Supporting information

Materials:

The SnO_2 Sputtering target (99.99%) was purchased from Beijing Dream Material Technology Co., Ltd. The SnO_2 colloidal dispersion (12% in H_2O) was obtained from Xi'an Yuri Solar Co., Ltd. Other materials similar to our previous report [1].

SnO_2 thin film sputtering:

The magnetron sputtering system we use is the MSP-300B from Beijing Chuangshiweina Technology Co., LTD. The SnO_2 thin film was deposited on well-cleaned FTO glass (20 × 20 mm^2) by radio frequency magnetron sputtering in room temperature. The substrate located in central plate which distanced 8 cm down to target that angled 45 degrees vertically. The sputtering chamber pumped to pressure down to 2×10^{-3} Pa to pre-evacuate, and then kept 1 Pa sputtering pressure with intrusion of 10 sccm Ar (99.99 %) gas. The 8 inches target was sputtered with 100W power and a bias voltage of 135 V. The substrate was rotated in clockwise with 30 RPM for 20 second, and then annealed at 500 ℃ in air atmosphere.

SnO_2 thin film spin coating:

100 μL diluted (1: 3 in water) SnO_2 colloidal was spin coated with the speed of 3000RPM for 30 s on FTO glass substrate, followed by thermal annealing at 200 °C for 40 minutes. Based on extensive literature reports employing identical or similar colloidal formulations and processing parameters, the resulting spin coating SnO_2 layer typically exhibits a thickness of 10–15 nm, which ensures full substrate coverage while maintaining low electrical resistance and high optical transparency [2, 3].

Device preparation:

FTO substrates with the area of 20 × 20 mm^2 were cleaned in deionized water, acetone, and isopropanol (IPA) for 10 minutes each. Subsequently, the substrates were dried under a compressed dry air and subjected to UV-ozone treatment for 15 minutes.

A colloidal SnO_2 solution was diluted threefold with deionized water.

The perovskite precursor solution with a composition of $FA_{0.9}Cs_{0.07}MA_{0.03}Pb(I_{0.92}Br_{0.08})_3$ (1.35 M) was prepared by dissolving 12.8 mg MAI, 27 mg FABr, 49.2 mg CsI, 79.2 mg $PbBr_2$, 380.8 mg FAI, and 1182.4 mg PbI_2 in 2 mL of a mixed solvent consisting of DMSO and DMF in a volume ratio of 4:1 (V_{DMSO}/V_{DMF}= 4/1). This solution was stirred at room temperature for 12 hours inside a glovebox and subsequently filtered through a 0.22 μm PTFE syringe filter prior to use.

Perovskite films were fabricated using a two-step spin-coating protocol: an initial spin at 1000 rpm for 10 s, followed by a second spin at 4000 rpm for 30 s. During the latter step, 260 μL of ethyl acetate (EA) was dispensed onto the spinning substrate between 28 and 30 seconds before the end of the program. The resulting films were then annealed at 100 °C for 40 minutes.

Next, a passivation layer was formed by spin-coating a 2.3 mg/mL solution of iBA-Br in IPA onto the perovskite surface at 4000 rpm for 20 seconds, followed by a short annealing step at 100 °C for 4–5 minutes.

The Spiro-OMeTAD hole-transport layer (HTL) was prepared by dissolving 72.3 mg of Spiro-OMeTAD in 1 mL of chlorobenzene (CB), along with 28.8 μL of 4-tert-butylpyridine (tBP) and 17.5 μL of a lithium bis(trifluoromethanesulfonyl)imide (Li-TFSI) stock solution (520 mg Li-TFSI in 1 mL acetonitrile). A 40 μL aliquot of this HTL precursor solution was then spin-coated onto the perovskite film at 3000 rpm for 30 seconds.Finally, an 80 nm-thick silver (Ag) electrode was thermally evaporated onto the HTL. [1].

