

## REVIEW

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# Two-dimensional transition metal dichalcogenide-based counter electrodes for dye-sensitized solar cells

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Dye-sensitized solar cells (DSSCs) are gaining considerable interest as alternatives to semiconductor-based thin film solar cells. The noble metal platinum (Pt) is conventionally used as a counter electrode (CE) material for fabricating DSSCs, since Pt is expensive and scarce, therefore, new materials have been explored to develop cost-effective Pt-free counter electrodes. Two-dimensional (2D) graphene-based counter electrodes have achieved the highest power conversion efficiency (PCE,  $\eta$ ) of 13%, which has stimulated research activities in 2D layered transition metal dichalcogenides (TMDs) for developing Pt-free DSSCs. In this review, progress made on alternative counter electrodes for fabricating low-cost Pt-free DSSCs, based on earth-abundant 2D TMDs including MoS<sub>2</sub>, WS<sub>2</sub>, TiS<sub>2</sub>, FeS<sub>2</sub>, CoS<sub>2</sub>, NiS<sub>2</sub>, SnS<sub>2</sub>, MoSe<sub>2</sub>, NbSe<sub>2</sub>, TaSe<sub>2</sub>, NiSe<sub>2</sub>, FeSe<sub>2</sub>, CoSe<sub>2</sub>, Bi<sub>2</sub>Se<sub>3</sub> and their based composites, are discussed and summarized. Also, the considerable progress made on thin films of MoS<sub>2</sub> and MoS<sub>2</sub> based carbon, graphene, carbon nanotubes (CNTs), carbon nanofibers (CNFs), and poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) composites as efficient counter electrodes (CEs) for DSSCs are discussed, in terms of their electrochemical and photovoltaic properties. At present, PCE values higher than that of standard Pt CE have been recorded for a number of TMD-based CEs, which include MoS<sub>2</sub> and MoSe<sub>2</sub>/thin films deposited on Mo foil, MoS<sub>2</sub>/CNTs, MoS<sub>2</sub>/graphene, MoS<sub>2</sub>/carbon, MoSe<sub>2</sub>/PEDOT:PSS, NbSe<sub>2</sub>, FeS<sub>2</sub>, FeSe<sub>2</sub> nanosheets, TiS<sub>2</sub>/graphene, and NiS<sub>2</sub>/graphene hybrid systems in DSSCs, for the reduction of triiodide (I<sub>3</sub><sup>−</sup>) to iodide (I<sup>−</sup>). The highest PCE ( $\eta$  = 10.46%) *versus* Pt CE ( $\eta$  = 8.25%) at 1 Sun (100 mW cm<sup>−2</sup>, AM 1.5G) was measured for DSSCs having a low cost and flexible CoSe<sub>2</sub>/carbon-nanoclimbing wall counter electrode deposited on a nickel foam. Though TMD-based materials show great potential for solar cell devices, their long-term stability is equally important. The DSSCs with a TiS<sub>2</sub>/graphene hybrid, and TiS<sub>2</sub>/PEDOT:PSS composite CEs, showed stability up to 20 to 30 days, respectively, without any measurable degradation in the photovoltaic performance. The long-term stability of TMDs-based DSSCs under different environmental conditions is also described in view of their commercial applications.

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## 1. Introduction: dye-sensitized solar cells (DSSCs)

Silicon has been traditionally used in fabricating solar cells. O'Regan and Grätzel<sup>1</sup> in 1991 demonstrated dye-sensitized solar cells (DSSC) as a low-cost approach and as an alternative to silicon solar cells. The concept of a DSSC system was hypothesized based on photosynthesis in nature. The first DSSC was

fabricated using nanocrystalline porous TiO<sub>2</sub> as optically transparent thin-film photoelectrodes and a ruthenium(II)-bipyridyl complex as a photosensitizer (dye), which generated a power conversion efficiency of 7.9% for the triiodide/iodide (I<sub>3</sub><sup>−</sup>/I<sup>−</sup>) redox couple. This inspired a new field of research based on DSSCs where a broad range of novel materials are now being explored for electrodes (photoanode and counter electrode (CE; cathode)), photosensitizers (dyes), and reduction-oxidation (redox) electrolytes for fabricating DSSC devices.

The commonly used components in dye-sensitized solar cells are a photoanode, a CE, a photosensitizing dye, and an electrolyte. These include tris(2,2'-bipyridyl)cobalt(II/III) [Co(bpy)<sub>3</sub>] (Co<sup>2+</sup>/Co<sup>3+</sup>), triiodide/iodide (I<sub>3</sub><sup>−</sup>/I<sup>−</sup>) and 5,5'-dithiobis(1-methyltetrazole)/1-methyltetrazole-5-thiolate (T<sub>2</sub>/T<sup>−</sup>) as redox couples, poly(3,4-ethylenedioxythiophene) (PEDOT), poly(styrenesulfonate) (PSS), poly(3-hexylthiophene) (P3HT), 2,2',7,7'-tetrakis(*N,N*-*p*-dimethoxy-phenylamino)-9,9'-spirobifluorene (spiro-OMETAD) as solid-state hole-transport

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materials (HTM); *cis*-bis(isothiocyanato)bis(2,2'-bipyridyl-4,4'-dicarboxylato)ruthenium(II), (N3 dye), ditetrabutylammonium *cis*-bis(isothiocyanato)bis(2,2'-bipyridyl-4,4'-dicarboxylato)ruthenium(II), where tetrabutyl-ammonium cation:  $[(C_4H_9)_4N^+]$  (N719 dye), and (tris(cyanato)-2,2',2''-terpyridyl-4,4',4''-tricarboxylate)ruthenium(II) (N749 or black dye) as photosensitizing dyes, are regularly used. The dye-sensitized mesoporous  $TiO_2$  is used as a photoanode, while the Pt-coated fluorine-doped tin oxide (FTO) on a glass substrate is used as a CE, which facilitates the catalysis process. The counter electrode in a DSSC device acts as a catalyst. Pt counter electrodes yield the maximum electrocatalytic activity for the triiodide/iodide ( $I_3^-/I^-$ ) redox couple, but are poorly effective for iodine-free redox couple such as  $Co^{2+}/Co^{3+}$  and  $T_2/T^-$ . Transparent conducting oxides such as FTO or indium-tin oxide (ITO) on glass is the common substrate used in assembling DSSCs with different CE materials. The power conversion efficiency of DSSCs is governed by many factors including light absorbing capacity of photosensitizing dyes and catalytic materials.

