Electronic Supplementary information (ESI)

Highly Efficient and Bending Durable Perovskite Solar Cells: Toward Wearable Power Source

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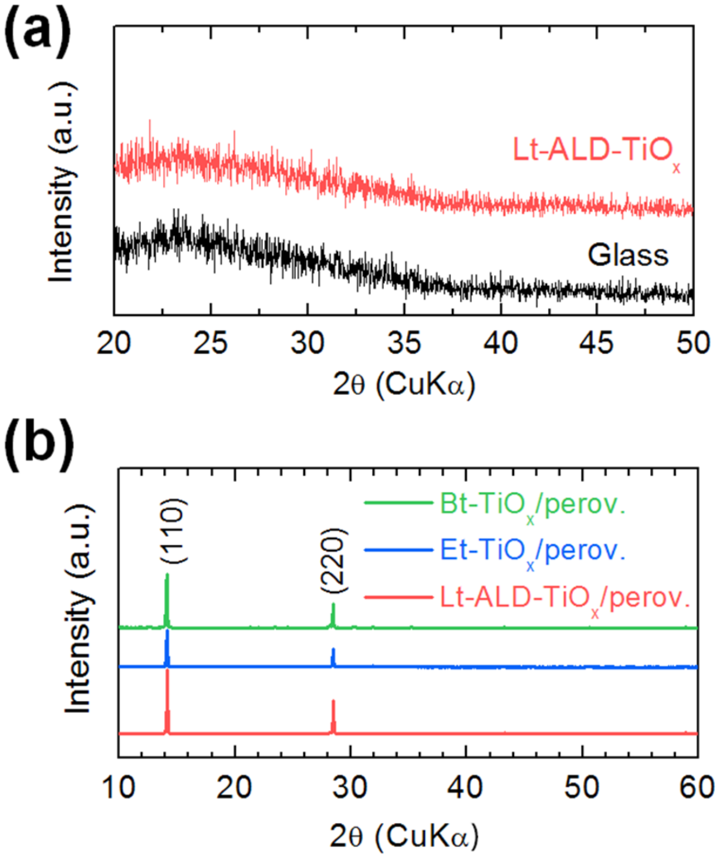


Fig. S1 X-ray diffraction (XRD) patterns of the materials. **(a)** Glazing incidence XRD patterns of Lt-ALD-TiO_x layer (100 nm) on glass substrate with the incident angle of 1.0^o. **(b)** Powder XRD patterns of the $CH_3NH_3PbI_{3-x}Cl_x$ layers on the different TiO_x layers.