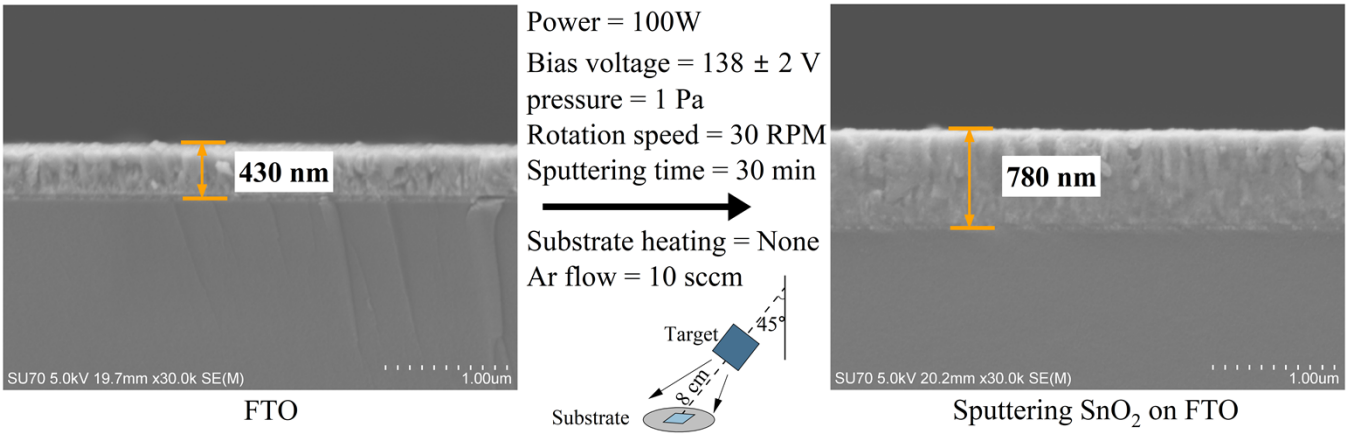
Characterization:

The characterization method also similar our previous report[1].

Sputtering parameters:

Since the sputtering parameters affect most the thickness in single target sputtering with single gas environment, we explore optimal thickness of SnO_2 thin film at different sputtering times. The 30 minutes sputtering was performed under fixed parameters in

order to obtain deposition speed of ~2 Å/s. Subsequently, according to the device performance of different deposition thicknesses at different annealing temperature, As shown in Figure S2, the optimal parameters were determined to be sputtering time of 20 s (thickness ~ 5nm) and annealing temperature of 500 °C. For the case of sputtering time less than 20 s, because the sputtering rate is relatively large and will produce instability which different batches has large similarity.



FTO

Sputtering SnO_2 on FTO

Figure S1. Cross sectional SEM image of FTO before and after 30 minutes sputtering