The classical photosensitizing dyes were developed by Grätzel's research team,<sup>2,3</sup> including N3 dye that absorbs up to 800 nm, and N749 dye (also known as black dye) which absorbs sunlight in the longer wavelength region up to 920 nm. In 2014, Mathew *et al.*<sup>4</sup> used graphene nanoplatelets as a CE, a new push-pull porphyrin with a donor- $\pi$ -bridge acceptor (D- $\pi$ -A) chemical structure as a sensitizing dye, and Co(II)/Co(III) redox mediator for developing a DSSC, which exhibited a  $J_{sc}$  of  $18.1 \text{ mA cm}^{-2}$ ,  $V_{oc}$  of 0.91 V, FF of 0.78 and the highest power conversion efficiency (PCE) of 13% under  $100 \text{ mW cm}^{-2}$  (AM 1.5) illumination. The high PCE of DSSCs originated from a molecularly engineered porphyrin dye, 4-(7-{2-[(2Z,7Z,11E,16Z)-7,17-bis[2,6-bis(octyloxy)phenyl]-12-bis[{4-[2,4-bis(hexyloxy)phenyl]phenyl}]amino]-21,23,24,25-tetraaza-22-zincacetyclo[9.9.3.13,6.113,16.08,23.018,21]-pentacosa 1(20),2,4,6(25),7,9,11,13(24),14,16,18-undecane-2-yl]-ethynyl}-2,1,3-benzothiadiazole-4-yl)benzoic acid, coded as SM315 dye. The sensitizing dyes as a light harvester play a very significant role in achieving high PCE for DSSCs, therefore, dyes such as N3, N719, N749, Y123, Z907, JK-303 those absorb as much sunlight as possible is of a great interest, *i.e.*, Y123 dye = 3-[6-[4-bis(2',4'-dihexyloxybiphenyl-4-yl)amino]phenyl]-4,4-dihexylcyclopenta-[2,1-*b*:3,4-*b'*]dithiophene-2-yl]-2-cyanoacrylic acid; Z907 = *cis*-bis(isothiocyanato) (2,2'-bipyridyl-4,4'-dicarboxylato) (4,4'-di-nonyl-2'-bipyridyl)ruthenium(II); and JK-306 = (*E*)-3-{5'-[4-bis(2',4'-dihexyloxybiphenyl-4-yl)amino]phenyl}-2,2'-bithiophene-5-yl]-2-cyanoacrylic acid. The many types of dye-sensitizers such as ruthenium dyes, metal-free organic dyes, porphyrin dyes, quantum dots, and perovskites have been explored for DSSCs. Over the past 30 years, significant progress has been made in exploring diverse aspects of DSSC components, including dye-sensitizers, CEs, electrolytes and photoanodes, and many outstanding reviews are available in the literature on this exciting research topic.<sup>5-17</sup> Chemical structures of photosensitizing dyes generally used in evaluating the photovoltaic performance of CEs in DSSCs are also discussed elsewhere. Many different types of Pt-free CE materials have been studied for DSSCs including carbon-based materials such as carbon black, mesoporous carbon, carbon nanotubes

(CNTs), carbon fibers, fullerenes, graphene-based materials, metals, transition metal oxides, sulfides, carbides, nitrides, selenides, tellurides, chalcogenides, layered double hydroxides, phosphides and their alloys, conducting polymers such as PEDOT:PSS and other composites materials.<sup>18-22</sup>

Platinum (Pt) and ITO are the traditional materials used in fabricating different types of solar cell devices. In DSSCs, the Pt deposited on a FTO transparent conductive glass substrate is used as a CE for the reduction of triiodide ( $I_3^-$ ) ions to iodide ( $I^-$ ) ions. In this case, Pt acts as a catalyst for the regeneration of redox couples while FTO acts as an electron collector. Pt is a highly expensive metal which has been identified as one of the most critically important metals for the U.S. economic growth.<sup>23,24</sup> Among electrocatalysts for DSSCs, Pt shows the best photovoltaic performance due to its high conductivity, chemical stability, and electrochemical activity but it is scarce. The current idea is to explore new alternative catalytic materials to replace the conventional Pt CE in DSSCs using easily available, inexpensive, highly electrically conductive, and high electrocatalytic activity materials. Earth-abundant 2D materials that offer high optical transparency and high electrocatalytic activity have been explored as potential candidate materials for CEs (cathode) and for replacing Pt in DSSC devices. During the last decade, graphene-based materials in the form of their thin films, nanosheets, fibers, multilayers, nanoplatelets, quantum dots, nanofoams and their nanocomposites with metals, CNTs, organic polymers, upconversion nanoparticles, titanium dioxide ( $TiO_2$ ), ionic liquids, and halide perovskites, have been extensively investigated as Pt-free CEs for DSSCs<sup>25</sup> and heterojunction solar cells.<sup>26,27</sup> The merit of graphene-based CEs in DSSC devices includes their high optical transparency, high electrical conductivity, large effective specific surface area, and the flexibility to fabricate them on different types of substrates.

Layered 2D TMDs are graphene analogs, therefore, research activities have been strongly diverted towards this new class of low-cost 2D materials. Among 2D TMDs, transition-metal disulfides and diselenides such as  $MoS_2$ ,  $MoSe_2$ ,  $WS_2$ ,  $TiS_2$ ,  $NbSe_2$ ,  $TaSe_2$ ,  $NiSe_2$ ,  $FeSe_2$ ,  $CoSe_2$ ,  $SnS_2$ ,  $Bi_2Se_3$  and other TMD thin films have been investigated as CEs to fabricate Pt-free DSSCs. The CE acts as an electrocatalyst, and is one of the main components of a DSSC device which facilitates the reduction of triiodide ( $I_3^-$ ) ions to iodide ( $I^-$ ) ions in a redox electrolyte for dye generation. In this review, electrochemical and photovoltaic properties of low-cost catalytic CEs developed from earth-abundant TMDs and their composites with carbon, graphene, CNTs, carbon nanofibers, PEDOT:PSS and other materials are discussed. The impact of materials processing and morphology associated with PCEs of DSSCs has also been analyzed. Finally, this review discusses the electrochemical and environmental stability of TMDs-based CEs for DSSCs.

## 2. Two-dimensional transition metal dichalcogenides (2D TMDs)

Two-dimensional (2D) transition metal dichalcogenides (TMDs), *i.e.*  $MX_2$  where M is a transition metal (Mo, W, Ti, Zr,



**Table 1** Library of 2D materials. Blue cells represent monolayers of 2D materials showing stability under ambient conditions; green denotes probability of stability of 2D materials in air; pink denotes 2D unstable materials in air, but may be stable under inert atmosphere. Grey cells show 3D compounds easily exfoliated down to monolayers. Reprinted with permission from ref. 32, A. K. Geim and I. V. Grigorieva, van der Waals heterostructures. *Nature*, 2013, **499**, 419–425. Copyright© Nature Publishing Group

| Graphene family  | Graphene   | hBN<br>'white graphene'   | BCN   | Fluorographene  | Graphene oxide |
|------------------|--|---|---|---|----------------|
| 2D chalcogenides | MoS <sub>2</sub> , WS <sub>2</sub> ,<br>MoSe <sub>2</sub> , WSe <sub>2</sub> | Semiconducting dichalcogenides:<br>MoTe <sub>2</sub> , WTe <sub>2</sub> , ZrS <sub>2</sub> , ZrSe <sub>2</sub> and so on  |   | Metallic dichalcogenides: NbSe <sub>2</sub> ,<br>NbS <sub>2</sub> , TaS <sub>2</sub> , TiS <sub>2</sub> , NiSe <sub>2</sub> and so on |                |
|                  |  |   |   | Layered semiconductors: GaSe,<br>GaTe, InSe, Bi <sub>2</sub> Se <sub>3</sub> and so on  |                |
| 2D oxides        | Micas, BSCCO   | MoO <sub>3</sub> , WO <sub>3</sub>  | Perovskite-type:<br>LaNb <sub>2</sub> O <sub>7</sub> ,<br>(Ca,Sr) <sub>2</sub> Nb <sub>3</sub> O <sub>10</sub> ,<br>Bi <sub>4</sub> Ti <sub>3</sub> O <sub>12</sub> ,<br>Ca <sub>2</sub> Ta <sub>2</sub> TiO <sub>10</sub><br>and so on | Hydroxides: Ni(OH) <sub>2</sub> , Eu(OH) <sub>2</sub><br>and so on  |                |
|                  | Layered Cu<br>oxides   | TiO <sub>2</sub> , MnO <sub>2</sub> ,<br>V <sub>2</sub> O <sub>5</sub> , TaO <sub>3</sub> , RuO <sub>2</sub><br>and so on |   | Others  |                |

