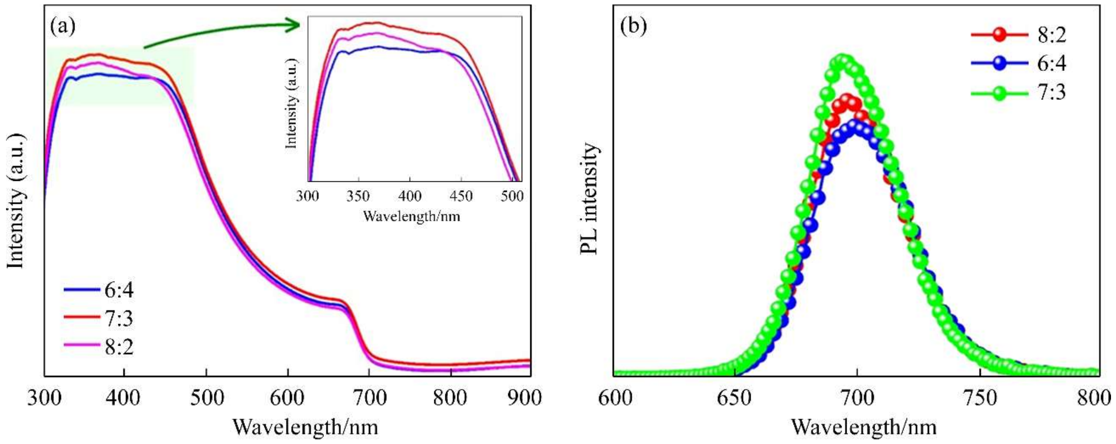

Figure S1 (a) UV–Vis absorption spectra of perovskite film treated with different ratio of mixed anti-solvent; (b) Photoluminescence (PL) spectra of perovskite film using different ratio of mixed anti-solvent

