Supplementary information

Inkjet-printed Ce-doped SnO_x electron transport layer for improved performance of planar perovskite solar cells

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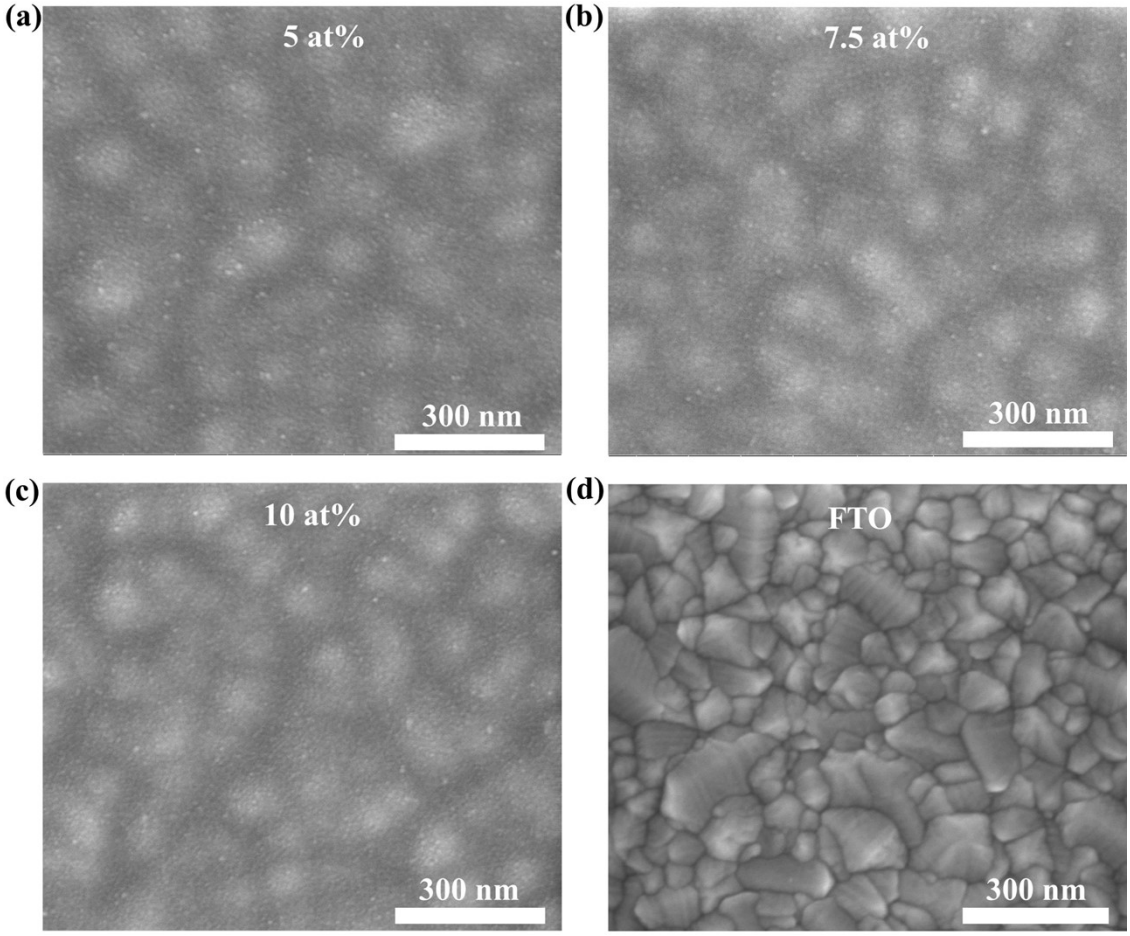

Figure S1. (a-c) Top-view SEM images of inkjet-printed Ce-doped SnO_x thin films at various doping levels. (d) Bare FTO is shown as a reference. Note that the larger 100 nm-scale structures are the large grains of the FTO substrate under the SnO_x films.