Hf, V, Nb, Ta, Tc, Re, Pd, Pt) and X is a chalcogen (S, Se, Te), such as MoS<sub>2</sub>, WS<sub>2</sub>, MoSe<sub>2</sub>, WSe<sub>2</sub>, form 2D layered structures and are abundantly available in nature. In a MX<sub>2</sub> monolayer structure (X–M–X), an atomic layer of a transition metal (M) is sandwiched between two chalcogen (X) atomic layers, where transition metal atoms (M) such as Mo and W are covalently bonded with chalcogen atoms (X) such as S, Se, Te. Each layer is 6–7 Å thick in the TMD layered structures. Weak van der Waals interactions occur between two adjacent MX<sub>2</sub> layers of TMDs, whereas the intra-layer M–X bonds are covalent.<sup>28–31</sup> From an electrical point of view, MoS<sub>2</sub>, MoSe<sub>2</sub>, WS<sub>2</sub> and WSe<sub>2</sub> are semiconductors, WTe<sub>2</sub> and TiSe<sub>2</sub> are semimetals, VSe<sub>2</sub> and NbS<sub>2</sub> are metals, while NbSe<sub>2</sub> and TaS<sub>2</sub> are superconductors in their bulk crystalline forms.<sup>26,30</sup> Geim and Grigorieva<sup>32</sup> created a library of 2D materials (Table 1) where the 2D materials were classified into three different classes. Their graphene family includes graphene-based materials hBN, and BCN; the 2D chalcogenides include a large family of TMDs having insulator to semiconducting to metallic behavior; and the 2D oxides include layered oxides, perovskite-based materials, hydroxides, and others. The 2D TMDs include MoS<sub>2</sub>, WS<sub>2</sub>, VS<sub>2</sub>, NbS<sub>2</sub>, ZrS<sub>2</sub>, TiS<sub>2</sub>, NbSe<sub>2</sub>, WSe<sub>2</sub>, MoSe<sub>2</sub>, ZrSe<sub>2</sub>, WTe<sub>2</sub>, and MoTe<sub>2</sub>, and layered semiconductor chalcogenides such as GaSe, GaTe, InSe, Bi<sub>2</sub>Se<sub>3</sub>, and Bi<sub>2</sub>Te<sub>3</sub>. 2D materials represented by different colors denote their stability under ambient conditions. 2D materials among the graphene family have been extensively studied so far. 2D TMDs such as MoS<sub>2</sub>, WS<sub>2</sub>, WSe<sub>2</sub> and MoSe<sub>2</sub> are structurally similar. Among 2D TMDs, W based materials have stronger spin–orbit coupling while Se materials exhibit lower stability.

Research activities into 2D TMDs were intensified after the monolayers of MoS<sub>2</sub> showed high carrier mobility of 100 cm<sup>2</sup> V<sup>−1</sup> s<sup>−1</sup> and on/off current ratios of >10<sup>8</sup> because of the interesting bandgap of MoS<sub>2</sub>.<sup>33</sup> The monolayers of MoS<sub>2</sub> are direct semiconductors whereas MoS<sub>2</sub> bilayers, trilayers, few-layers are indirect semiconductors. Thickness dependent bandgap energies of 2D TMDs-based semiconductors, including MoS<sub>2</sub>, MoSe<sub>2</sub>, MoTe<sub>2</sub>, WS<sub>2</sub>, and WSe<sub>2</sub> (2H–MX<sub>2</sub>), were calculated by

Yun *et al.*<sup>34</sup> using the first-principles calculations as shown in Fig. 1.<sup>34</sup> As the number of layers in the TMDs is reduced to a single layer, the band curvatures lead to significant changes of effective masses. When a single layer of the TMDs is strained, the direct bandgap turns to an indirect bandgap. It was found that bandgap energy and effective masses are reduced by tensile strain, contrary to the compressive strain that increases both parameters. Also the applied larger tensile stress gives rise to a metallic character. This study emphasized the electronic structures of 2D TMDs.

The photoluminescence and absorption spectra of monolayers of MoS<sub>2</sub>, MoSe<sub>2</sub>, WS<sub>2</sub>, and WSe<sub>2</sub> have been measured.<sup>35</sup> TMDs as bulk crystals are indirect-bandgap semiconductors, however they become direct-bandgap semiconductors as their thickness is reduced to monolayers. The bandgap increases as the number of layers decreases. Photoluminescence peaks at

