Aroused by the research on graphene in recent years, two-dimensional (2D) layered transition metal dichalcogenides (LTMDs) have attracted intensive attention because of their unique physical and chemical properties. Molybdenum disulfide (MoS$_2$), as a typical 2D LTMD material, has attracted intensive attention recently due to its desirable electronic structure. Specifically, the sandwiched S–Mo–S layers in a hexagonally packed MoS$_2$ lattice are held together by weak van der Waals bonds. In addition, compared with bulk MoS$_2$, more active sites can be found on the edges of MoS$_2$ nanosheets. Owing to its unique structure and properties, MoS$_2$ has been employed in diverse fields such as transistors, photodetectors, Li-ion batteries, and dye-sensitized solar cells. Owing to its unique structure and properties, MoS$_2$ has been employed in diverse fields such as transistors, photodetectors, Li-ion batteries, and dye-sensitized solar cells.

To directly grow ultrathin MoS$_2$ atomic layers with extraordinary properties on the desired substrate. Therefore, it is desirable to look for greatly simplifying approaches for directly preparing layered MoS$_2$ atomic layers with extraordinary properties on the desired substrate.

In this study, we report a one-step and low-cost solution-phase method to directly fabricate large-area ultrathin MoS$_2$ nanofilms on a fluorine-doped tin oxide (FTO) glass substrate. This study, we report a one-step and low-cost solution-phase method to directly fabricate large-area ultrathin MoS$_2$ nanofilms on a fluorine-doped tin oxide (FTO) glass substrate.
8.3%, which was better than that of the DSSCs based on platinized counter electrodes.

Fig. 1a shows a typical scanning electron microscopy (SEM) image of a commercial FTO glass substrate; the clean surface is covered by tin dioxide (SnO$_2$) nanocrystals. Different from the pristine FTO glass, MoS$_2$ nanofilms were found covering the substrates of the MoS$_2$-5 and MoS$_2$-10 samples after reaction times of 5 h and 10 h, respectively (Fig. 1b and c). Meanwhile, the coverage of MoS$_2$ nanofilms highly increased as the reaction time increased from 5 h to 10 h. Fig. 1d shows the SEM image of a MoS$_2$-15 sample; the whole surface of the FTO glass is uniformly covered by ultrathin MoS$_2$ nanofilms, which is beneficial for its application as a counter electrode in DSSCs. In principle, the area of the FTO substrate covered with as-grown MoS$_2$ nanofilms is only limited by the diameter of the autoclave, which can be easily scaled up by increasing the size of the autoclave. Fig. S1† shows optical images of the pristine FTO substrate and the MoS$_2$-15 sample with a large area of 4 cm × 4 cm.

To further characterize the structural features of ultrathin MoS$_2$ nanofilms, transmission electron microscopy (TEM) and high-resolution TEM (HRTEM) studies were performed on the MoS$_2$-15 nanofilm. Fig. 2a shows a typical TEM image of the MoS$_2$-15 nanofilm loaded on a TEM grid, which reveals that most areas of the MoS$_2$ nanofilm are very uniform and with a flat and smooth surface. Fig. 2b displays a HRTEM image of the MoS$_2$-15 nanofilm; the cross-section of the MoS$_2$ nanofilm can be clearly observed and indicates a thickness of only a few atomic layers. The distance between two adjacent atomic planes is 0.62–0.63 nm, which is in accordance with the interplanar distance of the (002) planes of crystalline hexagonal MoS$_2$.

To identify the compositions of MoS$_2$-x nanofilms ($x = 5, 10, 15$), the characterization of X-ray photoelectron spectroscopy (XPS) was carried out, as shown in Fig. 3a. The C 1s peak, which can be found in all three samples and is generally believed to have arisen from the adventitious carbon caused by exposure to the atmosphere, is used as the standard for binding energy calibration. With the energy of the C 1s peak set at 284.6 eV, the energy of each peak in the three samples was determined. Besides the C 1s peak, the spectra are dominated by the photoelectron peaks of Sn, O, Mo, and S. Among them, the peaks of Sn and O are derived from the SnO$_2$ film on the FTO glass substrates. The binding energies of Mo 3d$_{3/2}$, Mo 3d$_{5/2}$, S 2p$_{3/2}$, and S 2p$_{1/2}$ are located at 231.5 ± 0.2, 228.2 ± 0.3, 162.2 ± 0.2, and 161.1 ± 0.3 eV, respectively, which are in agreement with previous studies and confirm that the chemical composition of the as-obtained nanofilm is MoS$_2$. Much weaker peaks of Mo and S can be found in the XPS spectrum of MoS$_2$-5 compared to MoS$_2$-10 and MoS$_2$-
15, indicating that the amount of MoS₂ is lower, which is ascribed to the shorter reaction time and lower surface coverage. On increasing the reaction time, higher Mo and S peaks can be found in the corresponding MoS₂-15 sample, because more areas on the surface of the FTO glass substrate are covered by the MoS₂ nanofilm, which is also in accordance with the SEM image (Fig. 1d).

