

## Supplementary information

Facile doping of 2,2,2-Trifluoroethanol to single-walled carbon nanotubes electrodes for durable perovskite solar cells

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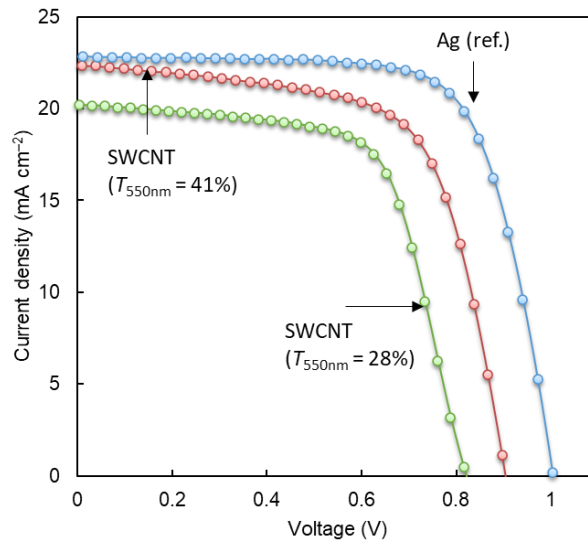


Figure S1.  $J$ - $V$  characteristics of the present perovskite solar cells.

Table S1. Photovoltaic performance of the cells with SWCNTs.

Electrode	$J_{sc}$ (mA cm <sup>-2</sup> )	$V_{oc}$ (V)	FF	$\eta$ (%)	$R_s$ ( $\Omega$ cm <sup>2</sup> )	$R_{sh}$ ( $\Omega$ cm <sup>2</sup> )
SWCNT ( $T_{550nm} = 41\%$ )	22.4	0.904	0.654	13.2	6.01	503
SWCNT ( $T_{550nm} = 28\%$ )	20.2	0.821	0.662	11.0	8.47	723
Ag (ref.)	22.8	1.00	0.715	16.4	5.21	4281

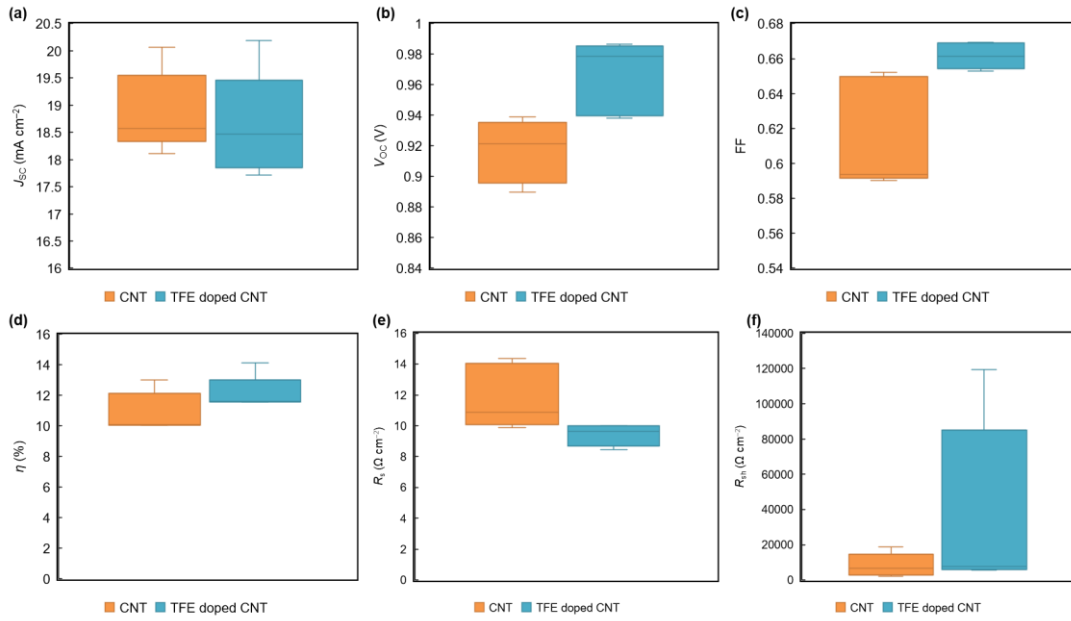


Figure S2. Device performance. (a)-(f) Statistics deviation of the photovoltaic parameters of the perovskite solar cells with TFE-doped CNT. The statistical data was collected from five cells.