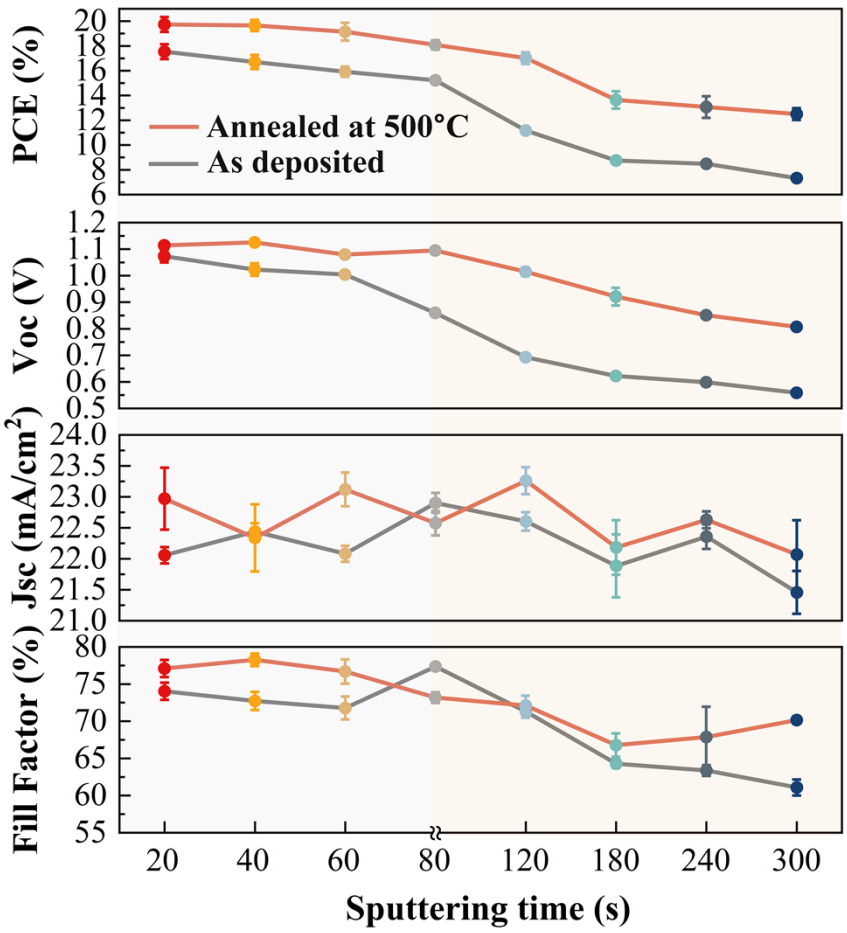


Figure S2 Performance of the device based on SnO_2 under different sputtering time

