Supporting Information for

Atomic layer deposition of SnO_2 using hydrogen peroxide improves efficiency and stability of perovskite solar cell

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Figure S1-S6

Table S1-S4

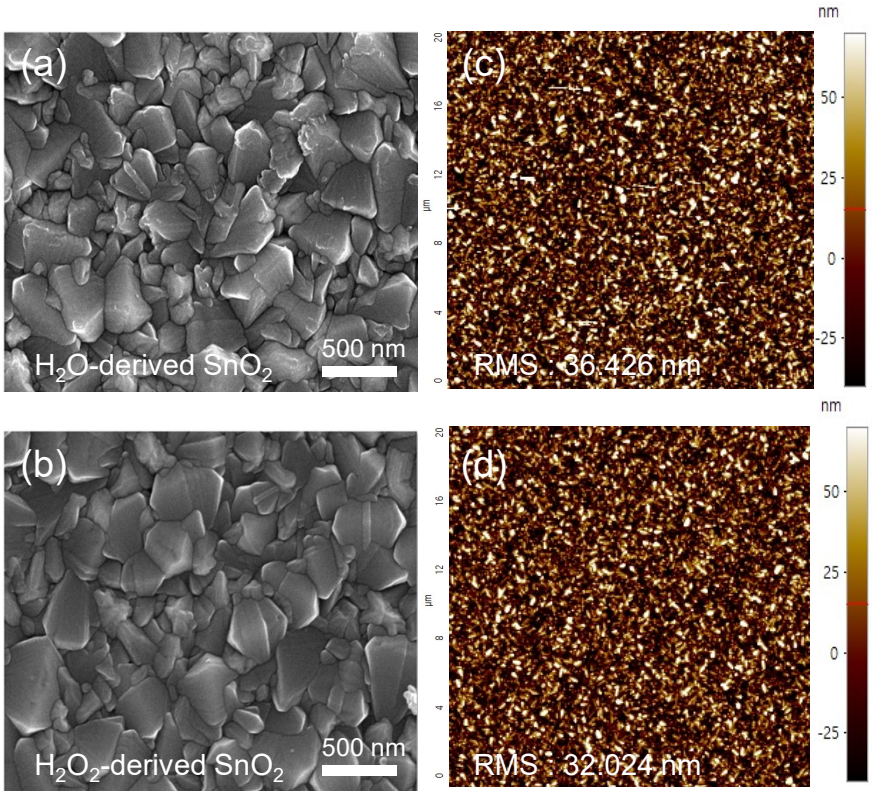

Figure S1. Top-view SEM images of (a) the H_2O-derived SnO_2 and (b) the H_2O_2-derived SnO_2 on the FTO substrate. AFM images of (c) the H_2O-derived SnO_2 and (d) the H_2O_2-derived SnO_2 on the FTO substrate. RMS is root mean square.

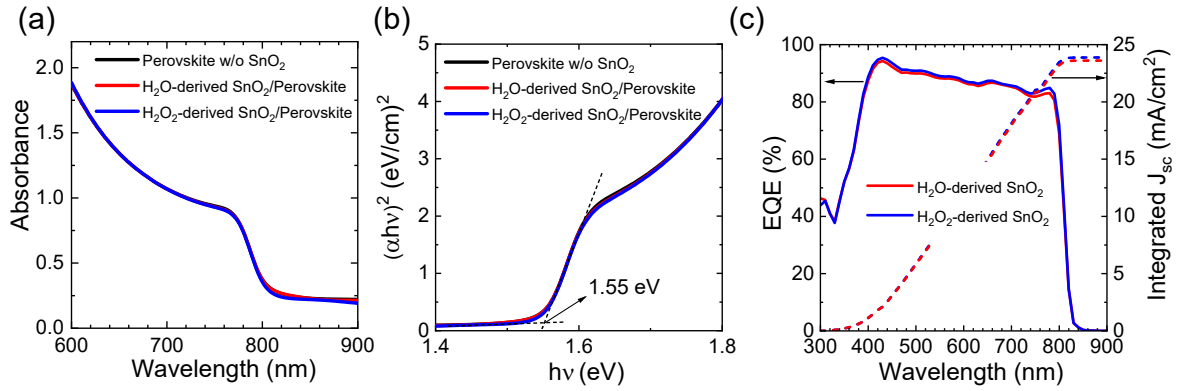

Figure S2. (a) Absorbance and (b) Tauc plot of the perovskite films without and with SnO_2 layer (H_2O-derived and H_2O_2-derived SnO_2). Films were deposited on a glass substrate. (c) External quantum efficiency (EQE) spectra and integrated J_{sc} of PSCs based on the H_2O-derived and H_2O_2-derived SnO_2.