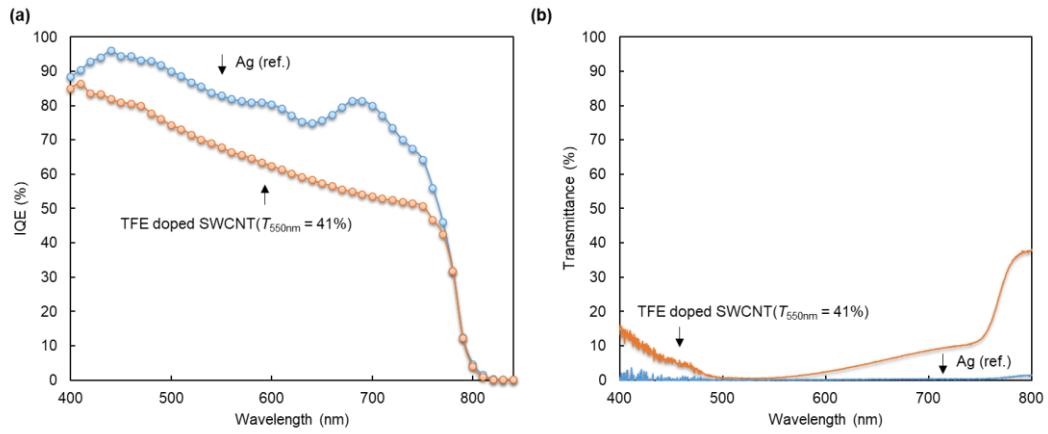


Figure S3. (a) IQE spectra calculated by EQE results and light absorption efficiency. (b) transmittance spectra of the perovskite solar cells.

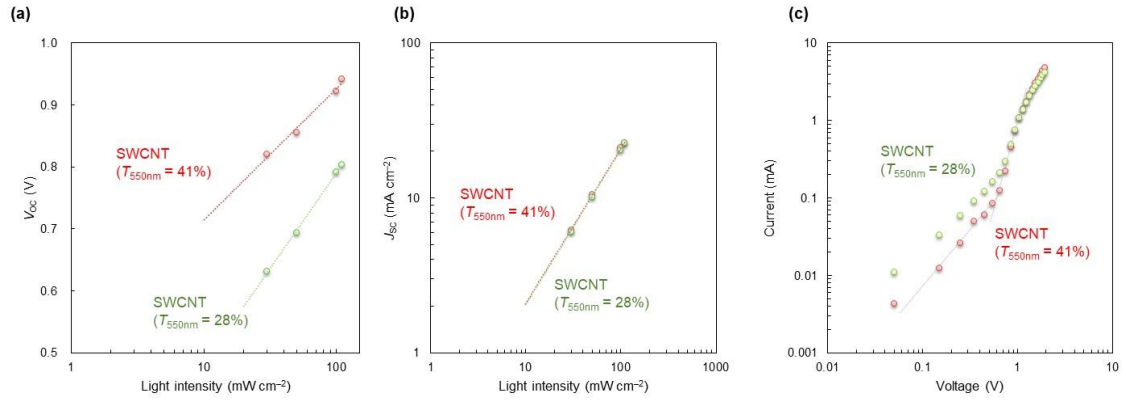


Figure S4. Light intensity dependence of  $J$ - $V$  characteristics of (a)  $V_{OC}$  and (b)  $J_{SC}$  for devices with SWCNTs. (c) Dark current-voltage curves for the devices without TFE.

Table S2. Photovoltaic performance of the cells with SWCNTs non-doped TFE.

Electrode	$m$	$\alpha$	$V_{TFL}$ (V)	$D_{trap}$ ( $\text{cm}^{-3}$ )
SWCNT ( $T_{550\text{nm}} = 41\%$ )	3.59	1.00	0.55	$1.14 \times 10^{16}$
SWCNT ( $T_{550\text{nm}} = 28\%$ )	5.21	1.00	0.65	$1.34 \times 10^{16}$

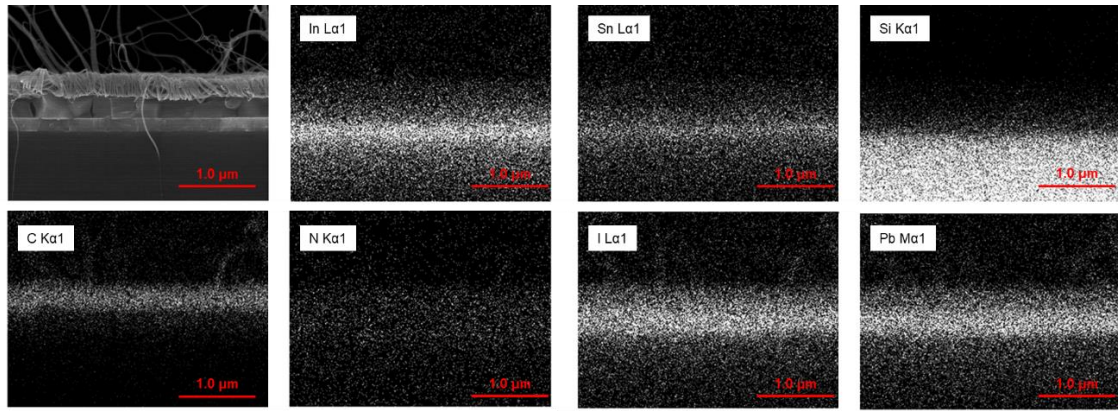


Figure S5. Elemental mapping images of In L, Sn L, Si K, C L, N K, I L and Pb M lines for the perovskite solar cell with TFE-doped SWCNT electrode.

