Supporting Information

SnO_2-Ti_3C_2 MXene electron transport layers for perovskite solar cells

Lin Yang[a], Yohan Dall'Agnese[a], Kanit Hantanasirisakul[b], Christopher E. Shuck[b], Kathleen Maleski[b], Mohamed Alhabeb[b], Gang Chen[a], Yu Gao[a], Yoshitaka Sanehira[c], Ajay Kumar Jena[c], Liang Shen[d], Chunxiang Dall'Agnese[a,*], Xiao-Feng Wang[a,*], Yury Gogotsi[a,b], Tsutomu Miyasaka[c]

[a] *Key Laboratory of Physics and Technology for Advanced Batteries (Ministry of Education), College of Physics, Jilin University, 2699 Qianjin Street, Changchun 130012, China*

[b] *A. J. Drexel Nanomaterials Institute, and Department of Materials Science and Engineering, Drexel University, Philadelphia, Pennsylvania 19104, United States*

[c] *Graduate School of Engineering, Toin University of Yokohama, 1614 Kurogane-cho, Aoba, Yokohama, Kanagawa 225-8503, Japan*

[d] *State Key Laboratory on Integrated Optoelectronics, College of Electronic Science and Engineering, Jilin University, 2699 Qianjin Street, Changchun 130012, China*

Corresponding Authors

* Chunxiang Dall'Agnese, *E-mail:* chunxiang@dallagnese.fr

* Xiao-Feng Wang, *E-mail:* xf_wang@jlu.edu.cn

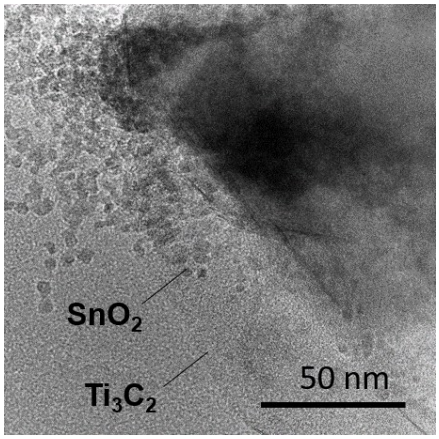

Figure S1. TEM image of SnO_2-Ti_3C_2 (1.0 wt.‰) nanocomposites.