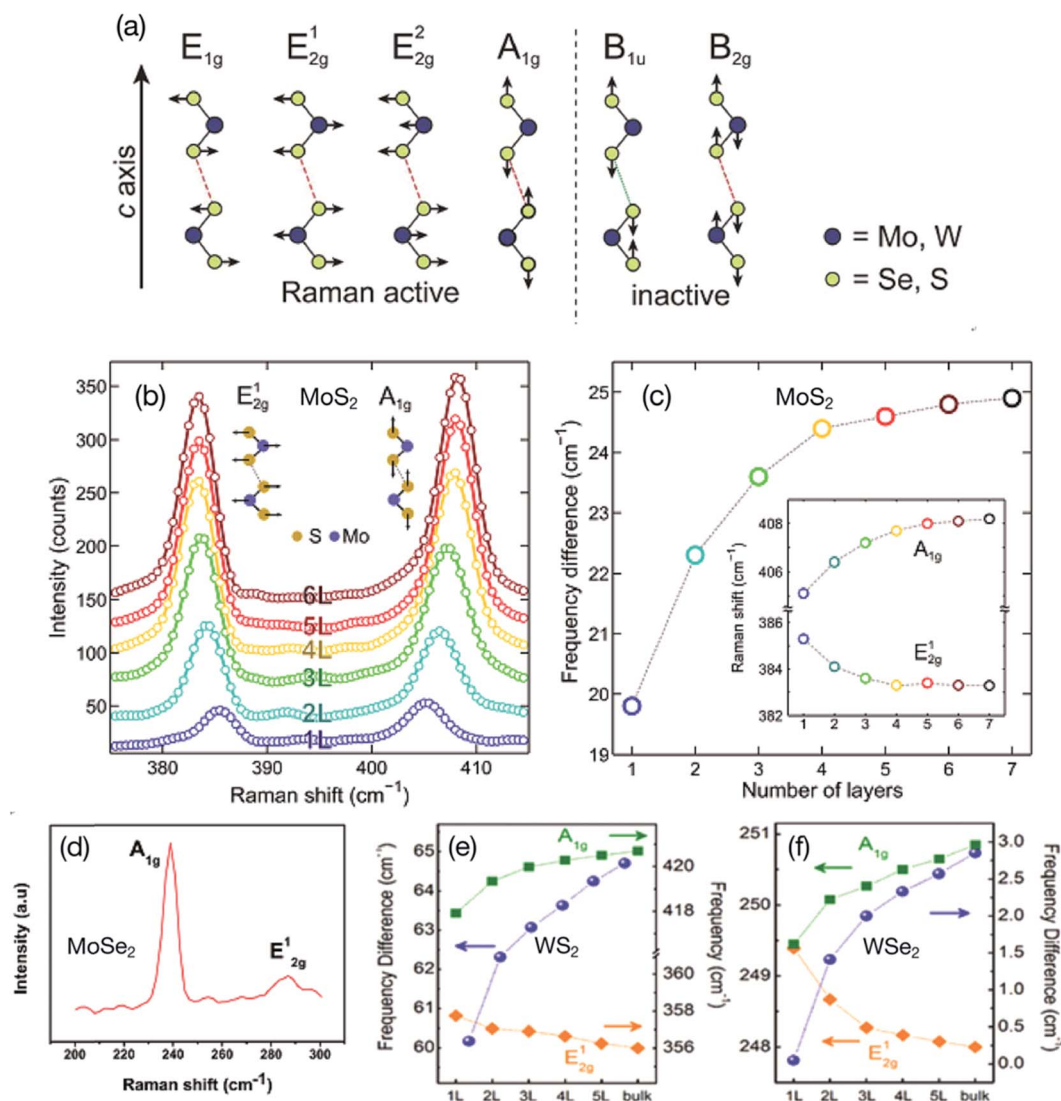


**Fig. 1** Colored lines representing thickness dependence of bandgap energies of 2D TMDs including MoS<sub>2</sub>, MoSe<sub>2</sub>, MoTe<sub>2</sub>, WS<sub>2</sub>, and WSe<sub>2</sub> attain (2H–MX<sub>2</sub> semiconductors). Reprinted with permission from ref. 34, W. S. Yun, S. W. Han, S. C. Hong, I. G. Kim and J. D. Lee, thickness and strain effects on electronic structures of transition metal dichalcogenides: 2H–MX<sub>2</sub> semiconductors (M = Mo, W; X = S, Se, Te). *Phys. Rev. B*, 2012, **85**, 033305. Copyright© American Physical Society.

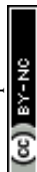


1.84 eV for MoS<sub>2</sub>, 1.65 eV for WSe<sub>2</sub> and 1.56 eV for MoSe<sub>2</sub> have been observed.<sup>36</sup> The indirect bandgap at 1.2 eV for bulk crystals of WSe<sub>2</sub> was reported,<sup>37</sup> whereas the monolayer showed a photoluminescence peak at 1.65 eV (752 nm). In the case of bulk crystals of MoSe<sub>2</sub>, the indirect bandgap was measured as 1.1 eV (1.13  $\mu$ m) while the monolayer exhibited a photoluminescence peak at 1.57 eV (792 nm). The photoluminescence emission peak for monolayer WS<sub>2</sub> appeared at 1.97 eV.<sup>38</sup>

Mechanical exfoliation is the most common approach for peeling off monolayers or a few-layers of TMD materials from their bulk crystals,<sup>39–41</sup> which is a top-down method. A second widely used approach is chemical vapor deposition (CVD), which is a bottom-up method to consecutively deposit desired thickness layers of TMDs.<sup>42–45</sup> Other approaches for preparing layers of TMDs include chemical,<sup>46</sup> lithium intercalation,<sup>47–49</sup> and ultrasonic-assisted liquid exfoliation in organic solvents,<sup>50–54</sup> and salt-assisted liquid-phase exfoliation,<sup>55</sup> all of



**Fig. 2** (a) Schematic representation of the four Raman active modes and two Raman inactive modes of TMDs MX<sub>2</sub> (M = Mo, W and X = Se, S). Reprinted with permission from ref. 37, P. Tonndorf, R. Schmidt, P. Böttger, X. Zhang, J. Borner, A. Liebig, M. Albrecht, C. Kloc, O. Gorgan, D. R. T. Zahn, S. M. de Vasconcellos and R. Bratschitsch, Photoluminescence Emission and Raman Response of Monolayer MoS<sub>2</sub>, MoSe<sub>2</sub>, and WSe<sub>2</sub>. *Opt. Express*, 2013, **21**, 4908–4916. Copyright© Optical Society of America. (b) Raman spectra of mechanically exfoliated MoS<sub>2</sub> flakes deposited onto a transparent poly(dimethylsiloxane) (PDMS) substrate with different number of layers, single-layer to six-layers of MoS<sub>2</sub>. (c) Peak frequency difference ( $\Delta$ ) between Raman modes as a function of the number of MoS<sub>2</sub> layers. Reprinted with permission from ref. 60, A. Castellanos-Gomez, J. Quereda, H. P. van der Meulen, N. Agrait and G. Rubio-Bollinger, spatially resolved optical absorption spectroscopy of single- and few-layer MoS<sub>2</sub> by hyperspectral imaging. *Nanotechnol.*, 2016, **27**, 115705. Copyright© Institute of Physics (IOP). (d) Raman spectrum of few-layer MoSe<sub>2</sub> nanosheets showing two distinct Raman active modes;  $A_{1g}$  and  $E_{2g}^1$ . Reprinted with permission from ref. 61, S. K. Balasingam, J. S. Lee and Y. Jun, few-layered MoSe<sub>2</sub> nanosheets as an advanced electrode material for supercapacitors, *Dalton Trans.*, 2015, **44**, 15491–15498. Copyright© Royal Society of Chemistry. (e, f) Thickness dependence of Raman  $A_{1g}$  and  $E_{2g}^1$  modes of 1 to 5 layers and bulk WS<sub>2</sub> and WSe<sub>2</sub>. Reprinted with permission from ref. 62, W. Zhao, Z. Ghorannevis, K. K. Amara, J. R. Pang, M. Toh, X. Zhang, C. Kloc, P. H. Tan and G. Eda, lattice dynamics in mono- and few-layer sheets of WS<sub>2</sub> and WSe<sub>2</sub>. *Nanoscale*, 2013, **5**, 9677–9683. Copyright© Royal Society of Chemistry.





which can prepare mono-layers to multi-layers of TMDs, such as MoS<sub>2</sub>, MoSe<sub>2</sub>, WS<sub>2</sub>, and WSe<sub>2</sub>.