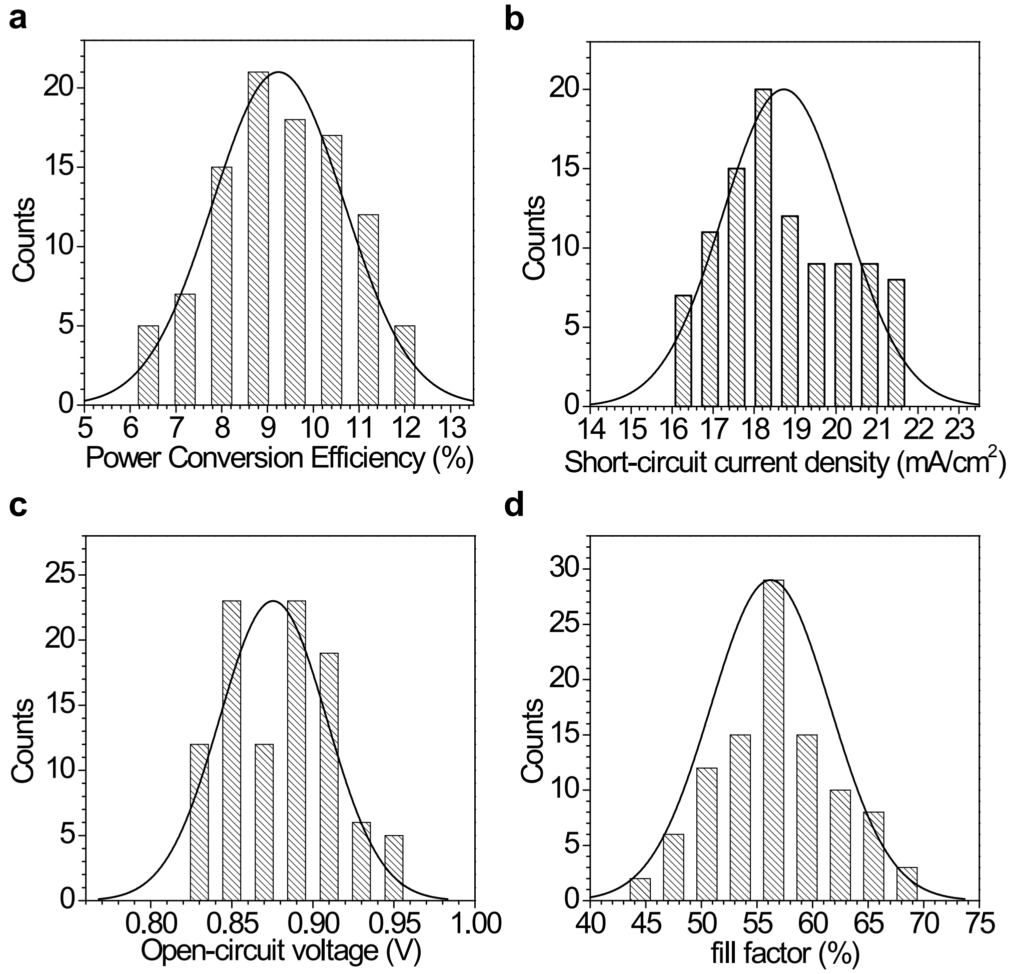
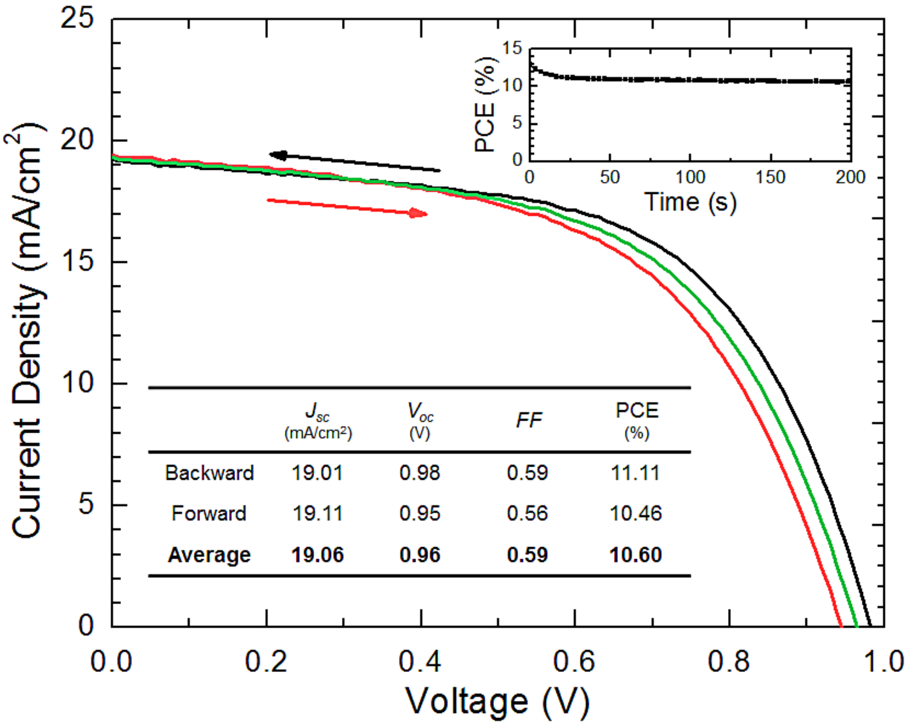


Fig. S2 Histograms of the parameters of the flexible solar cells employing Lt-ALD-TiO_x ultrathin layer. 100 devices were tested for the statistics. **(a)** Power conversion efficiency PCE, **(b)** short-circuit current density J_{sc}, **(c)** open-circuit voltage V_{oc}, and **(d)** fill factor FF.



	J_{sc} (mA/cm²)	V_{oc} (V)	*FF*	PCE (%)
Backward	19.01	0.98	0.59	11.11
Forward	19.11	0.95	0.56	10.46
Average	**19.06**	**0.96**	**0.59**	**10.60**

Fig. S3 Representative *J-V* curves of the perovskite solar cell (PEN/ITO/Lt-ALD-TiO_x/$CH_3NH_3PbI_{(3-x)}Cl_x$/spiro-MeOTAD/Ag) measured with the scan directions of forward (black) and reverse (red) with the scanning rate of 10 mV/s, under AM 1.5 G illumination. The green curve shows the average of two *J-V* curves. The inset tables summarize the parameters. The inset plot shows the static PCE, as a function of time, obtained with applying the maximum power output potential (i.e. 0.72 V, here), under AM 1.5 G illumination.