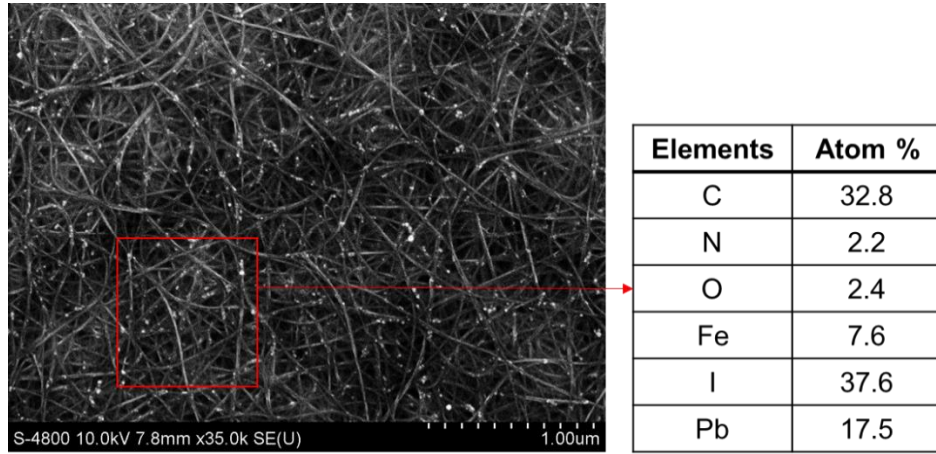


Fig. S6. SEM image and EDX data of the SWCNT ( $T_{550\text{nm}} = 41\%$ ) film.

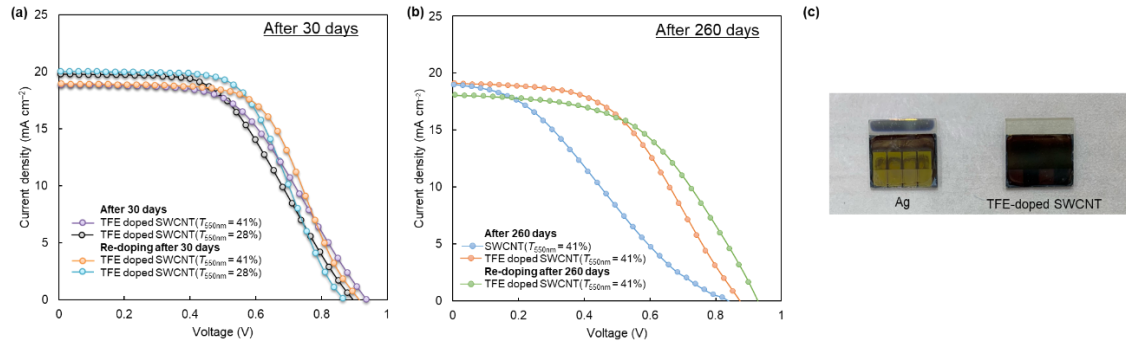


Fig. S7. Time-dependent evaluation. Time-dependent evaluation.  $J-V$  characteristics of the cells after (a) after 30 days and (b) after 260 days, respectively. (c) photograph of the backside of the present perovskite solar cells after 260 days.

Table S3. Photovoltaic performance of the cells with SWCNTs after 30 days and 260 days.

Electrode	$J_{sc}$ ( $\text{mA cm}^{-2}$ )	$V_{oc}$ (V)	FF	$\eta$ (%)	$R_s$ ( $\Omega \text{ cm}^2$ )	$R_{sh}$ ( $\Omega \text{ cm}^2$ )
After 30 days						
TFE doped SWCNT ( $T_{550\text{nm}} = 41\%$ )	18.9	0.937	0.521	9.2	20.3	2912
TFE doped SWCNT ( $T_{550\text{nm}} = 28\%$ )	19.8	0.897	0.505	9.0	19.6	4455
Re-doping after 30 days						
TFE doped SWCNT ( $T_{550\text{nm}} = 41\%$ )	19.0	0.915	0.596	10.3	13.7	3850
TFE doped SWCNT ( $T_{550\text{nm}} = 28\%$ )	20.0	0.869	0.585	10.2	13.6	69975
After 260 days						
SWCNT( $T_{550\text{nm}} = 41\%$ )	19.0	0.834	0.299	4.8	27.8	337
TFE doped SWCNT ( $T_{550\text{nm}} = 41\%$ )	19.1	0.873	0.491	8.2	19.7	1324
Re-doping after 260 days						
TFE doped SWCNT ( $T_{550\text{nm}} = 41\%$ )	18.1	0.928	0.510	8.6	15.0	970