Raman scattering methods for single-layer, multi-layer and bulk 2D TMDs, including MoS<sub>2</sub>, MoSe<sub>2</sub>, WS<sub>2</sub>, and WSe<sub>2</sub>, in terms of phonons with respect to the number of layers, has been reviewed and analyzed.<sup>56,57</sup> Tonndorf *et al.*<sup>37</sup> studied photoluminescence and Raman characteristics of the monolayers of MoS<sub>2</sub>, MoSe<sub>2</sub>, and WSe<sub>2</sub>. Fig. 2a shows a schematic representation of the four Raman active modes and two Raman inactive modes of TMDs MX<sub>2</sub> (M = Mo, W and X = Se, S) as predicted for the D6h point group.<sup>58</sup> The Raman active modes include three in-plane modes referred as E<sub>1g</sub>, E<sub>2g</sub><sup>1</sup>, and E<sub>2g</sub><sup>2</sup>, and one out-of-plane mode referred as A<sub>1g</sub>. However, experimentally only the two active Raman modes E<sub>2g</sub><sup>1</sup> and A<sub>1g</sub> were observed. The active Raman E<sub>2g</sub><sup>2</sup> mode appears at very low frequencies, whereas the E<sub>1g</sub> mode is forbidden.<sup>59</sup> A systematic study of the optical absorption of single-layer and few-layers of MoS<sub>2</sub> from the 385 nm (3.22 eV) to 1000 nm (1.24 eV) spectral range was conducted by Castellanos-Gomez *et al.*<sup>60</sup> using a hyperspectral imaging technique. Poly(dimethylsiloxane) (PDMS) was used as a transparent substrate for depositing mechanically exfoliated MoS<sub>2</sub> thin films. The optical absorbance spectra of MoS<sub>2</sub> flakes consisting of single-layer to six-layer were recorded as a function of different excitation wavelengths. The bandgap of a monolayer MoS<sub>2</sub> was measured as 1.85 eV, which decreased with increasing number of MoS<sub>2</sub> layers, reaching a bandgap value of 1.35 eV for the bulk MoS<sub>2</sub>. Fig. 2b and c shows Raman spectra for the E<sub>2g</sub><sup>1</sup> and A<sub>1g</sub> modes of the exfoliated MoS<sub>2</sub> flakes ranging from single-layer to six-layer, and the variation of peak frequency difference ( $\Delta$ ) between the E<sub>2g</sub><sup>1</sup> and A<sub>1g</sub> modes as a function of the number of MoS<sub>2</sub> layers. The  $\Delta$  value increases with the increasing number of layers from 19.8 cm<sup>-1</sup> for a single-layer to 25 cm<sup>-1</sup> for bulk MoS<sub>2</sub>.

Raman spectroscopy for few-layer MoSe<sub>2</sub> nanosheets was recorded by Balasingam *et al.*<sup>61</sup> which showed Raman peaks at 239 cm<sup>-1</sup> and 287.11 cm<sup>-1</sup> (Fig. 2d) corresponding to the A<sub>1g</sub> mode (out-of-plane) and E<sub>2g</sub><sup>1</sup> mode (in-plane) of MoSe<sub>2</sub>, respectively. For bulk crystal MoSe<sub>2</sub>, the A<sub>1g</sub> and E<sub>2g</sub><sup>1</sup> modes appear at 242 cm<sup>-1</sup> and 286 cm<sup>-1</sup>, respectively. The red shift in the A<sub>1g</sub> mode and a blue shift in the E<sub>2g</sub><sup>1</sup> mode indicate the formation of a few-layered MoSe<sub>2</sub> nanosheet. Raman spectra of monolayers, few-layers and bulk WS<sub>2</sub> and WSe<sub>2</sub> were evaluated by Zhao *et al.*<sup>62</sup> Thickness dependent Raman A<sub>1g</sub> and E<sub>2g</sub><sup>1</sup> modes of 1 to 5 layers, as well as bulk WS<sub>2</sub> and WSe<sub>2</sub>, are shown in (Fig. 2e and f). As discussed above, the frequency difference ( $\Delta$ ) can be used to distinguish the number of layers. McCreary *et al.*<sup>38</sup> reported the E<sub>2g</sub><sup>1</sup> mode at 357.5 cm<sup>-1</sup> (in-plane) and A<sub>1g</sub> mode at 419 cm<sup>-1</sup> (out-of-plane) with a frequency difference ( $\Delta$ ) of 61.5 cm<sup>-1</sup> for WS<sub>2</sub> monolayer. Photoluminescence emission and Raman scattering of 2D TMDs have been extensively studied and analyzed by several research groups around the world.<sup>63–71</sup>

### 3. TMD-based counter electrodes for DSSCs

The new materials used as CE in DSSC devices are generally characterized by their molecular structure and surface

morphology using a wide variety of spectroscopic techniques, including X-ray diffraction (XRD), Raman spectroscopy, X-ray photoelectron spectroscopy (XPS), UV-vis (Ultraviolet-visible) spectrometry, atomic force microscopy (AFM), field-emission scanning electron microscopy (FESEM), high-resolution transmission electron microscopy (HRTEM) and energy dispersive X-ray spectroscopy (EDX). The electrochemical catalytic activity and photovoltaic performance of CE in DSSCs are evaluated using different methods. Electrocatalytic activity can be evaluated by cyclic voltammetry (CV), rotating disk electrode (RDE) for determining rate constant and effective catalytic surface area, interfacial charge transfer parameters (series resistance and charge-transfer resistance) measurements by electrochemical impedance spectroscopy (EIS) and Tafel polarization plots for electrocatalytic ability, incident photon-to-current conversion efficiency (IPCE) spectra measurements; these measurements of a DSSC device and their electro-catalytic activities are compared with a standard Pt CE. Photovoltaic tests of a DSSC device are performed by measuring photocurrent density–voltage (*J*–*V*) characteristic curves of CE under a simulated solar illumination at 100 mW cm<sup>-2</sup> (AM 1.5G) corresponding to 1 Sun intensity unless specified for other sunlight intensity. The photovoltaic and electrochemical parameters of the DSSC system include short-circuit photocurrent density (*J*<sub>sc</sub>), open-circuit voltage (*V*<sub>oc</sub>), fill factor (FF), power conversion efficiency (PCE) which is the solar-to-electricity conversion efficiency ( $\eta$ ), series resistance (*R*<sub>s</sub>), charge-transfer resistance (*R*<sub>CT</sub>) at the CE/electrolyte interface, capacitance, and Nernst diffusion impedance (*Z*<sub>N</sub>). When using a new material as a CE catalyst, the electrochemical and photovoltaic properties of a DSSC device are compared with a conventional Pt CE due to its optimal electrocatalytic activity and chemical stability in the electrolyte. The dye-adsorbed TiO<sub>2</sub> mesoporous film deposited on a FTO glass substrate is used as a photoanode (working electrode) of the DSSC device. The ruthenium N719 dye has been commonly used for the reduction of triiodide (I<sub>3</sub><sup>-</sup>) to iodide (I<sup>-</sup>). DSSCs are assembled with different CE to be studied, and filled with the same redox electrolyte solution such as triiodide/iodide (I<sub>3</sub><sup>-</sup>/I<sup>-</sup>) redox couple. The CE reduces the triiodide (I<sub>3</sub><sup>-</sup>) ions to iodide ions (I<sup>-</sup>). For example, a typical iodide electrolyte solution contains 0.1 M of LiI, 0.05 M of iodine (I<sub>2</sub>), 0.6 M of 1,2-dimethyl-3-*n*-propylimidazolium iodide (DMPII), and 0.5 M of 4-*tert*-butylpyridine (TBP) in acetonitrile. All these spectroscopic techniques and electrochemical measurements were performed, which have been discussed throughout this review as needed in order to evaluate the potential of 2D TMDs (such as MoS<sub>2</sub>, WS<sub>2</sub>, TiS<sub>2</sub>, FeS<sub>2</sub>, CoS<sub>2</sub>, NiS<sub>2</sub>, SnS<sub>2</sub>, MoSe<sub>2</sub>, NbSe<sub>2</sub>, TaSe<sub>2</sub>, NiSe<sub>2</sub>, FeSe<sub>2</sub>, CoSe<sub>2</sub>, Bi<sub>2</sub>Se<sub>3</sub> and their based hybrids/composites) as CE for fabricating low-cost Pt-free DSSCs.