The results acquired from Raman spectroscopy (Fig. 3b) also confirmed the growth of MoS₂ nanofilms. From MoS₂-5 to MoS₂-15, the Raman peaks emerging at 378 and 405 cm⁻¹ correspond to the E₂g¹ and A₁g modes of MoS₂ respectively. The intensity of E₂g¹ and A₁g modes rise from minimal to high as the reaction time increases, indicating that more MoS₂ nanofilms are grown on FTO glass substrates. The two Raman peaks also provide insights into the structure of the MoS₂ nanofilm. The E₂g¹ mode, also called the in-plane Mo–S phonon mode, was excited from the terrace-terminated film, while the A₁g mode, also called the out of plane Mo–S phonon mode, was excited for the edge-terminated film.⁴⁰ The relative integral peak intensity of these two phonon modes can give some texture information of the layered MoS₂ nanofilms. As shown in the Raman spectrum of MoS₂-15 (Fig. 3b), the integral intensity of the A₁g mode is twice that of the E₂g¹ mode, indicating that the vibration of the A₁g mode is predominant in the layered MoS₂ nanofilms. Fig. 3c shows the XRD patterns of pristine FTO glass and MoS₂-x nanofilms, respectively. The characteristic peaks of MoS₂ are very weak, owing to the ultra-thin thickness. The intensity of FTO peaks decreases as the growth time increases, indicating that more and more area of the FTO substrate is covered by MoS₂; thus some XRD signals of FTO are concealed.

The platinized-FTO glass and MoS₂-x covered FTO glass counter electrodes were respectively assembled into DSSCs (Fig. 4a), and their current density–voltage (J–V) characteristics were measured. The photovoltaic performance was characterized by four important parameters, including short-circuit density (J_sc), open-circuit voltage (V_oc), fill factor (FF), and conversion efficiency (η). Fig. 4b shows the J–V plots of the DSSCs using the pristine FTO, platinized-FTO and MoS₂-x covered FTO glass substrates as the counter electrodes under illumination, respectively. The corresponding measured photovoltaic parameters are listed in Table 1. The DSSC with a pristine-FTO glass counter electrode displays a very poor photovoltaic performance, because the pristine FTO electrode has little catalytic activity for tri-iodide reduction. In contrast, the DSSCs based on platinized-FTO and MoS₂-x covered FTO glass electrodes exhibit much better photovoltaic performances. The Pt-based DSSC has a J_sc of 13.77 mA cm⁻², a V_oc of
0.74 V, an FF of 0.74, and a η of 7.53%. For the three MoS2-x based DSSCs, they show gradually improved photovoltaic performances as the growth time x increases, which is ascribed to the increased coverage of MoS2 nanofilms grown on the surface of the FTO glass. Compared with the Pt-based DSSC, all three MoS2-x based DSSCs exhibit comparable V OC, smaller FF, but much larger J SC, which results in an excellent η of 6.0%–8.3%. These values are equivalent to or even higher than that of the Pt-based DSSC. The highest η among these different DSSCs is obtained from the DSSC based on the MoS2 nanofilms with the longest growth time (MoS2-15).