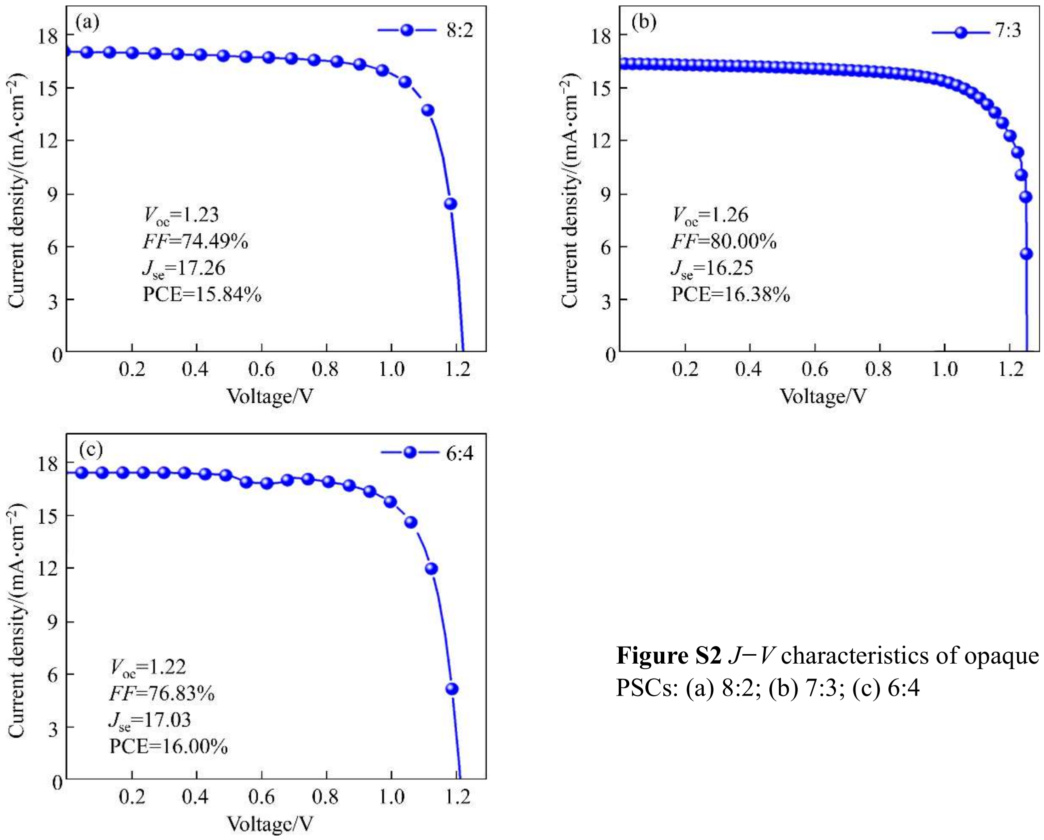

Figure S2 $J-V$ characteristics of opaque PSCs: (a) 8:2; (b) 7:3; (c) 6:4

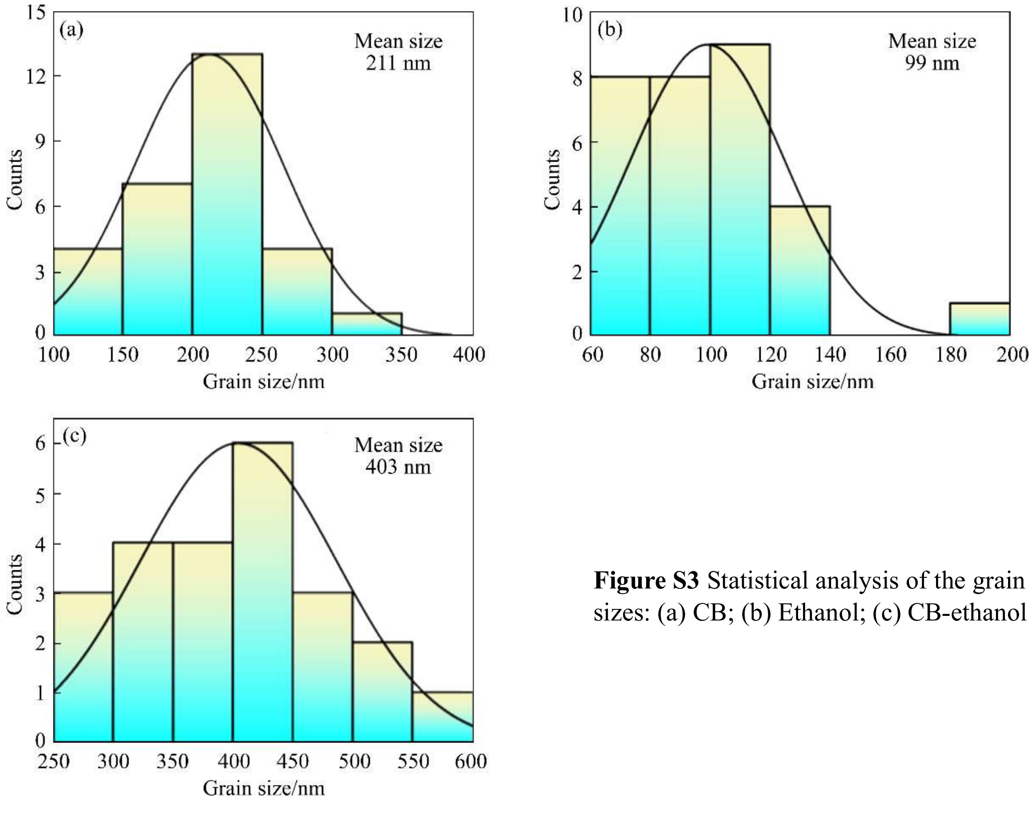

Figure S3 Statistical analysis of the grain sizes: (a) CB; (b) Ethanol; (c) CB-ethanol

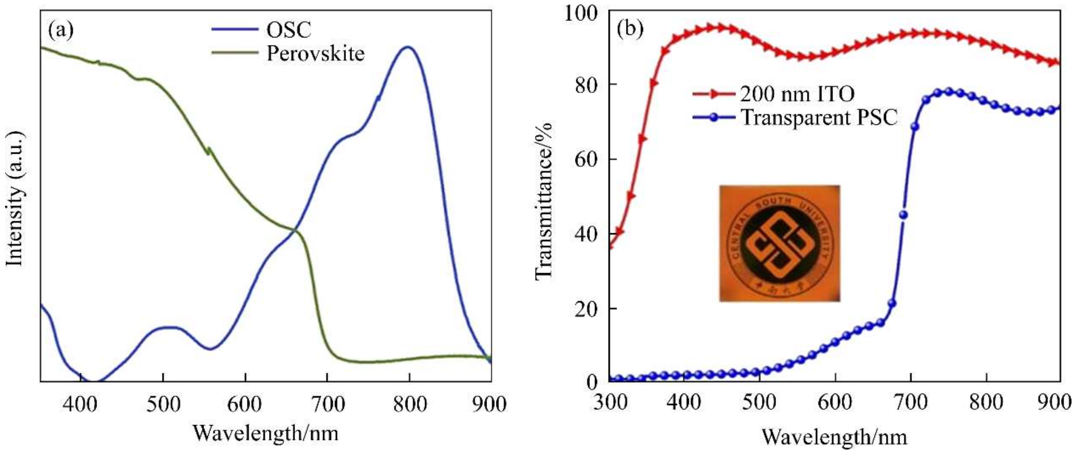

Figure S4 (a) UV-Vis absorption spectra of perovskite and OSC; (b) Transmittance of ITO and ST-PSC