#### 3.1 MoS<sub>2</sub> counter electrodes

**3.1.1 Pristine MoS<sub>2</sub>.** TMDs have been traditionally used as solid lubricants<sup>72–80</sup> but recently have found the potential for applications in the fields of electronics and photonics. Like 2D graphene-based materials, layered transition-metal



dichalcogenides  $\text{MX}_2$  ( $\text{M} = \text{W}, \text{Mo}, \text{Hf}, \text{Nb}, \text{Re}, \text{Ta}$ ;  $\text{X} = \text{S}, \text{Se}, \text{Te}$ ) have become of great interest due to their unique electronic and photonic properties and a very wide range of applications in field-effect transistors (FETs),<sup>81–99</sup> photodetectors,<sup>100–102</sup> light-emitting diodes (LEDs),<sup>103,104</sup> ferroelectric memories,<sup>105</sup> static random access memory (RAM),<sup>83</sup> high-frequency resonators,<sup>106</sup> supercapacitors,<sup>107,108</sup> energy conversion and storage devices,<sup>109–112</sup> gas sensors,<sup>113,114</sup> biosensors,<sup>115,116</sup> biomedical applications,<sup>117</sup> organic solar cells,<sup>118</sup> and photonics/optoelectronics.<sup>119,120</sup>

TMDs are one of the 2D graphene analogs which show great potential for both bulk-heterojunction (BHJ) and dye-sensitized solar cells. A review article on atomically thin  $\text{MoS}_2$  layers used as the electron-transport layer (ETL), hole-transport layer (HTL), interfacial layer, and protective layer in fabricating bulk-heterojunction (BHJ) solar cells has been recently published by Singh *et al.*<sup>118</sup> Here, the applications of  $\text{MoS}_2$  thin films as CEs for fabricating Pt-free dye-DSSCs are discussed.

Polytypism in  $\text{MoS}_2$  has been studied by using Raman spectroscopy.<sup>121</sup> Layered  $\text{MoS}_2$  exists in 2H, 3R and 1T phases where monolayers are stacked in a different sequence.<sup>122–124</sup> The semiconducting 2H- $\text{MoS}_2$  phase of the bulk crystal contains two-layer per unit cell stacked in a hexagonal symmetry, where each Mo atom is coordinated with six sulfur (S) atoms. The 3R- $\text{MoS}_2$  phase contains three-layer per unit cell stacked in a rhombohedral symmetry. The metallic 1T phase contains one  $\text{MoS}_2$  layer per unit cell in tetragonal symmetry with octahedral coordination. A structural phase transition of 2H- $\text{MoS}_2$  to 1T- $\text{MoS}_2$  (2H  $\rightarrow$  1T) has been reported due to a lithium ion

intercalation process.<sup>122–125</sup> The metallic 1T phase of  $\text{MoS}_2$  exhibits very interesting electronic properties.<sup>126–129</sup> Therefore, Wei *et al.*<sup>130</sup> used metastable 1T metallic phase  $\text{MoS}_2$  in fabricating DSSCs. In that work,  $\text{MoS}_2$  films were deposited on FTO glass substrate by a hydrothermal method, performing reactions at 180 or 200 °C for 24 hours. The  $\text{MoS}_2$  films prepared at 200 °C showed lumps, while those grown at 180 °C had flower-like structures. High-angle annular dark-field scanning transmission electron microscopy (HAAD-FSTEM) images, Raman spectroscopy, and XPS also showed the formation of 2H and 1T metallic phases of  $\text{MoS}_2$ . Fig. 3 represents the  $J$ - $V$  curves of 2H- $\text{MoS}_2$  and flower-structured 1T metallic phase  $\text{MoS}_2$ . The flower-structured 1T metallic  $\text{MoS}_2$  film was grown onto an FTO substrate as a CE of DSSC, which exhibited PCE ( $\eta$ ) of 7.08%, that is a three times higher PCE compared with 2H phase  $\text{MoS}_2$  ( $\eta = 1.72\%$ ) and comparable to a Pt CE ( $\eta = 7.25\%$ ). Such a large difference in PCE values of 1T and 2H phases occurs because the electrical conductivity of 1T- $\text{MoS}_2$  is  $10^7$  times larger compared with 2H- $\text{MoS}_2$ , which gives rise to a higher electrocatalytic activity for the 1T phase than that of the 2H phase. The 1T- $\text{MoS}_2$  CE also demonstrated lower charge-transfer resistance ( $R_{\text{CT}}$ ). The IPCE curves and CV measurements also showed a better electrocatalytic activity of 1T- $\text{MoS}_2$  CE in DSSC than that of 2H- $\text{MoS}_2$ .

A very interesting study was conducted by Infant *et al.*<sup>131</sup> who developed CE materials for DSSCs by vertically oriented  $\text{MoS}_2$  on an FTO substrate, in order to increase the reflectivity of  $\text{MoS}_2$  CE. Fig. 4 shows high resolution SEM images of CVD-deposited  $\text{MoS}_2$  thin films, the reflectivity of  $\text{MoS}_2$  CE measured by UV-vis spectrophotometer, and CV measurements using standard hydrogen electrode (SHE) as a reference electrode. The high quality thin films of  $\text{MoS}_2$  were obtained at the optimum conditions of 600 °C with a 15 minute reaction time at a flow rate of 50 sccm. The FTO substrate is damaged if temperature is increased above 600 °C and the reaction time is over 15 minutes, leading to excessive deposition of sulfur on the surface. The layered  $\text{MoS}_2$  thin films are polycrystalline and have 0.18–0.27 nm spacing as evidenced by the TEM image and SEAD pattern. The CVD-prepared  $\text{MoS}_2$  thin films are vertically oriented on the FTO substrate, which yields more active sites and eventually enhance the reflectivity so that more photons are absorbed, and also created active edge sites facilitating the generation of the  $\text{I}^-/\text{I}_3^-$  redox couple. The reflectance of vertically inclined  $\text{MoS}_2$  films on the FTO substrate was measured by a UV-vis spectrophotometer between 350–800 nm wavelength for reaction temperatures varying from 400 to 700 °C, a reaction time ranging from 5 to 30 minutes, and different flow rates of Ar gas (Fig. 4). The maximum reflectance of 38% was observed for a vertically inclined  $\text{MoS}_2$  thin film under optimized conditions, due to high crystallinity, and the inclined angle of 26° was estimated that supports the reflectivity of photons to dye molecules. The reflectivity of 38% was observed for  $\text{MoS}_2$  thin films prepared at 50 sccm due to its crystallinity and higher inclination angle, which contributes to more absorption photons, and hence leads to a higher PCE of 7.50% compared to PCE of 7.38% for 150 sccm with 25% reflectivity, due to smaller angle of  $\text{MoS}_2$  inclination. This approach yielded a PCE of 7.50% for the  $\text{MoS}_2$  CE, exceeding the PCE of Pt based CE ( $\eta =$