Table 1 Photovoltaic parameters and EIS parameters of the DSSCs using pristine, platinized, MoS2-5 based, MoS2-10 based, and MoS2-15 based FTO glass substrates as the counter electrodes

<table>
<thead>
<tr>
<th>Electrodes</th>
<th>JSC (mA cm⁻²)</th>
<th>VOC (V)</th>
<th>FF</th>
<th>η (%)</th>
<th>R{s}/Ω</th>
<th>R{ct}/Ω</th>
<th>C/µF</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTO</td>
<td>6.59</td>
<td>-0.68</td>
<td>0.05</td>
<td>0.24</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Pt</td>
<td>13.77</td>
<td>-0.74</td>
<td>0.74</td>
<td>7.53</td>
<td>36.3</td>
<td>13.1</td>
<td>3.9</td>
</tr>
<tr>
<td>MoS2-5</td>
<td>15.77</td>
<td>-0.76</td>
<td>0.52</td>
<td>5.96</td>
<td>50.9</td>
<td>118.8</td>
<td>1.8</td>
</tr>
<tr>
<td>MoS2-10</td>
<td>15.94</td>
<td>-0.71</td>
<td>0.63</td>
<td>7.14</td>
<td>50.4</td>
<td>21.2</td>
<td>2.8</td>
</tr>
<tr>
<td>MoS2-15</td>
<td>16.96</td>
<td>-0.74</td>
<td>0.66</td>
<td>8.28</td>
<td>38.8</td>
<td>12.9</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Fig. 4 (a) Schematic diagram of a DSSC with a counter electrode based on MoS2 nanofilms. J–V plots of DSSCs using pristine, platinized, MoS2-5 based, MoS2-10 based, and MoS2-15 based FTO glass substrates as counter electrodes under (b) full light conditions and (c) dark conditions, respectively. (d) Nyquist plots of DSSCs using pristine, platinized, MoS2-5 based, MoS2-10 based, and MoS2-15 based FTO glass substrates as the counter electrodes under dark conditions. (e) Linear fitting of the capacitive current densities of Pt-based and MoS2-15-based counter electrode, respectively. (f) CV curves of Pt-based, MoS2-10 based, and MoS2-15 based counter electrodes for iodide species at a scanning rate of 100 mV s⁻¹.
electrode. This result is also revealed by the EIS analysis, as shown in Fig. 4d. Thus, in the MoS2-based DSSCs, the increased series resistance results in low FF, especially in MoS2-5 based and MoS2-10 based DSSCs. $J_{SC}$ is another important factor for the photovoltaic performance of a DSSC. In Fig. 4b and Table 1, the $J_{SC}$ values of the three MoS2-based DSSCs are larger than that of the Pt-based DSSC. The corresponding DSSC of the MoS2-15 based counter electrode displays the highest $J_{SC}$. This may have resulted from the large surface area of the MoS2 nanofilm owing to its 2D layered structure, which makes the oxidized species in the electrolyte rapidly and effectively capture electrons at the counter electrode/electrolyte interface, leading to a significant decrease of charge recombination and the corresponding increase of $J_{SC}$. Accordingly, because the increase in $J_{SC}$ is much more remarkable than the decrease in FF, the efficiency of DSSC is considerably enhanced by using the MoS2-15 covered FTO glass as the counter electrode.