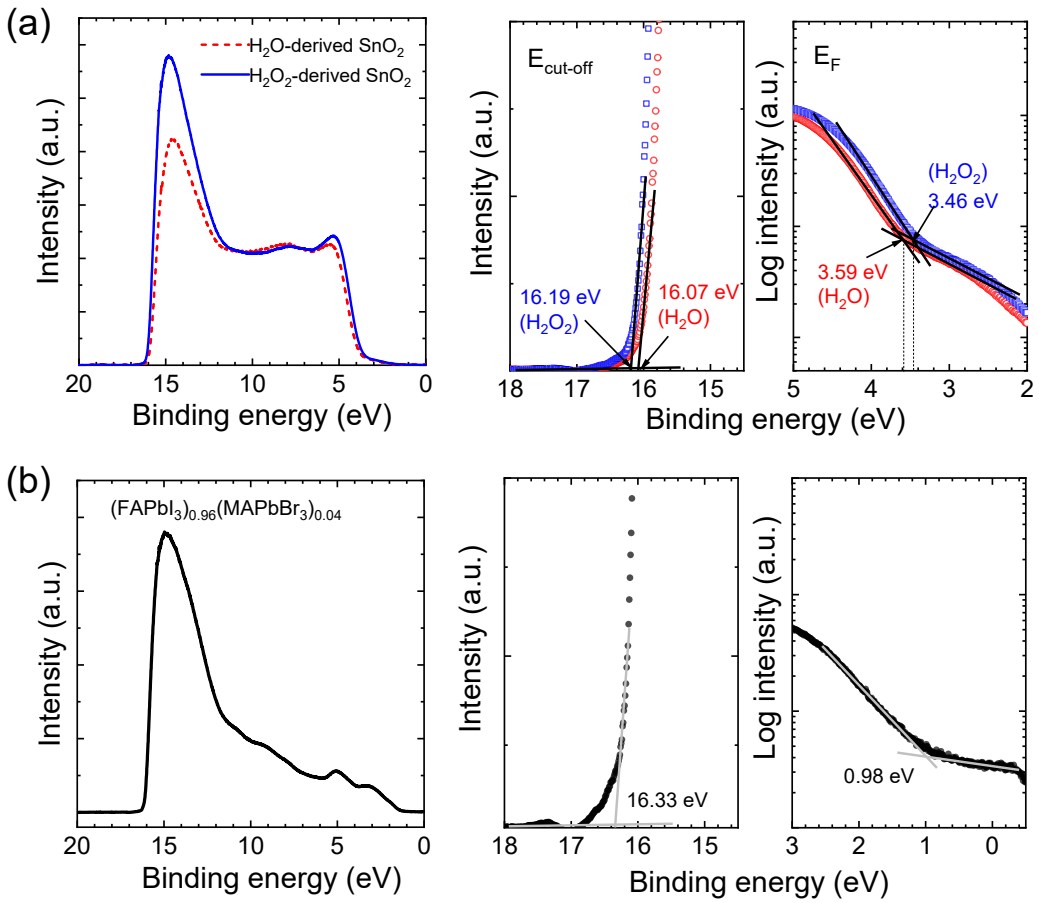

Figure S3. UPS spectra of (a) ALD-processed SnO_2 depending on oxygen source of H_2O and H_2O_2 and (b) $(FAPbI_3)_{0.96}(MAPbBr_3)_{0.04}$ perovskite, showing the full range (left panel), the cut-off energy (middle panel) and Fermi edge (middle panel).

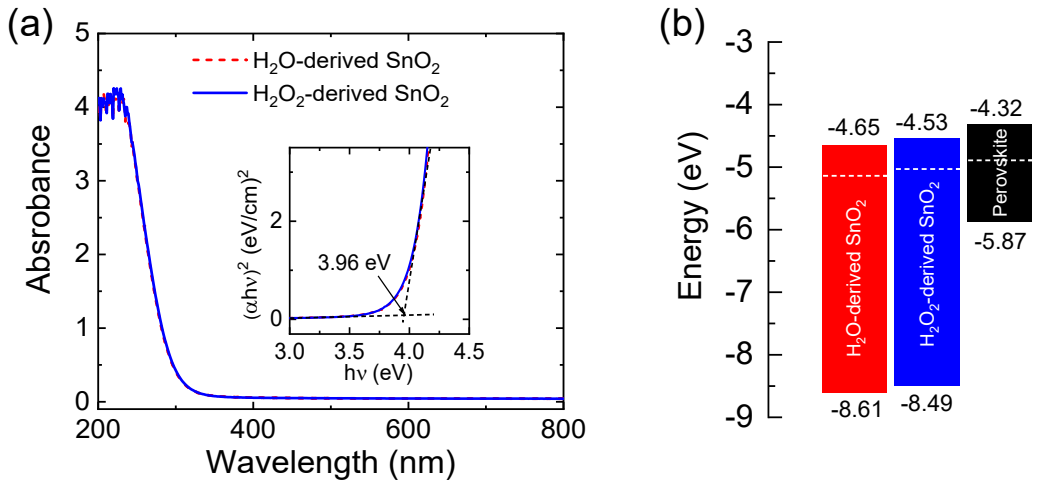

Figure S4. (a) UV-Vis spectra of the ALD-processed SnO_2 films deposited on a glass substrate. Inset shows Tauc plot. (b) Energy level diagram of the H_2O-derived SnO_2, H_2O_2-derived SnO_2, and perovskite layer based on the data obtained from UPS and UV-Vis spectroscopy.