Fig. 3 Photocurrent density–voltage ( $J$ - $V$ ) curves of 2H-type  $\text{MoS}_2$  and flower-structured 1T metallic phase  $\text{MoS}_2$ . Insert shows high-angle annular dark-field scanning transmission electron microscopy (HAAD-FSTEM) confirming 2H and 1T metallic phase of  $\text{MoS}_2$ . Reprinted with permission from ref. 130, W. Wei, K. Sun and Y. H. Hu, an efficient counter electrode material for dye-sensitized solar cells—flower-structured 1T metallic phase  $\text{MoS}_2$ . *J. Mater. Chem. A*, 2016, 4, 12398–12401. Copyright© Royal Society of Chemistry.





Fig. 4 SEM (a) and high resolution SEM (b) of CVD-deposited MoS<sub>2</sub> thin films. The highest quality thin films of MoS<sub>2</sub> were prepared at 600 °C with 15 minute reaction time at the Ar flow rate of 50 sccm. (c) Optical properties of MoS<sub>2</sub> thin films between 350–800 nm range prepared at different temperature. (d) Flow rates of Ar gas between 50 to 450 sccm for preparing MoS<sub>2</sub> thin films by CVD technique. (e) Cyclic voltammetry (CV) plots using standard hydrogen electrode (SHE) as a reference electrode and (f) photocurrent density–voltage ( $J$ – $V$ ) curves of MoS<sub>2</sub> and Pt based CEs prepared at 50 and 150 sccm flow rates of Ar gas. Reprinted with permission from ref. 131, R. S. Infant, X. Xu, W. Yang, F. Yang, L. Hou and Y. Li, highly active and reflective MoS<sub>2</sub> counter electrode for enhancement of photovoltaic efficiency of dye sensitized solar cells. *Electrochim. Acta*, 2016, 212, 614–620. Copyright© Elsevier.

7.28%). The MoS<sub>2</sub> CE shows a higher  $J_{sc}$  value of 15.2 mA cm<sup>-2</sup>, and is higher than Pt CE ( $J_{sc}$  = 14.6 mA cm<sup>-2</sup>) due to high reflectivity. The  $R_{CT}$  of MoS<sub>2</sub> CE was lower than Pt CE, indicating the higher electro-catalytic activity of vertically inclined MoS<sub>2</sub> film on the FTO substrate was due to more active edge sites, which gives rise to enhanced electrocatalytic activity of the MoS<sub>2</sub> CE. Two redox peaks are observed in the CV curves of Pt and MoS<sub>2</sub> CEs, one corresponding to the reduction of I<sub>3</sub><sup>-</sup>, which is a cathodic peak ( $V_{pc}$ ), and the other corresponding to the oxidation of I<sup>-</sup>, which is an anodic peak ( $V_{pa}$ ). The value of anodic peak to cathodic peak separation ( $V_{pp}$ ) was found to be less for the MoS<sub>2</sub> CE (0.456 V) than that of Pt (0.484 V), which also indicates a better electrocatalytic activity of MoS<sub>2</sub> CE due to the presence of active edge sites, as evidenced in the SEM images.

Vertical MoS<sub>2</sub> nanosheets on different substrates using CVD and CS<sub>2</sub> as a sulfur precursor have been developed.<sup>132</sup> The DSSC CEs with vertical MoS<sub>2</sub> nanosheets showed a comparable electro-catalytic activity to Pt CE for the triiodide (I<sub>3</sub><sup>-</sup>) reduction, resulting from large specific surface areas and more active edges. Li *et al.*<sup>133</sup> prepared molybdenum disulfide-based CEs for DSSCs with different morphologies (multilayers, few-layers and nanoparticles) using the thermal decomposition method. The X-ray diffraction and transmission electron microscopy showed edge area to basal-plane ratio in the following order: MoS<sub>2</sub> nanoparticles > multilayered MoS<sub>2</sub> > few-layered MoS<sub>2</sub>. A similar order was observed for the PCE values with corresponding CEs-based DSSCs. The MoS<sub>2</sub> nanoparticles-based CE had the minimum  $R_{CT}$ , while the few-layered MoS<sub>2</sub> based CE had the maximum, as measured by EIS. The active sites of MoS<sub>2</sub>





responsible for the reduction of triiodide lie on the edges of layered materials, instead of their basal planes. MoS<sub>2</sub> nanoparticle CE showed the highest PCE value of 5.41%, compared with 6.58% of Pt CE. A novel approach for improving PCE of MoS<sub>2</sub> CE based DSSCs has been developed,<sup>134</sup> where electrocatalytic activity was enhanced by artificially generating active edge sites on MoS<sub>2</sub> atomic layers by hole patterning. The PCE of the DSSC increased from 2% to 5.8% after applying the hole patterning approach. Al-Mamun *et al.*<sup>135</sup> deposited MoS<sub>2</sub> nano-scale thin films onto FTO substrates using a low temperature one-pot hydrazine assisted hydrothermal method. Both the hydrothermal reaction temperature as well as the different molar ratio of reaction precursors was found to impact the structure and performance of MoS<sub>2</sub> films used as CEs for DSSCs. The MoS<sub>2</sub> thin films having surface exposed layered nanosheets were obtained by the hydrothermal process with a molar ratio of reaction precursors as 1 : 28 of (NH<sub>4</sub>)<sub>6</sub>Mo<sub>7</sub>O<sub>24</sub>·4H<sub>2</sub>O and NH<sub>2</sub>-CSNH<sub>2</sub> (thiourea) at 150 °C for 24 hours, referred to as MS-150-28. The molar ratio of (NH<sub>4</sub>)<sub>6</sub>Mo<sub>7</sub>O<sub>24</sub>·4H<sub>2</sub>O and NH<sub>2</sub>CSNH<sub>2</sub> was fixed at 1 : 7, 1 : 14, 1 : 28 and 1 : 42 and the hydrothermal temperature was maintained at either 120, 150, 180 or 210 °C. The DSSCs having MoS<sub>2</sub> CEs fabricated using different molar ratios of reaction precursors at a temperature of 150 °C (referred to as MS-150-7, MS-150-14, MS-150-28 and MS-150-42) exhibited PCEs of 3.70, 4.97, 7.41 and 4.96%, respectively. The DSSCs with MS-120-28, MS-180-28, and MS-210-28 CEs showed PCEs of 5.52, 7.15 and 5.47%, respectively. The MoS<sub>2</sub> film based CEs showed a PCE of 7.41%, higher than the Pt electrode based DSSCs ( $\eta$  = 7.13%) using TiO<sub>2</sub> photoanodes sensitized by N719 dye.