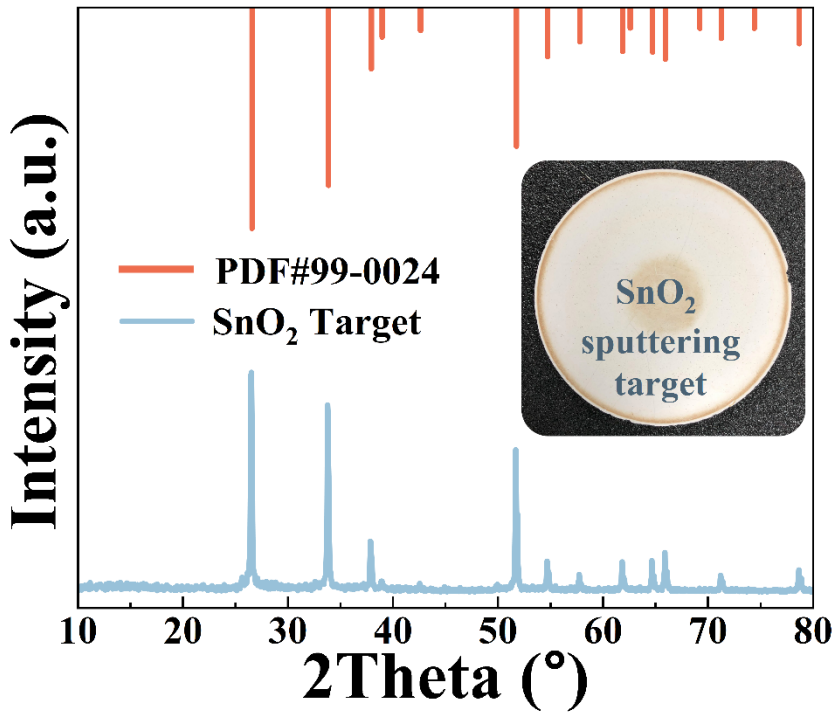


Figure S3. The XRD spectra SnO_2 Sputtering target

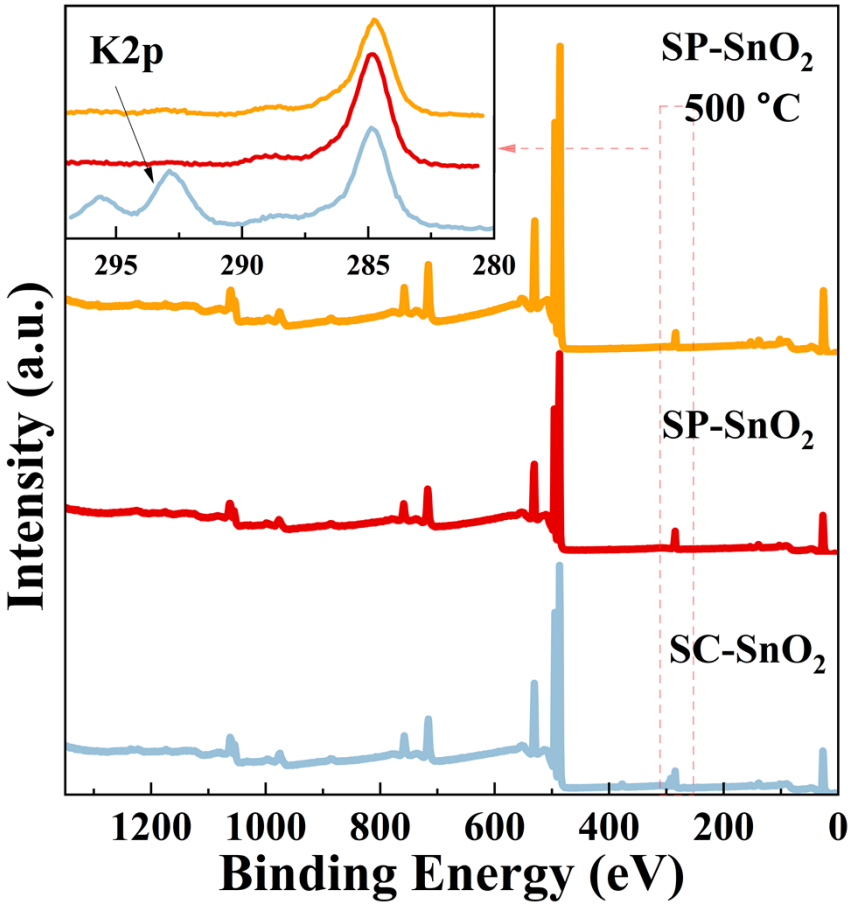


Figure S4. The XPS survey spectra for spin-coated and sputtered SnO2 thin films

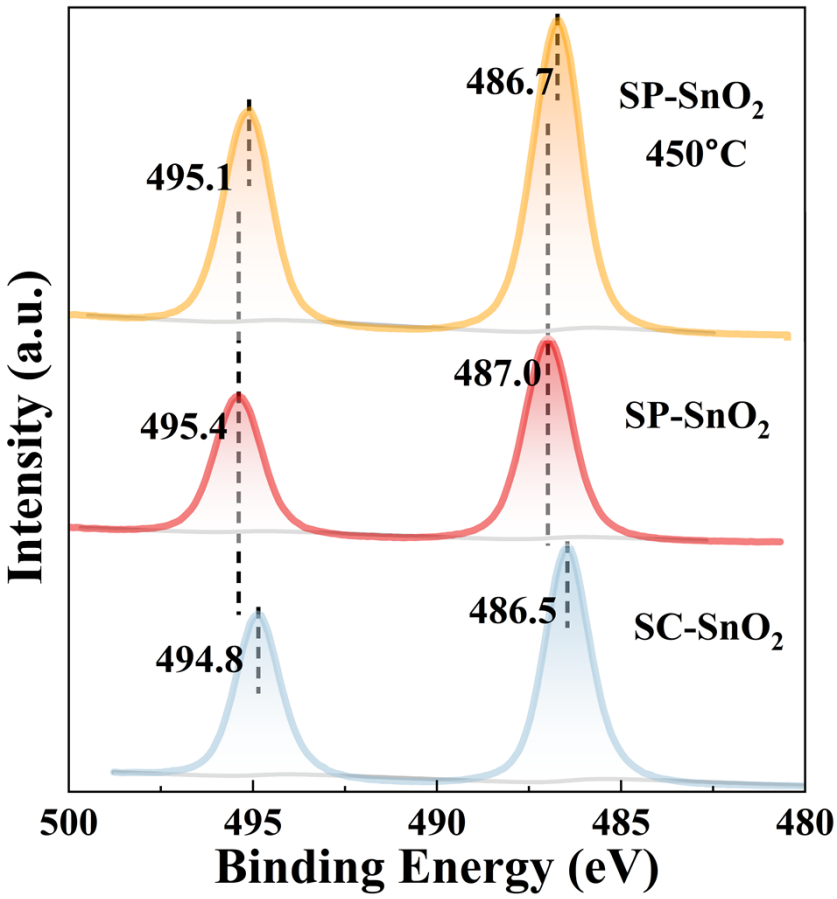


Figure S5. Sn 3d biding energy from XPS