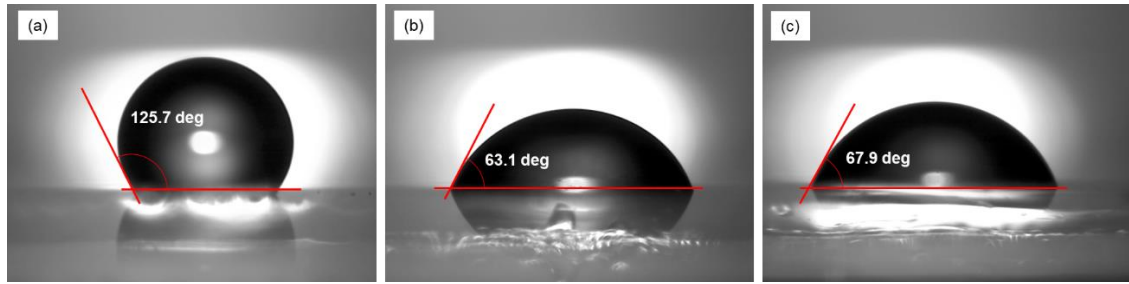


Fig. S8. Photographs of water contact angle tests of (a) glass/SWCNT/EtOH, (b) glass/SWCNT/spiro-OMeTAD and (c) glass/SWCNT/spiro-OMeTAD/TFE, respectively.

Table S4. Comparison of carbon nanotubes as hole transport materials in perovskite solar cells.

Device structure	PCE (%)	Ref.
FTO/TiO <sub>2</sub> /CH <sub>3</sub> NH <sub>3</sub> PbBr <sub>3</sub> /CNTs/PMMA/Au	5.82	[66]
FTO/TiO <sub>2</sub> /CH <sub>3</sub> NH <sub>3</sub> PbI <sub>3-x</sub> Cl <sub>x</sub> + Al <sub>2</sub> O <sub>3</sub> /P <sub>3</sub> HT/SWCNTs/PMMA/Ag	14.2	[67]
FTO/c-TiO <sub>2</sub> /m-TiO <sub>2</sub> /CH <sub>3</sub> NH <sub>3</sub> PbI <sub>3</sub> /SWCNT/GO/PMMA/Au	13.3	[68]
FTO/TiO <sub>2</sub> /CH <sub>3</sub> NH <sub>3</sub> PbI <sub>3-x</sub> Cl <sub>x</sub> + Al <sub>2</sub> O <sub>3</sub> /P <sub>3</sub> HT/SWCNTs/undoped-Spiro-OMeTAD/Ag	15.4	[69]
FTO/SnO <sub>2</sub> /FA <sub>0.83</sub> MA <sub>0.17</sub> Pb(I <sub>0.87</sub> Br <sub>0.17</sub> ) <sub>3</sub> /SWCNTs/undoped-Spiro-OMeTAD/Ag	18.8	[70]
FTO/SnO <sub>2</sub> /FA <sub>0.83</sub> MA <sub>0.17</sub> Pb(I <sub>0.87</sub> Br <sub>0.17</sub> ) <sub>3</sub> /EVA-SWCNTs/undoped-Spiro-OMeTAD/Au	16.8	[71]
FTO/SnO <sub>2</sub> /FA <sub>0.83</sub> MA <sub>0.17</sub> Pb(I <sub>0.87</sub> Br <sub>0.17</sub> ) <sub>3</sub> /EVA-MWCNTs/undoped-Spiro-OMeTAD/Au	17.1	[71]
ITO/SWCNTs/PEDOT:PSS/MAPbI <sub>3</sub> /PCBM/Ag	12.5	[72]
ITO/Z7-MWCNTs/MAPbI <sub>3</sub> /PCBM/BCP/Ag	17.2	[73]
ITO/NiO <sub>x</sub> -CNT/MAPbI <sub>3</sub> /PCBM/Ag	16.9	[74]
ITO/SnO <sub>2</sub> /CH <sub>3</sub> NH <sub>3</sub> PbI <sub>3</sub> /Spiro-OMeTAD/TFE-doped SWCNT( <i>T</i> <sub>550nm</sub> = 41%)	14.1	This work
ITO/SnO <sub>2</sub> /CH <sub>3</sub> NH <sub>3</sub> PbI <sub>3</sub> /Spiro-OMeTAD/TFE-doped SWCNT( <i>T</i> <sub>550nm</sub> = 28%)	11.9	This work

The table is cited from [75].