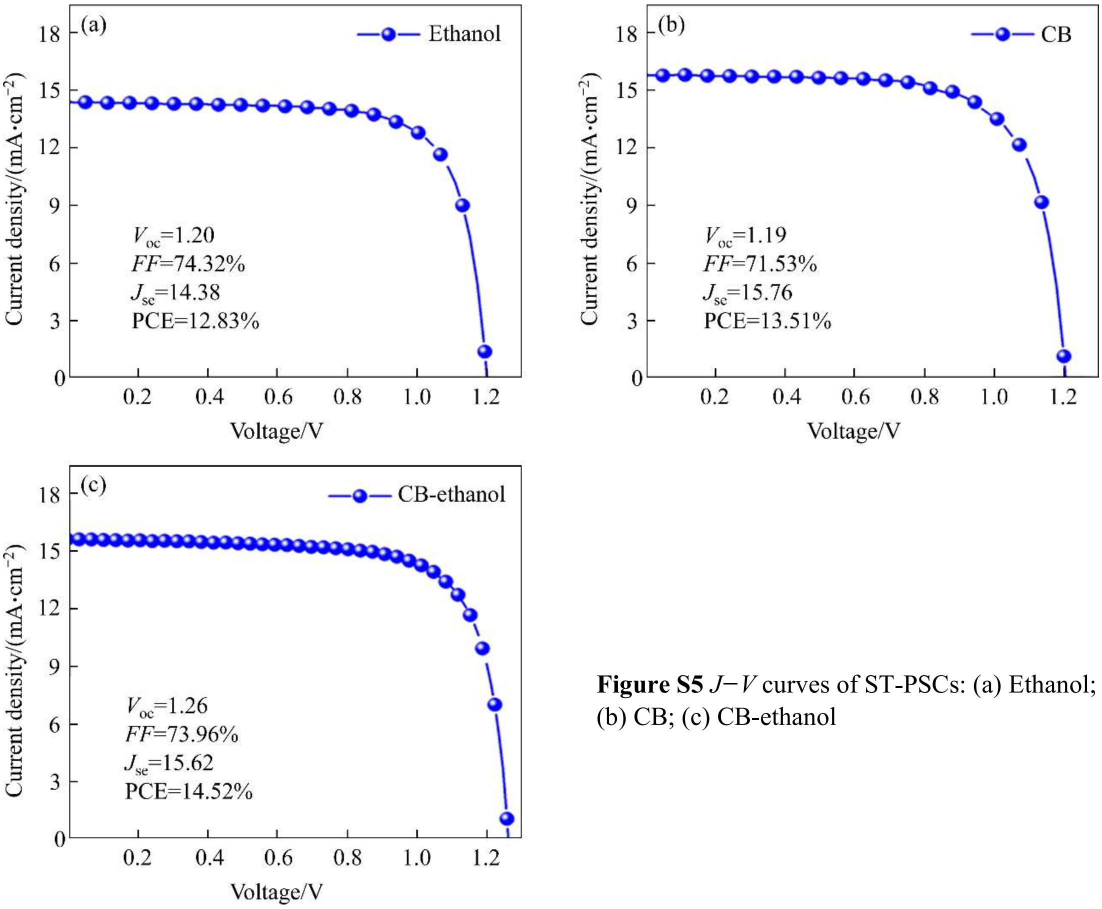

Figure S5 $J-V$ curves of ST-PSCs: (a) Ethanol; (b) CB; (c) CB-ethanol

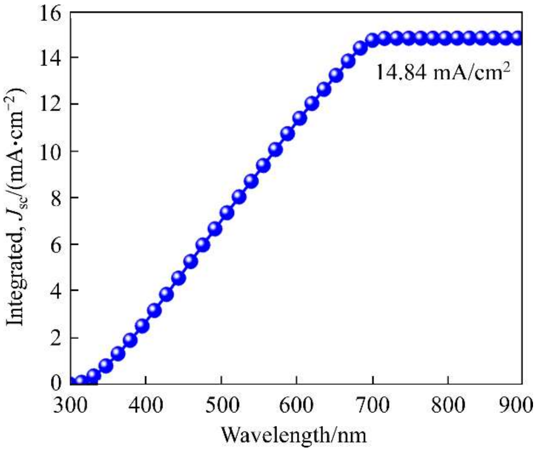

Figure S6 Integrated current density of ST-PSC

Table S1 Photovoltaic parameters of PSCs fabricated using distinct anti-solvents

Devices	V/V	J/(mA·cm^{-2})	FF/%	PCE/%
Ethanol	1.2	16.09	74.5	14.49
CB	1.2	16.35	76.59	15.09
CB-ethanol	1.26	16.25	80	16.38