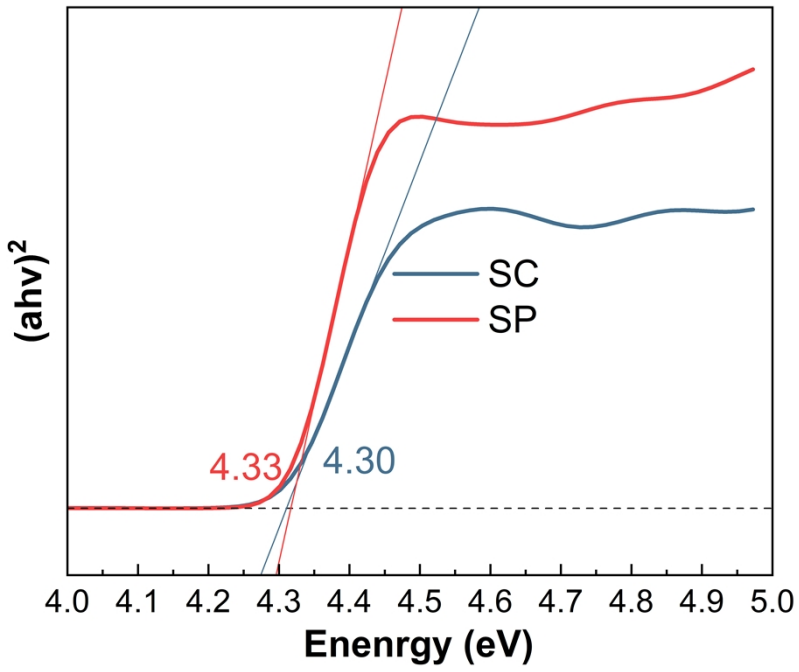


Figure S6. Tauc plots of spin coated and sputtered films

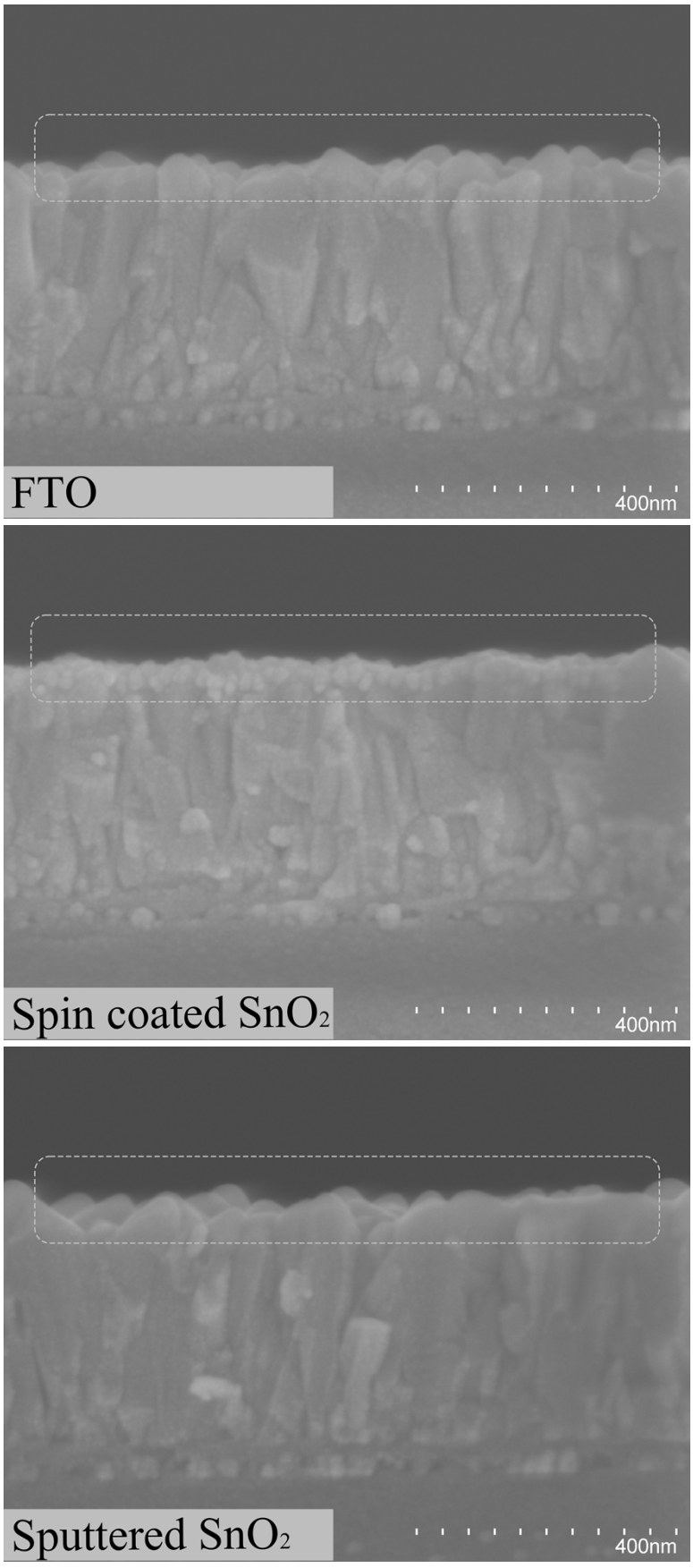


Figure S7. Cross sectional image for FTO, spin coated SnO_2 and sputtered SnO_2

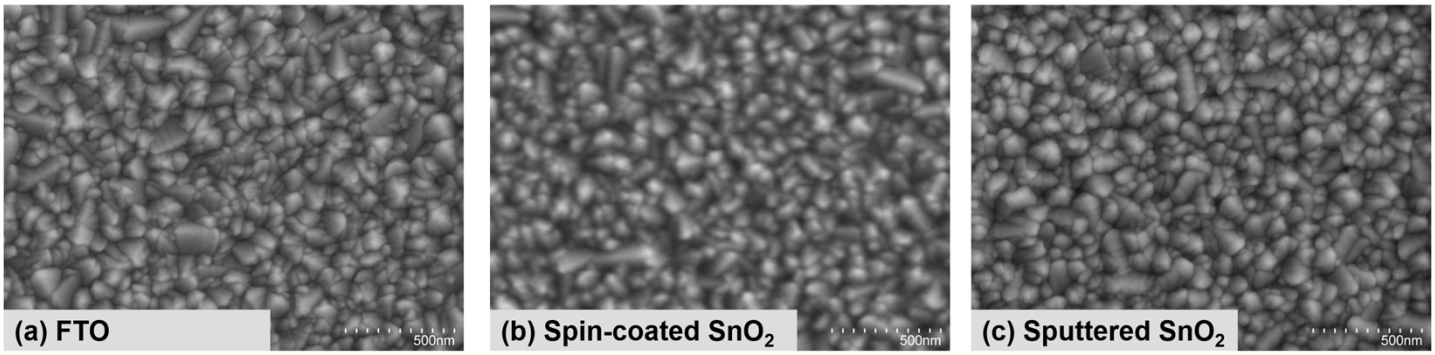


Figure S8. Top view SEM images for FTO, spin coated SnO_2 and sputtered SnO_2