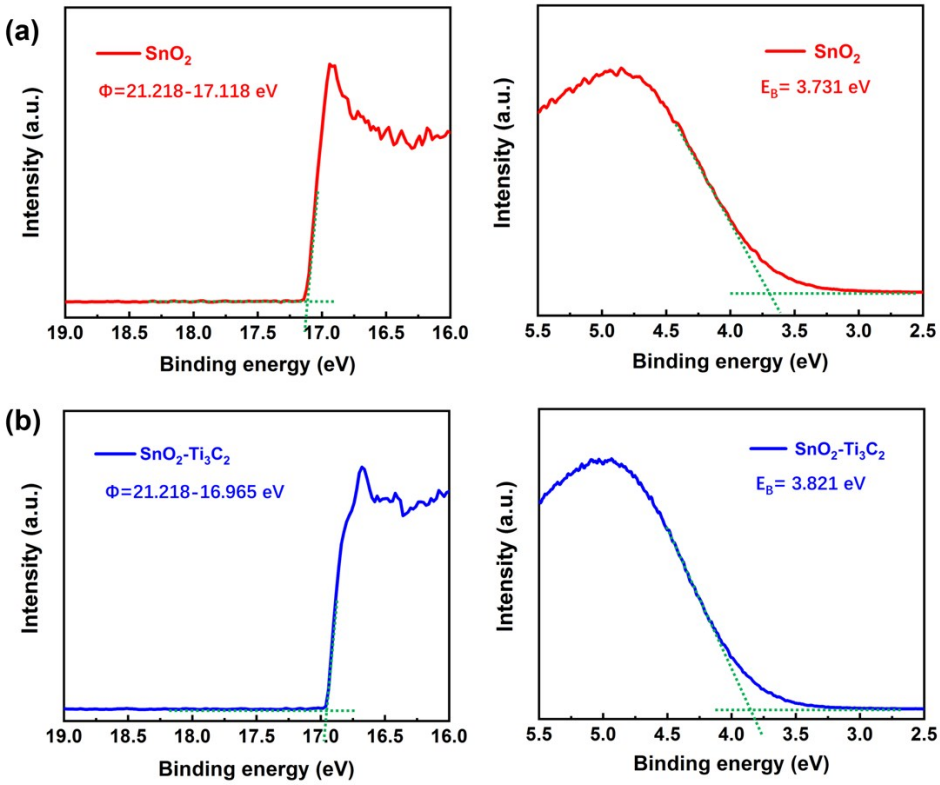

Figure S2. Ultraviolet photoelectron spectra of (a) SnO_2 and (b) SnO_2-Ti_3C_2 (1.0 wt.‰) films spin-coated onto ITO substrates. The HOMO energy levels were determined by the intersection of baseline with the tangent line of the spectra, that is, HOMO = – (Φ + E_B) (eV).

Table S1. Summary of the optoelectronic parameters of SnO_2 and SnO_2-Ti_3C_2 (1.0 wt.‰).

ETL	λ_{onset} (nm)	E_g (eV) [a]	HOMO (eV)	LUMO (eV) [b]
SnO_2	360	3.44	-7.83	-4.39
SnO_2-Ti_3C_2 (1.0 wt.‰)	360	3.44	-8.07	-4.63

[a] Calculated from the onset absorption: E_g (eV) = 1240 / λ_{onset} (nm).

[b] LUMO = HOMO + E_g.

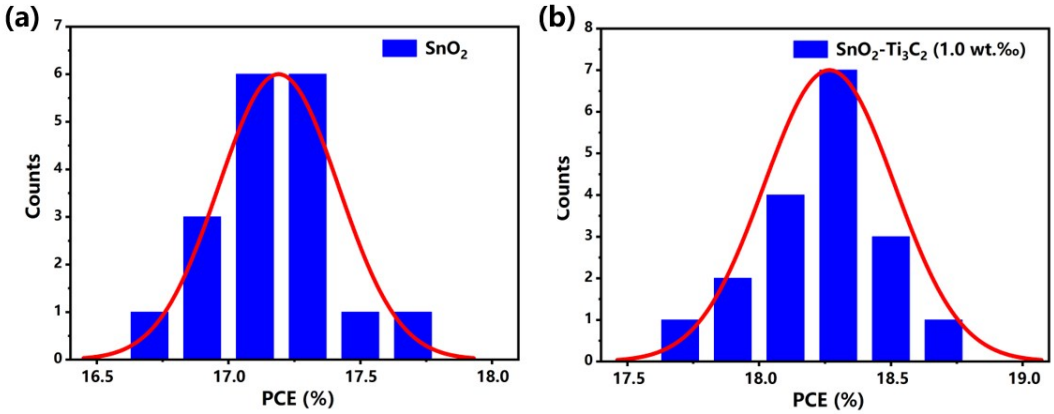

Figure S3. Histograms of power conversion efficiencies (PCE) measured for 18 cells using (a) SnO_2 and (b) SnO_2–Ti_3C_2 (1.0 wt.‰) ETLs, fitted with a Gaussian distribution (red line).

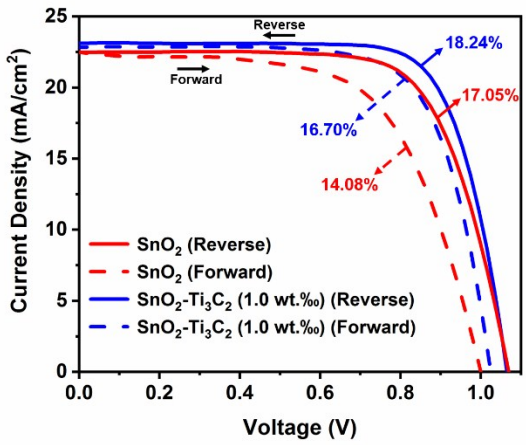

Figure S4. Forward and reverse scans of *J*–*V* curves for the devices based on SnO_2 and SnO_2-Ti_3C_2 (1.0 wt.‰) as ETLs.

