Supporting Information

SnO₂-Ti₃C₂ MXene electron transport layers for perovskite solar cells

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Figure S1. TEM image of SnO$_2$-Ti$_3$C$_2$ (1.0 wt.%) nanocomposites.

Figure S2. Ultraviolet photoelectron spectra of (a) SnO$_2$ and (b) SnO$_2$-Ti$_3$C$_2$ (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$_3$C$_2$ (1.0 wt.‰).

<table>
<thead>
<tr>
<th>ETL</th>
<th>$\lambda_{\text{onset}}$ (nm)</th>
<th>$E_g$ (eV) $^a$</th>
<th>HOMO (eV)</th>
<th>LUMO (eV) $^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SnO$_2$</td>
<td>360</td>
<td>3.44</td>
<td>-7.83</td>
<td>-4.39</td>
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<tr>
<td>SnO$_2$–Ti$_3$C$_2$ (1.0 wt.‰)</td>
<td>360</td>
<td>3.44</td>
<td>-8.07</td>
<td>-4.63</td>
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</tbody>
</table>

$^a$ Calculated from the onset absorption: $E_g$ (eV) = 1240 / $\lambda_{\text{onset}}$ (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$_3$C$_2$ (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$_3$C$_2$ (1.0 wt.‰) as ETLs.
Figure S5. (a) X-ray diffraction pattern of Glass/ITO/ETL/CH$_3$NH$_3$PbI$_3$ films, (b-d) the top-view SEM images of perovskite layer coated onto ITO/SnO$_2$, ITO/SnO$_2$-Ti$_3$C$_2$ (1.0 wt.%), and ITO/Ti$_3$C$_2$, respectively.

Figure S6. (a) The digital photo, and (b-d) top-view SEM images of SnO$_2$, SnO$_2$-Ti$_3$C$_2$ (1.0 wt.%) and Ti$_3$C$_2$ films spin-coated on ITO substrates.
Figure S7. Typical $J-V$ curves for the devices based on (a) SnO$_2$, (b) SnO$_2$-Ti$_3$C$_2$ (1.0 wt.%), and (c) Ti$_3$C$_2$ 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 $\mu$ represents electron mobility (cm$^2$ V$^{-1}$ s$^{-1}$), $J$ is the current density (mA cm$^{-2}$), $\varepsilon_0$ is the permittivity of free space (mA s V$^{-1}$ cm$^{-1}$), $\varepsilon_r$ 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.

<table>
<thead>
<tr>
<th>ETL</th>
<th>$R_s$ (Ω)</th>
<th>$R_{rec}$ (Ω)</th>
<th>C (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SnO$_2$</td>
<td>50.54</td>
<td>381.8</td>
<td>6.439E-9</td>
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<td>SnO$_2$-Ti$_3$C$_2$ (1.0 wt.%)</td>
<td>46.16</td>
<td>215.6</td>
<td>5.631E-8</td>
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<td>Ti$_3$C$_2$</td>
<td>44.29</td>
<td>197.1</td>
<td>9.862E-9</td>
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</table>
Figure S8. Stabilities of the SnO$_2^-$, SnO$_2$–Ti$_3$C$_2$ (1.0 wt.%)- and Ti$_3$C$_2$- based PSC devices exposed to ambient air without encapsulation.

Reference