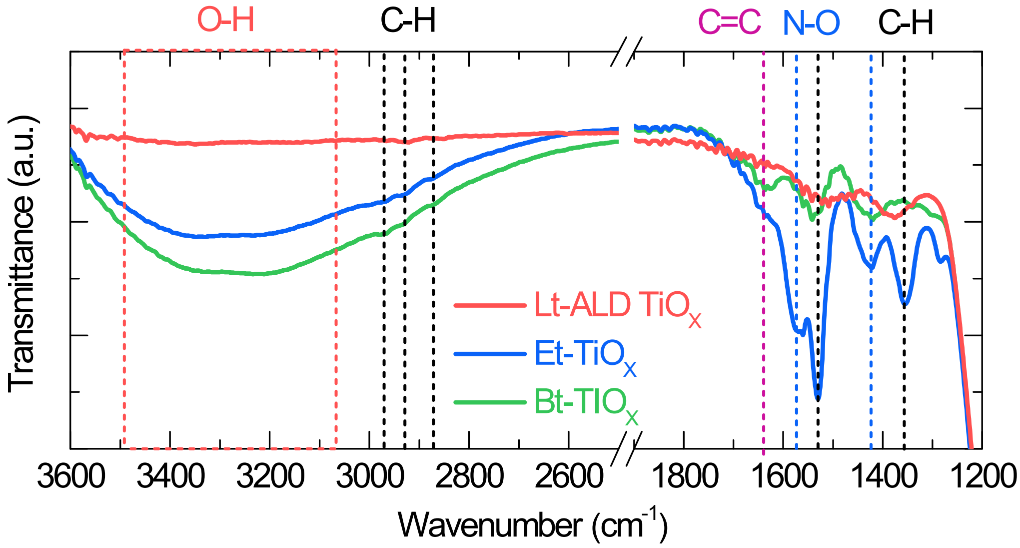


Fig. S4 FT-IR spectra (transmission mode) of Lt-ALD-, Et-, and Bt-TiO_x compact electron-collection layers prepared on Si wafer. The spectra were measured with Ge window.