To obtain better insight into the kinetics of the interfacial charge transfer process within the DSSCs, the EIS was measured. Fig. 4d shows the Nyquist plots of the DSSCs using the above-mentioned five kinds of different counter electrodes under dark conditions. Without any catalyst (Pt or MoS2) coated on the FTO glass, the pristine FTO glass-based DSSC displays the worst charge transfer performance among these DSSCs. Typically, the onset point of the first semicircle in the high frequency region corresponds to the Ohmic series resistance of the substrate ($R_s$). The semicircle in the low-frequency region corresponds to the charge transfer at the interface of the TiO2/dye/electrolyte, and the semicircle in the high-frequency region is attributed to the charge transfer at the interface of the counter electrode/electrolyte, including the charge transfer resistance ($R_{ct}$) and the corresponding capacitance ($C_{dt}$) at the interface of the counter electrode/electrolyte. To estimate the resistance parameters at the interface of the counter electrode/electrolyte of the Pt-based and all three MoS2-based DSSCs, the raw data were fitted using the Z-view software with the equivalent circuit (Fig. S2†) and the corresponding parameters are listed in Table 1. As mentioned above, due to the semiconductive characteristics of MoS2, the $R_s$ values of the three MoS2-based DSSCs are larger than that of the Pt-based DSSC. However, the MoS2-15 based DSSC shows a comparable $R_s$ value relative to the Pt-based DSSC, owing to the large-area and continuous MoS2 nanofilms uniformly covered on the substrate. The $R_s$ value of the MoS2-5 based DSSC is 118.8 Ω, which is much larger than that of the MoS2-10 based DSSC (21.2 Ω). This is mainly due to the higher MoS2 coverage of the MoS2-10 based counter electrode than that of the MoS2-5 based counter electrode, as confirmed by SEM (Fig. 1), XPS (Fig. 3a), and Raman results (Fig. 3b). The MoS2-15 based DSSC has a slightly lower $R_s$ value (12.9 Ω) than the Pt-based DSSC (13.1 Ω), indicating that the MoS2-15 based counter electrode has superior electrocatalytic activity compared to all other counter electrodes, including the Pt-based counter electrode. $C_{dt}$ is expected to be proportional to the specific surface area. Therefore, a larger $C_{dt}$ value refers to a larger catalytically-active surface area and thereby refers to a better electrocatalytic activity at the interface of the electrode/electrolyte. Table 1 shows that the $C_{dt}$ of MoS2-x based DSSCs increases as x increases, and finally reaches the largest value in MoS2-15 based DSSC. This is because most of the area of the FTO substrate on the MoS2-15 based electrode is covered by MoS2 nanofilms when compared to MoS2-5 and MoS2-10 (Fig. 1). Furthermore, the $C_{dt}$ value of MoS2-15 based DSSC is higher than that of Pt-based DSSC, suggesting that the MoS2-15 based counter electrode possesses a larger catalytically-active surface area than the Pt-based counter electrode, and thus the MoS2-15 based counter electrode displays a higher electrocatalytic activity towards tri-iodide reduction. Moreover, the Nyquist plots of MoS2-15 based DSSC under illumination were also recorded, as shown in Fig. S3.† Compared with the results under dark conditions, the impedance at the interface of the counter electrode/electrolyte becomes slightly smaller under illumination, while the charge transfer at the interface of the TiO2/dye/electrolyte changes a lot. This can be ascribed to the small recombination resistance owing to the introduction of light, especially at the interface of the TiO2/dye/electrolyte.

In order to exclude the working electrode effect, a symmetrical electrochemical cell with the structure of MoS2-15/electrolyte/MoS2-15 was fabricated and used for EIS analysis. Fig. S4† shows the Nyquist plot of the symmetrical electrochemical cell. The equivalent circuit diagram for fitting the EIS curve is shown in Fig. S4b.† Like the EIS result of the corresponding DSSC, the high-frequency semicircle in the EIS of the symmetrical electrochemical cell reveals the charge transfer process at the electrode/electrolyte interface. The fitting results of the Nyquist plot in Fig. S4a are shown in Table S1.† The EIS parameters of 2$R_s$, 2$R_{ct}$, and 1/2$C_{dt}$ are found to be 52.5 Ω, 10.1 Ω, and 16.1 μF, respectively, which are comparable with the EIS data of the MoS2-15 based DSSC (Table 1) and further confirm the superior electrocatalytic activity of the MoS2-15 based counter electrode.

An effective surface area is an important factor for the estimation of catalytic activity. Normally, the effective surface area is expected to be linearly proportional to the electrochemical double layer capacitance. The relative effective surface areas of Pt-based and MoS2-15 based counter electrodes were measured by the CV method in 0.5 M H2SO4 aqueous solution, as shown in Fig. S5a and b.† The electrochemical double layer capacitances can be estimated from the slopes of the curves in Fig. 4e, which represent the halves of the positive and negative current density differences at the center of the potential ranges vs. the voltage scan rates. Clearly, the capacitance of the MoS2-15 based counter electrode is much larger than that of the Pt-based counter electrode within the same potential range. This indicates that the MoS2-15 based counter electrode has a larger effective surface area than the Pt-based counter electrode, which is beneficial for its catalytic activity towards tri-iodide reduction.