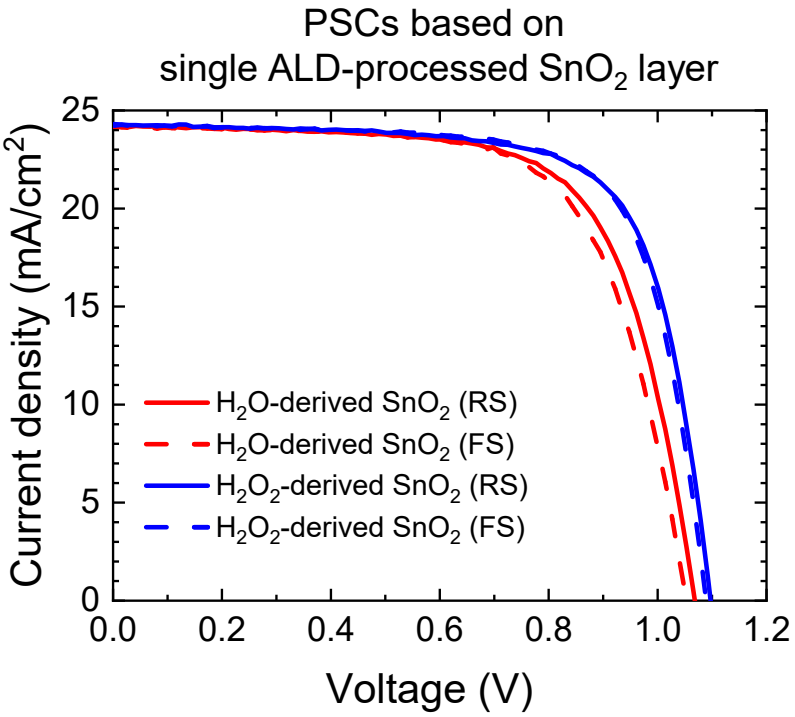

Figure S5. J-V curves of PSCs based on a single ALD-processed SnO_2 layer depending on oxygen source of H_2O and H_2O_2. FS (dashed lines) and RS (solid lines) represent the forward and reverse scanned data, respectively.