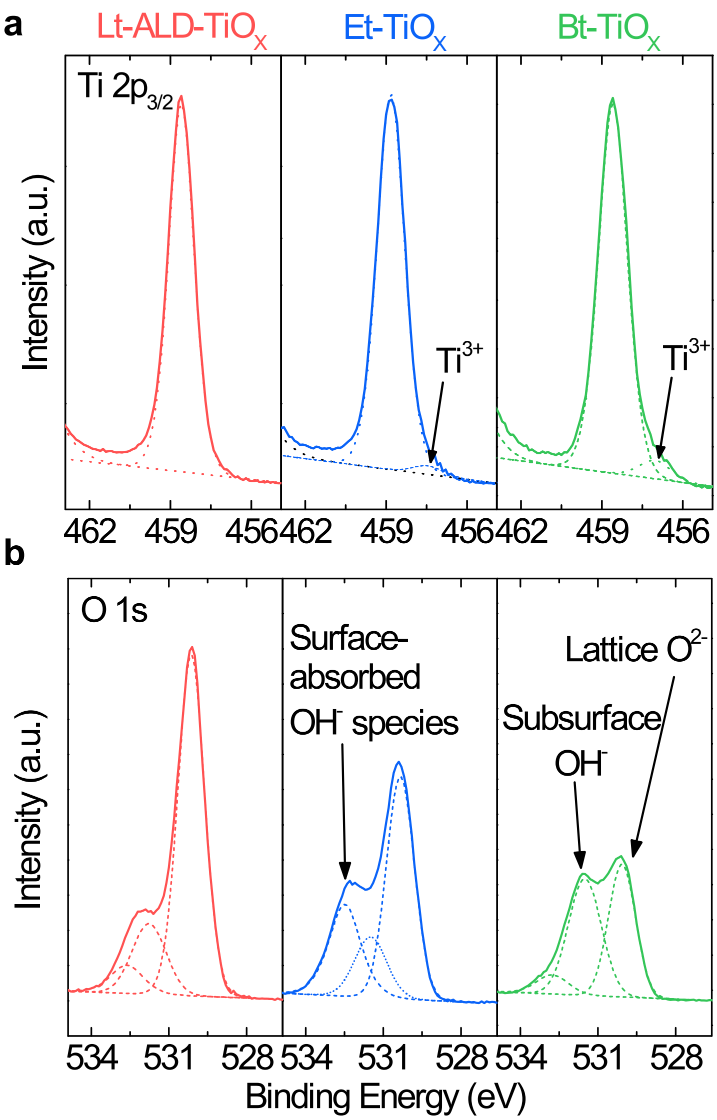


Fig. S5 XPS spectra of the Lt-ALD-, Et-, and Bt-TiO_x compact electron-collection layers. **(a)** Ti $2p_{3/2}$ and **(b)** O 1*s* of Lt-ALD-, Et-, and Bt-TiO_x compact electron-collection layers. The XP spectra were acquired using monochromatic Al–Kα radiation (100 W), and the core levels of O 1s and Ti $2p_{3/2}$ were calibrated with respect to the C 1s level at 284.5 eV.

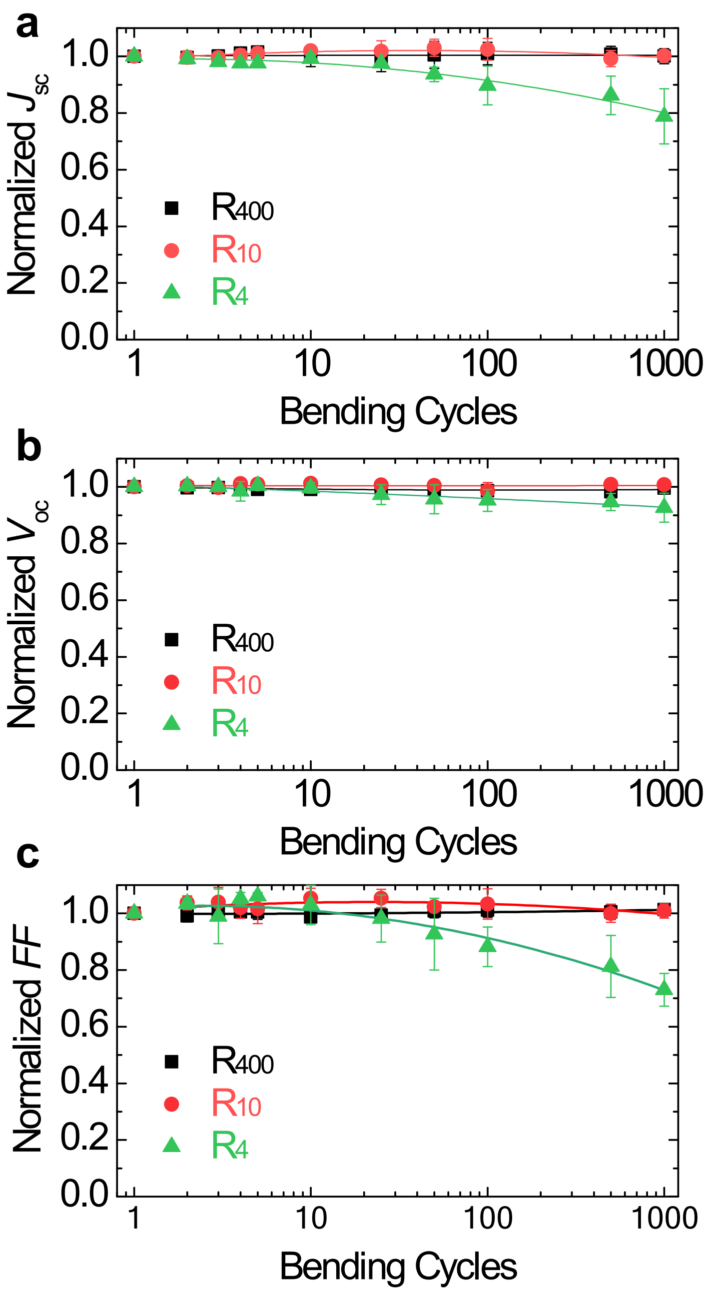


Fig. S6 Normalized device parameters of flexible perovskite solar cells as a function of bending cycles with diverse radii of 400, 10, and 4 mm (R_{400}, R_{10}, and R_4, respectively). **(a)** Normalized J_{sc}, **(b)** Normalized V_{oc} and **(c)** Normalized *FF*.