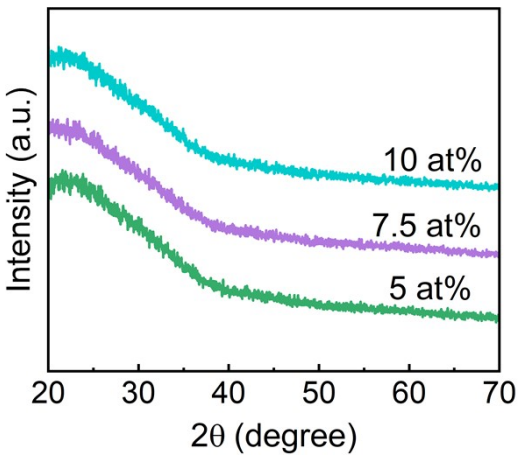

Figure S2. XRD spectra of inkjet-printed Ce-doped SnO_x thin films at various Ce doping levels.

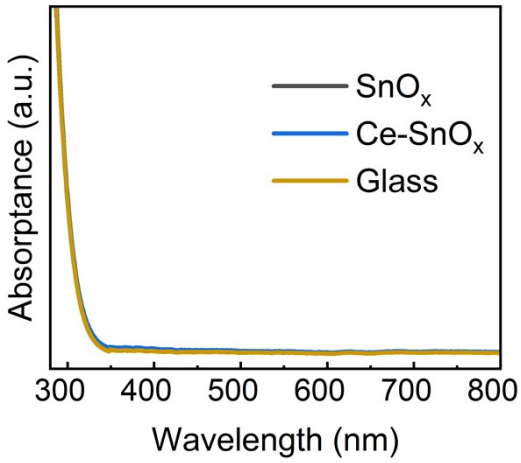

Figure S3. Absorptance of SnO_x and 2.5 at% Ce-SnO_x thin films on glass substrates.

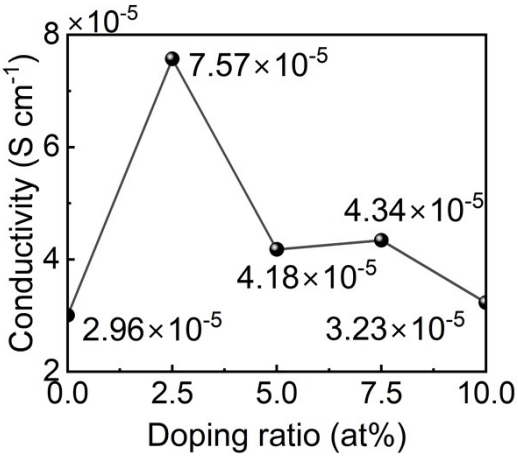

Figure S4. Conductivity of pristine SnO_x and Ce-doped SnO_x thin films with various Ce doping contents.

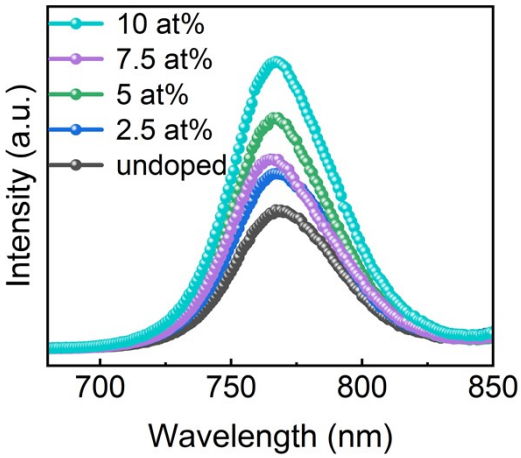

Figure S5. PL spectra of the perovskite films deposited on pristine SnO_x and Ce-doped SnO_x.