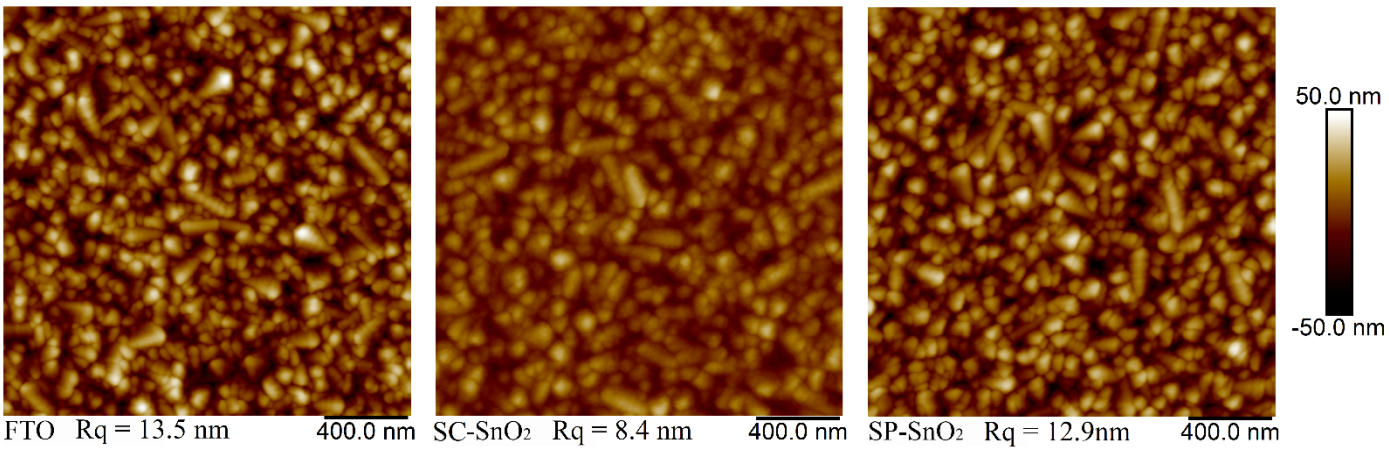


Figure S9. The AFM image of FTO and different SnO_2 thin films

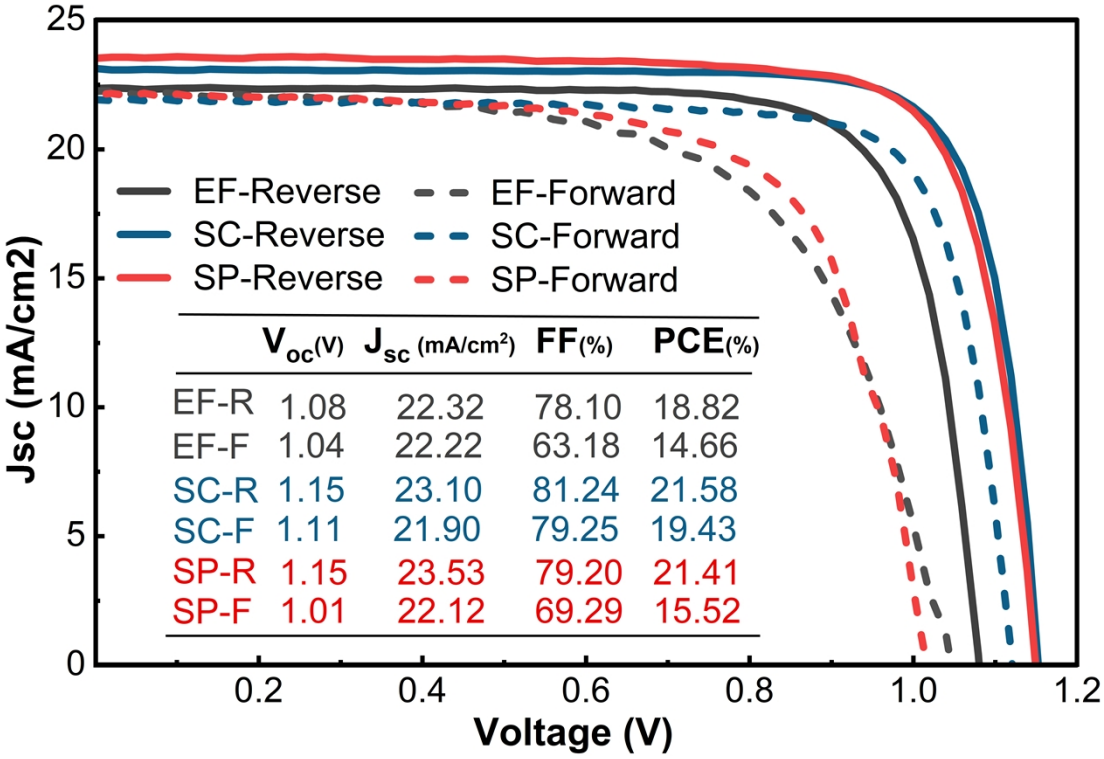


Figure S10. J-V curves of different ETL based device with reverse-forward scan

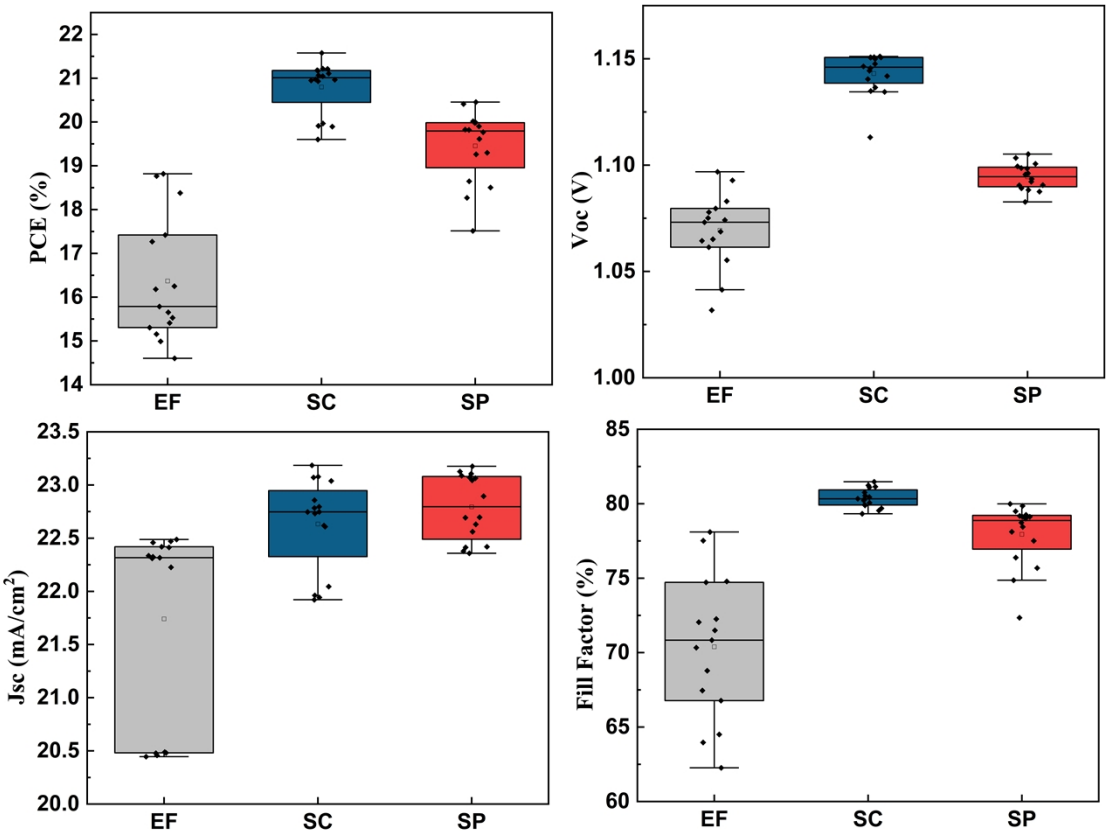


Figure S11. J-V Box plot with PCE, Voc, Jsc and Fill factor for different ETL device

References:

1. Deng, J., et al., *Impacts of cation modification on the carrier dynamics and chemical stability of SnO2-based buried interfaces in perovskite solar cells.* Chemical Engineering Journal, 2024. **495**: p. 153121.
2. Sharma, K.K., et al., *Synthesis of nanostructured cubic phase SnO2 thin film and its trace-level sensing of CO gas.* Nature Communications, 2025. **17**(1).
3. Du, B., et al., *Robust electron transport layers of SnO2 for efficient perovskite solar cells: recent advances and perspectives.* Journal of Materials Chemistry C, 2023. **11**(40): p. 13625–13646.