To further investigate the electrocatalytic activity for tri-iodide reduction, CV curves of the platinized-FTO, MoS2-10
based and MoS_{2-15} based FTO counter electrodes were measured using a three-electrode system at a scanning rate of 100 mV s\(^{-1}\), respectively (Fig. 4f). For all three CV curves, two pairs of redox peaks were observed. The left peak pair represents the redox transition between I\(^3^-\) and I\(^-\), while the right peak pair represents the I\(^2^-\)I\(^3^-\) transition.\(^{30}\) The electrocatalytic activity of the counter electrode material in a DSSC is directly related to the oxidation–reduction peaks on the left. Typically, the cathodic and anodic peaks on the left can be assigned to the reduction of I\(^3^-\) and the oxidation of I\(^-\), respectively. As shown in Fig. 4f, the MoS\(_2\)-10 based and MoS\(_2\)-15 based counter electrodes show similar anodic and cathodic peaks compared to the Pt-based counter electrode, which indicates that these three electrodes are almost equally effective for tri-iodide reduction. The peak-to-peak separation (\(E_{pp}\)) and peak current densities of the left peak pair are two important parameters for analyzing the catalytic activity of the counter electrodes. The \(E_{pp}\) values of the Pt based, MoS\(_2\)-10 based, and MoS\(_2\)-15 based counter electrodes were measured to be 0.47, 0.55, and 0.51 mV, respectively, suggesting that the catalytic activity of the MoS\(_2\)-10 based counter electrode is lower than those of the Pt and MoS\(_2\)-15 based counter electrodes. On the other hand, compared with Pt and MoS\(_2\)-10 based counter electrodes, the MoS\(_2\)-15 based counter electrode displays the highest current density at the anodic and cathodic peaks (Fig. 4f), indicating its excellent electrocatalytic activity. This enhancement can be ascribed to the considerably increased surface area of MoS\(_2\) nanofilms in the MoS\(_2\)-15 sample. Accordingly, the MoS\(_2\)-15 based counter electrode shows higher catalytic activity than the Pt-based counter electrode. Moreover, the cycle performances of Pt and MoS\(_2\)-15 based counter electrodes were measured by CV curves at a scanning rate of 100 mV s\(^{-1}\), as shown in Fig. S6.\(^{†}\) Similar to the Pt electrode, the CV curve of the MoS\(_2\)-15 based counter electrode after 50 cycles almost completely overlaps with its initial CV curve. This indicates that the MoS\(_2\)-15 based counter electrode has a good stability to remain intact after repeated cycling.

More CV curves of the Pt-based, MoS\(_2\)-10 based and MoS\(_2\)-15 based counter electrodes were measured at various scan rates (20, 40, 60, 80, and 100 mV s\(^{-1}\)), respectively, as shown in Fig. 5a–c. For all three counter electrodes, it can be clearly observed that the peak current density increases with the scan rate, which is mainly due to the thinner diffusion layer and the larger electrochemical polarization. Moreover, as the scan rate increases, the anodic and cathodic peaks shift positively and negatively, respectively. Based on the data in Fig. 5a–c, the profiles of the anodic and cathodic peak current densities of the left peak pairs versus the square root of the scan rates were plotted, as shown in Fig. 5d. The peak current densities of all three counter electrodes display a linear relationship with the square root of the scan rates, indicating that the redox reactions happening on the two MoS\(_2\)-based counter electrodes are dominated by diffusion-controlled ion transport as in the case of the Pt-based counter electrode. Furthermore, the linear relationship suggests that there is no specific interaction.

Fig. 5 CV curves of (a) Pt-based, (b) MoS\(_2\)-10 based, and (c) MoS\(_2\)-15 based counter electrodes at various scanning rates (20, 40, 60, 80, and 100 mV s\(^{-1}\)), respectively. (d) The relationship between the peak current density of the left peak pair and the square root of the scan rates.
between the redox couple and the MoS$_2$-based counter electrodes as in the case of the Pt-based counter electrode.

In summary, the direct growth of large-area and ultrathin MoS$_2$ nanofilms on FTO glass substrates was achieved by a facile and low-cost solution-phase process. The MoS$_2$-based counter electrodes exhibited an excellent catalytic activity for tri-iodide reduction according to the EIS and CV curves. When the MoS$_2$-based counter electrode was used in the DSSC, it displayed an impressive photovoltaic performance as high as 8.3%, which was better than that of the DSSC based on the Pt-based counter electrode. The successful fabrication of the MoS$_2$-based counter electrode with this greatly simplified preparation process to replace platinum can greatly decrease the manufacturing cost, promote the practical application of DSSCs and also provide a new insight for synthesizing novel counter electrodes with superior photovoltaic performances based on 2D nanomaterials.