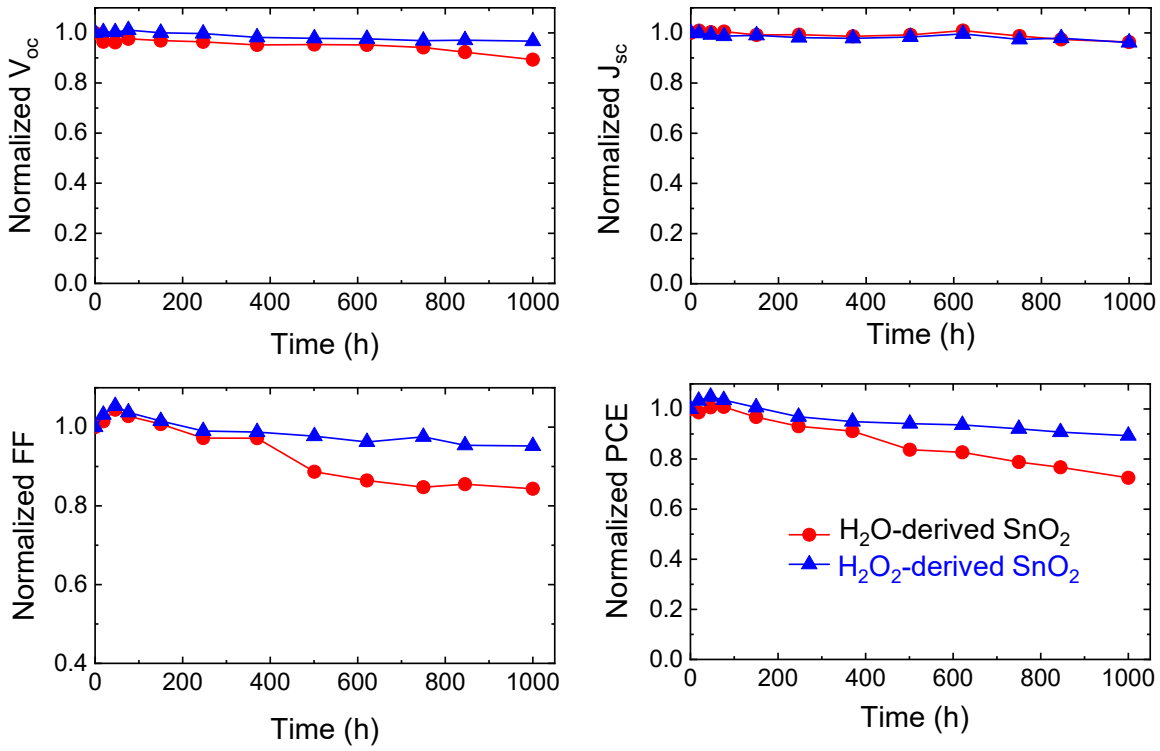

Figure S6. Storage stability showing normalized photovoltaic parameters of V_{oc}, J_{sc}, FF and PCE of PSCs based on the H_2O- and H_2O_2-derived SnO_2, measured for 1000 h under relative humidity of 30±10% at room temperature.

Table S1. Binding energies and arial ratio of O_{OH} peak to total peak in O 1s XPS spectra for the H_2O- and H_2O_2-derived SnO_2.

Sample	O 1s binding energy (eV)		Arial ratio of O_{OH} (%)
	O_{Sn}	O_{OH}	O_{OH} / O 1s
H_2O-derived SnO_2	530.68	532.08	25.47
H_2O_2-derived SnO_2	530.88	532.33	21.36

Table S2. Parameters for TRPL fitting using a biexponential decay equation with $I(t) = I_0 + A_1 \exp(-(t - t_0)/ \tau_1) + A_2 \exp(-(t - t_0)/\tau 2)$. Average lifetime ($\tau_{avg}$) was calculated by $\tau_{avg} = (A_1\tau_1^2 + A_2\tau_2^2) / (A_1\tau_1 + A_2\tau_2)$. Fitting reliability was confirmed by R^2.

	A_1 (%)	τ_1 (ns)	A_2 (%)	τ_2 (ns)	τ_{avg} (ns)	R^2
Glass/Perovskite	1702.34 (71.01%)	104.45	695.08 (28.99%)	1957.3	1743.1	0.984
Glass/H_2O-derived SnO_2/perovskite	301.81 (30.12%)	71.30	700.25 (69.88%)	486.69	462.02	0.995
Glass/H_2O_2-derived SnO_2/perovskite	266.78 (27.56%)	46.74	701.22 (72.44%)	390.27	375.30	0.996

Table S3. Photovoltaic parameters of short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and power conversion efficiency (PCE) of PSCs with the structure of FTO/ALD-SnO_2/$(FAPbI_3)_{0.96}(MAPbBr_3)_{0.04}$/Spiro-MeOTAD/Au.

ALD sample	Scan direction	J_{sc} (mA/cm^2)	V_{oc} (V)	FF (%)	PCE (%)
H_2O-derived SnO_2	Reverse	24.198	1.0685	0.6849	17.71
	Forward	24.179	1.0531	0.6738	17.16
H_2O_2-derived SnO_2	Reverse	24.299	1.0973	0.7159	19.09
	Forward	24.246	1.0891	0.7234	19.10

Table S4. Photovoltaic parameters of best-performing PSCs with the structure of FTO/bilayer (ALD-SnO_2/colloidal SnO_2)/$(FAPbI_3)_{0.96}(MAPbBr_3)_{0.04}$/Spiro-MeOTAD/Au.

Bilayer SnO_2 sample	Scan direction	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	PCE (%)
H_2O-derived SnO_2 / colloidal SnO_2	Reverse	24.073	1.1175	0.7961	21.42
	Forward	23.850	1.1140	0.7720	20.51
H_2O_2-derived SnO_2 / colloidal SnO_2	Reverse	24.112	1.1460	0.8085	22.34
	Forward	24.059	1.1348	0.8003	21.85

Table S5. Statistical photovoltaic parameters of PSCs employing a bilayer SnO_2 based on H_2O- and H_2O-derived SnO_2 as ETLs.

Bilayer SnO_2 sample	Scan direction	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	PCE (%)
H_2O-derived SnO_2 / colloidal SnO_2	Reverse	23.969 ±0.126	1.1200 ±0.010	0.7688 ±0.016	20.64 ±0.384
	Forward	24.068 ±0.090	1.0979 ±0.022	0.7673 ±0.014	20.28 ±0.545
H_2O_2-derived SnO_2 / colloidal SnO_2	Reverse	24.077 ±0.061	1.1352 ±0.013	0.7949 ±0.012	21.73 ±0.439
	Forward	24.095 ±0.090	1.1287 ±0.010	0.7837 ±0.012	21.31 ±0.244