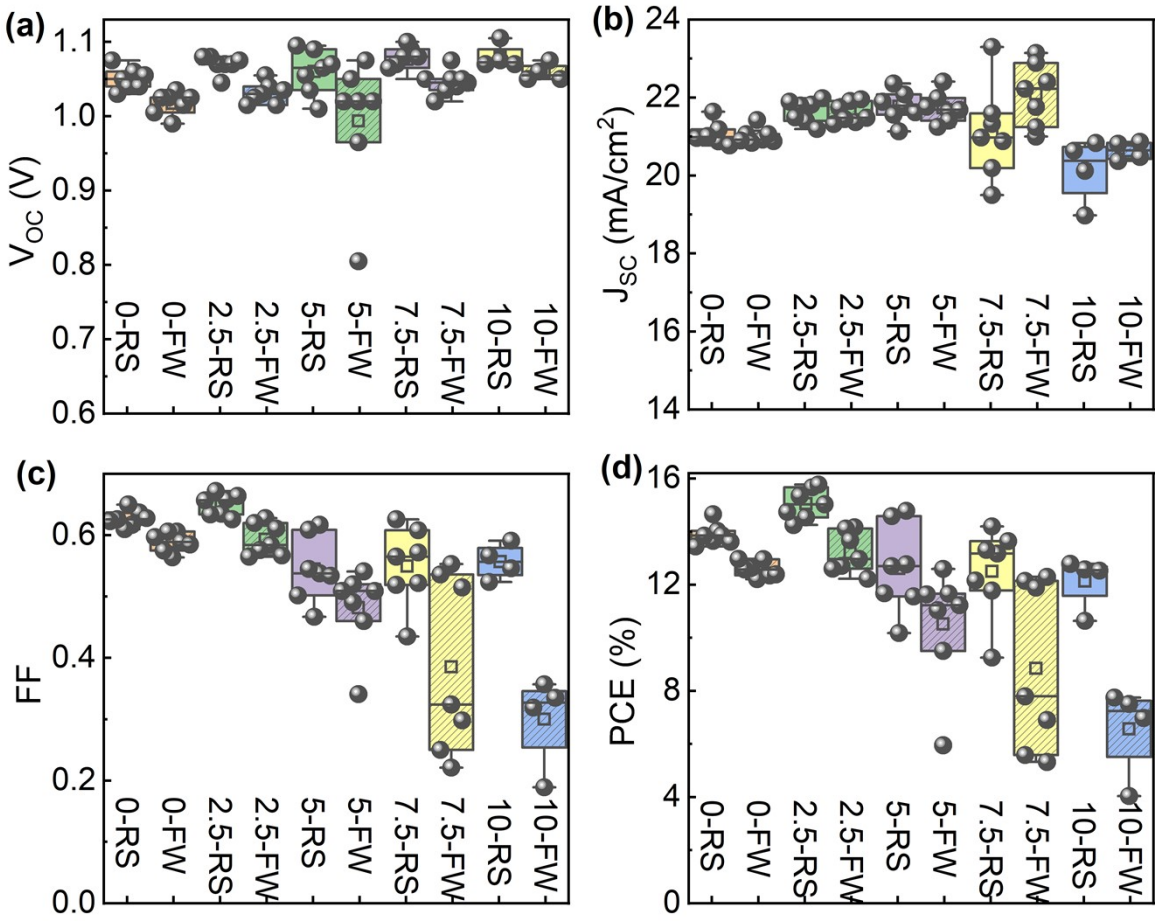

Figure S6. Distribution of photovoltaic parameters of PSCs based on inkjet-printed pristine SnO_x and Ce-doped SnO_x at various doping concentrations.

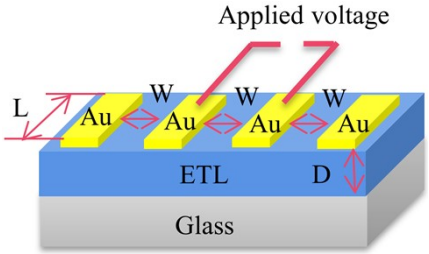

Figure S7. The device architecture for measuring the condcutivity of ETLs.