**Experimental methods**

**Direct fabrication of ultrathin MoS$_2$ nanofilms on a transparent conductive glass**

Ultrathin MoS$_2$ nanofilms were grown directly on fluorine-doped tin oxide (FTO) glass substrates by a facile and low-cost solution-phase approach. Typically, a FTO glass was sequentially cleaned by ultrasonication in acetone, ethanol and de-ionized (DI) water for 5 min. The FTO substrate was put into a Teflon-lined stainless steel autoclave, which contains 30 mg sodium molybdate (Na$_2$MoO$_4$) and 60 mg thioacetamide ((C$_2$H$_5$NS) dissolved in 30 mL DI water. The autoclave was placed in an oven and heated under 200 °C for a reaction time of 5–15 h. After the reaction, the autoclave was fetched out from the oven and rapidly cooled under tap water flushing for 10 min. Finally, the FTO substrate was taken out from the autoclave, washed with ethanol, and dried in air. We named MoS$_2$-x the MoS$_2$ nanofilm covered FTO counter electrode prepared by this process, where x corresponds to the growth time in the aqueous solution (x = 5, 10 or 15 h).

**Fabrication of DSSCs**

To investigate the role of MoS$_2$, DSSCs with MoS$_2$-x nanofilm covered FTO glass substrates as the counter electrodes were respectively assembled. The photoanodes were fabricated by screen-printing of TiO$_2$ nanoparticle paste (18NR-T, Dyesol) onto FTO glass substrates. Before assembling the DSSCs, the photoanodes were immersed in a 0.05 M titanium tetra-chloride (TiCl$_4$) solution at 70 °C for 30 min, rinsed with DI water and ethanol, and then annealed in air at 450 °C for 30 min. When the temperature was cooled down to 80 °C, the photoanodes were immersed in a 0.3 mM solution of cis-di(thiocyanato)-bis[2,2′-bipyridyl-4,4′-dicarboxylate] ruthenium(ii) (N719, Dalian HeptaChromaSolarTech, China) for 24 h. The dye-sensitized photoanodes were sandwiched together with the counter electrodes using a hot-melt Surlyn spacer with a thickness of ~25 μm. The electrolyte solution containing 0.05 M I$_2$, 1.0 M 1-propyl-3-methylimidazolium iodide, 0.5 M N-methylbenzimidazole and 0.1 M guanidinium thiocyanate was used as the electrolyte.

**Fabrication of a symmetrical electrochemical cell**

Two MoS$_2$-15 counter electrodes were separated by a hot-melt Surlyn spacer with a thickness of ~25 μm. A solution of acetonitrile containing 0.05 M I$_2$, 1.0 M 1-propyl-3-methylimidazolium iodide, 0.5 M N-methylbenzimidazole and 0.1 M guanidinium thiocyanate was used as the electrolyte.

**Characterization**

The morphological features of the samples were examined by scanning electron microscopy (SEM, HITACH S-4800) and transmission electron microscopy (TEM, JEM-2100). Raman spectroscopy was performed with a 488 nm laser excitation using a Renishaw InVia Raman microscope system. To investigate the components of the samples, X-ray photoelectron spectroscopy (XPS) was performed using a PHI-5000 VersaProbe X-ray photoelectron spectrometer with Al K$_\alpha$ X-ray radiation.

The effective surface areas of Pt-based and MoS$_2$-15 based electrodes were measured using the CV method. Typically, the electrochemical measurements were performed at room temperature using a standard three-electrode setup in 0.5 M H$_2$SO$_4$ solution. A Pt-based or MoS$_2$-15 based electrode was used as the working electrode. A Pt foil and an Ag/AgCl electrode were used as the counter electrode and reference electrode, respectively. The CV curves were measured at different scan rates (20, 40, 60, 80, and 100 mV s$^{-1}$) on a Chenhua CHI-760 electrochemical workstation.

The catalytic activities of MoS$_2$-x nanofilms towards tri-iodide reduction were also characterized at room temperature by using a standard three-electrode electrochemical cell setup in an acetonitrile solution containing 0.1 M LiClO$_4$, 10 mM LiI, and 1 mM I$_2$. The working, counter, and reference electrodes were MoS$_2$-x nanofilm covered FTO glass substrates, Pt foil, and Ag/AgCl, respectively. The curves of cyclic voltammetry (CV) were also measured at different scan rates (20, 40, 60, 80, and 100 mV s$^{-1}$) on a Chenhua CHI-760 electrochemical workstation.

The photovoltaic performances of the DSSCs were measured under simulated AM 1.5 G illumination provided by a solar light simulator (Oriel Solar Simulator, Model 91160). The current–voltage characteristics were recorded by using a Keithley 2400 source meter. The EIS data of DSSCs were also measured under dark and full-light conditions, respectively. With the help of Z-view software, the impedance parameters were determined. The active area of the DSSCs in this study is 0.16 cm$^2$. 

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