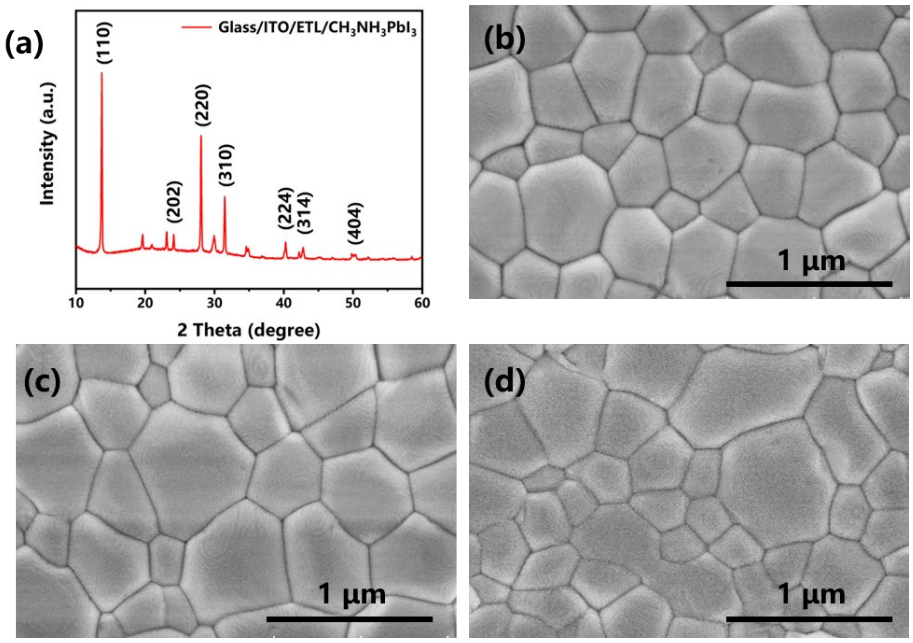

Figure S5. (a) X-ray diffraction pattern of Glass/ITO/ETL/$CH_3NH_3PbI_3$ films, (b-d) the top-view SEM images of perovskite layer coated onto ITO/SnO_2, ITO/SnO_2-Ti_3C_2 (1.0 wt.‰), and ITO/Ti_3C_2, respectively.

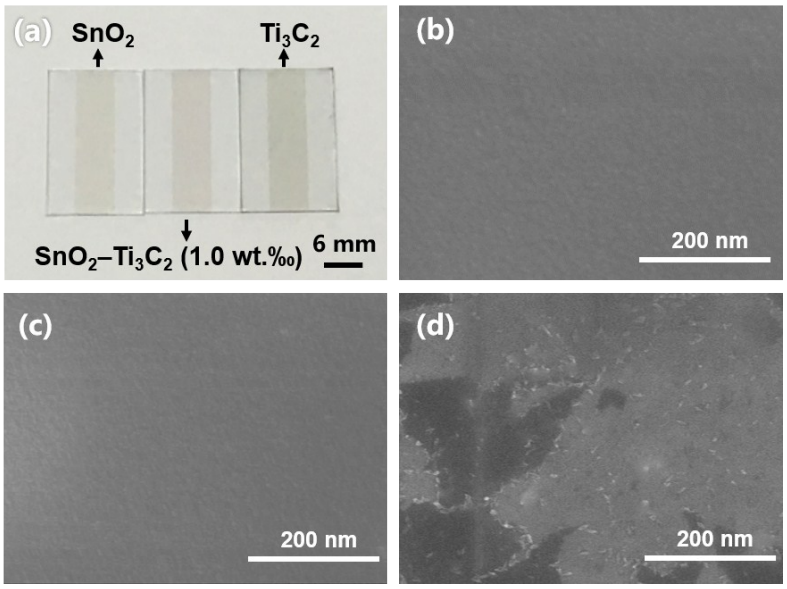

Figure S6. (a) The digital photo, and (b-d) top-view SEM images of SnO_2, SnO_2-Ti_3C_2 (1.0 wt.‰) and Ti_3C_2 films spin-coated on ITO substrates.