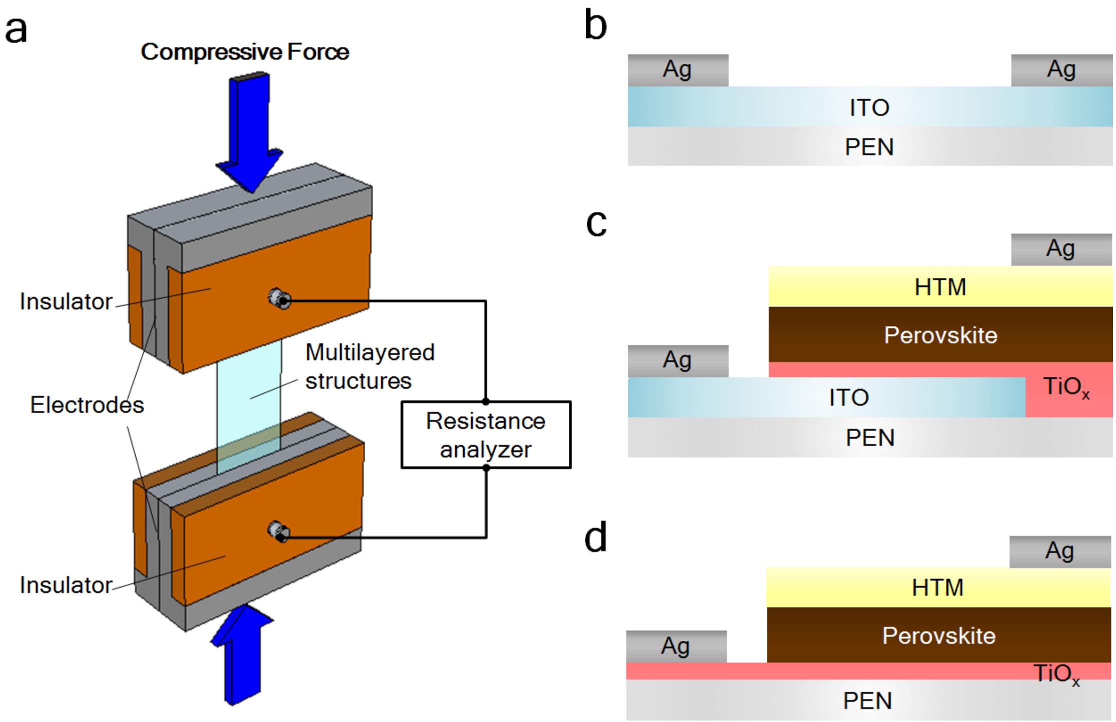


Fig. S7 Schematic images for in situ measurement of resistance and prepared multilayered structures. **(a)** Experimental scheme for in situ measurement of relative resistance change during the compressive bending cycle. **(b), (c) and (d)** Schematic of the designed multilayered structure: PEN/ITO/Ag, PEN/ITO/TiO_x/perovskite/spiro-MeOTAD/Ag, and PEN/TiO_x/perovskite/spiro-MeOTAD/Ag, respectively.

Table S1. Device characteristics of solar cells fabricated with various TiO_x electron collection layers.

TiO_x	J_{sc} (mA/cm^2)	V_{oc} (V)	*FF*	PCE (%)
Et-TiO_x	15.0	0.829	0.342	4.26
Bt-TiO_x	5.96	0.855	0.236	1.20
Lt-ALD-TiO_x	18.4	0.890	0.576	9.43

Table S2. Summary of the time-resolved photoluminescence lifetime parameters of PEN/ITO/TiO_x/$CH_3NH_3PbI_{(3-x)}Cl_x$ in Figure 2d (the samples were exposed to pulsed light for more than 1 hour to guarantee stable emission).

	A_1 (%)	t_1 (ns)	A_2 (%)	t_2 (ns)	A_3 (%)	t_3 (ns)	$\tau_{ave,int}$ (ns)
Et-TiO_x	9.27	29.4	25.4	139	65.3	418	383
Bt-TiO_x	9.26	27.9	33.5	143	57.3	488	435
Lt-ALD-TiO_x	7.68	43.8	16.8	121	75.5	561	537

A_i and t_i are amplitude ratio and lifetime of each component, respectively. Intensity weighted average lifetime was calculated by $\tau_{ave.\text{int}} = \frac{\sum_i A_i \tau_i^2}{\sum_i A_i \tau_i}$.