The electrical conductivity of ETLs was measured using a two-probe method [1]. As shown in **Figure S7**, the conductivity (σ) is determined using the equation:

$$\sigma = \frac{J}{E} = \frac{W}{R \times D \times L}$$

$$J = \frac{I}{D \times L}, E = \frac{V}{W}$$

where R is the resistance calculated from a current-voltage (I-V) curve using linear voltage sweeps, D is the thickness of the ETL, W and L are the channel width and length of 2 mm and 10 mm, respectively. The eventual estimated conductivity was an average value based on data obtained from two devices.

Table S1. Peak deconvolution of the O 1s XPS spectra of pristine SnO_x and 2.5 at% Ce-doped SnO_x.

Sample	Peak type	Peak position (eV)	Percentage (%)
SnO_x	O_L	531.15	75.89
	O_V	532.58	24.11
2.5 at% Ce-SnO_x	O_L	530.98	80.60
	O_V	532.43	19.40

Table S2. TRPL parameters of perovskite films deposited on pristine SnO_x and 2.5 at% Ce-doped SnO_x.

Sample	A_1	τ_1 (ns)	A_2	τ_2 (ns)	τ_{ave} (ns)
SnO_x	0.46	10	0.54	188	106
2.5 at% Ce-SnO_x	0.49	9	0.51	236	125

Table S3. Average (champion) photovoltaic parameters of the devices based on inkjet-printed pristine SnO_x ETLs and Ce-doped SnO_x ETLs at various doping levels.

Ce content	Scan direction	PCE (%)	V_{OC} (V)	J_{SC} (mA/cm^2)	FF (%)
pristine	reverse	13.87 ± 0.40 (14.66)	1.05 ± 0.02 (1.08)	21.06 ± 0.28 (20.96)	62.7 ± 1.3 (65.0)
	forward	12.58 ± 0.30 (12.97)	1.02 ± 0.02 (1.03)	21.01 ± 0.20 (20.90)	58.9 ± 1.6 (60.6)
2.5 at%	reverse	15.05 ± 0.58 (15.77)	1.07 ± 0.01 (1.08)	21.65 ± 0.29 (21.98)	64.9 ± 1.8 (66.4)
	forward	13.21 ± 0.78 (12.97)	1.03 ± 0.01 (1.03)	21.60 ± 0.26 (21.96)	59.3 ± 2.6 (57.6)
5 at%	reverse	12.61 ± 1.66 (14.78)	1.06 ± 0.03 (1.10)	21.78 ± 0.39 (21.89)	54.5 ± 5.4 (61.7)
	forward	10.52 ± 2.22 (11.23)	0.99 ± 0.09 (1.05)	21.73 ± 0.38 (21.76)	48.2 ± 6.7 (49.1)
7.5 at%	reverse	12.50 ± 1.66 (14.20)	1.08 ± 0.02 (1.05)	21.11 ± 1.20 (21.59)	55.0 ± 6.4 (62.6)
	forward	8.85 ± 3.16 (11.89)	1.05 ± 0.02 (1.02)	22.09 ± 0.80 (21.76)	38.5 ± 14.4 (53.6)
10 at%	reverse	12.13 ± 1.00 (12.78)	1.08 ± 0.02 (1.08)	20.14 ± 0.83 (20.12)	55.7 ± 2.9 (59.1)
	forward	6.57 ± 1.72 (7.75)	1.06 ± 0.01 (1.06)	20.63 ± 0.24 (20.48)	30.0 ± 7.6 (35.7)

References

[1] Chen, C.; Zhang, W.; Cong, J.; Cheng, M.; Zhang, B.; Chen, H.; Liu, P.; Li, R.; Safdari, M.; Kloo, L.; Sun, L., Cu(II) Complexes as p-Type Dopants in Efficient Perovskite Solar Cells. *ACS Energy Lett.* **2017,** *2* (2), 497-503.