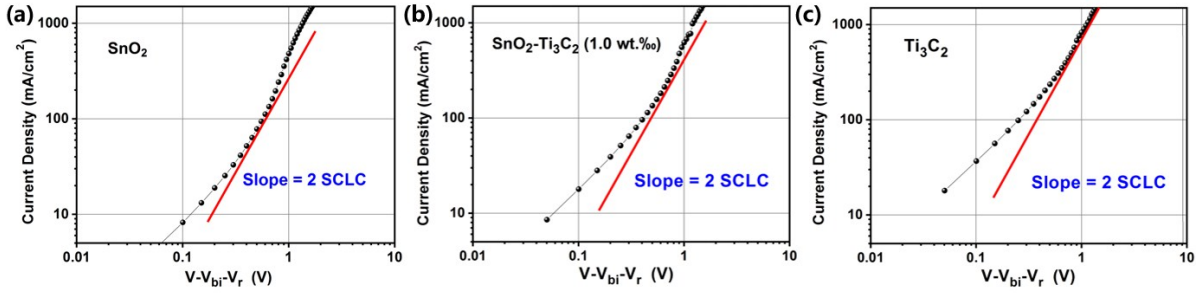

Figure S7. Typical *J–V* curves for the devices based on (a) SnO_2, (b) SnO_2 -Ti_3C_2 (1.0 wt.‰), and (c) Ti_3C_2 ETLs under dark, respectively.

The electron mobilities of ETLs were recorded by the *J-V* curves of electron-only device (ITO/TiO_2/ETL/BCP/Ag) under dark, and were calculated using the following equation [S1]:

$$J = 9\varepsilon_0\varepsilon_r\mu(V - V_{bi} - V_r)^2/8L^3$$

Where μ represents electron mobility ($cm^2\ V^{-1}\ s^{-1}$), J is the current density ($mA\ cm^{-2}$), ε_0 is the permittivity of free space ($mA\ s\ V^{-1}\ cm^{-1}$)), ε_r is the dielectric constant of ETLs (assumed as 3), V is the applied voltage (V), V_r is the voltage drop (V) due to the series resistance and contact resistance across the electrodes, V_{bi} is the built-in voltage (V), V-V_{bi}-V_r is obtained through a slope in the double log plot equals to 2, and L represents the thickness of ETLs film (cm).

Table S2. Fitting parameters for EIS data shown in Figure 5d.

ETL	R_s (Ω)	R_{rec} (Ω)	C (F)
SnO_2	50.54	381.8	6.439E-9
SnO_2 -Ti_3C_2 (1.0 wt.‰)	46.16	215.6	5.631E-8
Ti_3C_2	44.29	197.1	9.862E-9

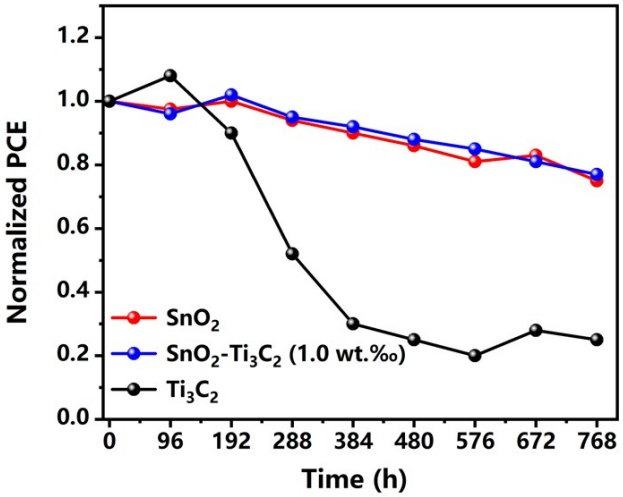

Figure S8. Stabilities of the SnO_2-, SnO_2–Ti_3C_2 (1.0 wt.‰)- and Ti_3C_2- based PSC devices exposed to ambient air without encapsulation.

Reference

S1. J. Song, E. Zheng, X.-F. Wang, W. Tian and T. Miyasaka, *Sol. Energy Mater. Sol. Cells*, 2016, **144,** 623-630.