Pulse electrochemical deposited thin films of molybdenum sulfide (MoS<sub>x</sub>) on indium tin oxide/poly(ethylene naphthalate) (ITO/PEN) substrates have been studied as flexible CEs for DSSC, and these showed a PCE of 4.39% for the triiodide (I<sub>3</sub><sup>-</sup>) reduction.<sup>136</sup> The nanostructured MoS<sub>2</sub> thin films developed by a low-temperature thermally reduced technique on a FTO substrate have also been used for DSSCs.<sup>137</sup> MoS<sub>2</sub> thin film annealed at 300 °C were also used as CEs for DSSCs, which showed a PCE of 6.351%, slightly lower than the Pt reference CE ( $\eta$  = 6.929%). The performance of DSSCs was impacted by the molar ratio of reaction precursors and the temperature of thermal reaction. Thermally reduced (TR) MoS<sub>2</sub> thin film annealed at 250 °C showed PCE of 1.917%, while those annealed at 350 °C showed PCE of 3.479%. The 300 °C annealed TR-MoS<sub>2</sub> CE also has larger exchange current density than those of 250 °C and 350 °C annealed TR-MoS<sub>2</sub> CEs and comparable with thermally deposited (TD) Pt CE. The  $R_{CT}$  values that correspond to the charge-transfer resistance at the electrolyte-electrode interface were 14.98  $\Omega$  cm<sup>2</sup> for TD-Pt CE and 30.98, 141.41  $\Omega$  cm<sup>2</sup> for TR-MoS<sub>2</sub> CEs annealed at 300 °C and 350 °C, respectively. TR-MoS<sub>2</sub> CEs annealed at 250 °C has no  $R_{CT}$  value being too large. The annealing temperature of 300 °C generates much larger active area, providing the highest electrocatalytic activity for the reduction of I<sub>3</sub><sup>-</sup>, while 350 °C annealing decreases the active sites of the edge-planes in MoS<sub>2</sub>. A PCE of 7.01% was achieved for DSSCs using pristine MoS<sub>2</sub> as a CE, chemically synthesized by low-temperature wet-chemical process, which has a comparable PCE of 7.31% for DSSCs

with Pt CEs.<sup>138</sup> The  $R_s$  and  $R_{CT}$  values of 23.51 and 18.50  $\Omega$  cm<sup>2</sup>, respectively, for the MoS<sub>2</sub> CE were lower than those of Pt CE (26.73 and 22.88  $\Omega$  cm<sup>2</sup>), suggesting better electro-catalytic activity of MoS<sub>2</sub> for the reduction of triiodide (I<sub>3</sub><sup>-</sup>).

A correlation between the electrical conductivity of the CE, PCE, and the crystallinity of MoS<sub>2</sub> was also demonstrated.<sup>139</sup> The XRD, XPS, EIS and Hall measurements established a link between the PCE, carrier concentration, mobility, and  $J_{sc}$  value. The DSSCs having pristine (non-annealed), vacuum-annealed and N<sub>2</sub>-annealed MoS<sub>2</sub> CEs showed PCE values of 1.0, 1.7 and 0.8%, respectively. Thermal annealing in vacuum was found to reduce the over-potential that leads to an increased  $J_{sc}$  value of 7.95 mA cm<sup>-2</sup> due to high MoS<sub>2</sub> crystallinity, whereas the N<sub>2</sub>-annealing of MoS<sub>2</sub> CEs increases over-potential, which gives rise to lower  $J_{sc}$  value of 4.35 mA cm<sup>-2</sup> due to the poor crystallinity of MoS<sub>2</sub>. Interestingly, the electrical conductivity of MoS<sub>2</sub> CEs follows the order: N<sub>2</sub>-annealed > vacuum-annealed > non-annealed MoS<sub>2</sub>. This indicates that the PCE of the DSSCs is influenced by the over-potential that involves an electron transferring from the MoS<sub>2</sub> CE to the electrolyte, instead of the electrical conductivity of the CE. Antonelou *et al.*<sup>140</sup> reported the growth of monolayer and few-layer MoS<sub>2</sub> films by the sulfuration of molybdenum (Mo) foils at 800 °C. The few-layer thick MoS<sub>2</sub> films were used as CEs for DSSCs for the reduction of I<sub>3</sub><sup>-</sup> to I<sup>-</sup>. The electrocatalytic activity of MoS<sub>2</sub> CE on flexible Mo substrates depends upon the number of monolayers in the DSSC. DSSCs having the MoS<sub>2</sub>/Mo CE yield a PCE of 8.4%, close to Pt/FTO-based DSSCs (PCE of 8.7%). Stability of a three-monolayer thick MoS<sub>2</sub> CE was studied for 100 consecutive cycles, where no degradation of the peak current density was noticed for 100 repeated cycles, confirming long term electrochemical stability in an electrolyte solution. MoS<sub>2</sub> layers with 1–2 nm thickness showed long term chemical stability of the DSSC device for the electrolyte solution comparable to Pt CE. The increased number of active sites due to a grainy surface texture of Mo foil leads to the higher electro-catalytic activity of MoS<sub>2</sub> films.

A very interesting comparison was made by Wu *et al.*<sup>141</sup> for chemically synthesized MoS<sub>2</sub> and WS<sub>2</sub> as CEs in the reduction of I<sub>3</sub><sup>-</sup> to I<sup>-</sup> and disulfide/thiolate (T<sub>2</sub>/T<sup>-</sup>) based DSSCs. The  $R_{CT}$  values of 0.5  $\Omega$  cm<sup>2</sup> for MoS<sub>2</sub> and 0.3  $\Omega$  cm<sup>2</sup> for WS<sub>2</sub>, respectively, compared with  $R_{CT}$  of 3.0  $\Omega$  cm<sup>2</sup> for Pt CE, indicates that both MoS<sub>2</sub> and WS<sub>2</sub> are as effective as CEs as standard Pt for triiodide (I<sub>3</sub><sup>-</sup>) reduction in DSSCs. The high FFs of 73% for MoS<sub>2</sub> CEs and 70% for WS<sub>2</sub> CEs also confirm high electro-catalytic activities for the reduction of triiodide (I<sub>3</sub><sup>-</sup>) to iodide (I<sup>-</sup>). Therefore, high PCE values of 7.59% for MoS<sub>2</sub> and 7.73% for WS<sub>2</sub> were observed, which are comparable to the PCE of 7.64% for Pt CEs in DSSCs under simulated AM 1.5 illumination. The  $Z_N$  of >100  $\Omega$  for triiodide (I<sub>3</sub><sup>-</sup>) reduction on the sulfide electrodes was found to be higher compared with a  $Z_N$  of 9.5  $\Omega$  on the Pt CE. The photocurrent density voltage ( $J$ - $V$ ) curves of the DSSCs having MoS<sub>2</sub>, WS<sub>2</sub>, and Pt based CEs for the triiodide/iodide (I<sub>3</sub><sup>-</sup>/I<sup>-</sup>) redox couple and disulfide/thiolate (T<sub>2</sub>/T<sup>-</sup>) redox couple are shown in (Fig. 5). The TiO<sub>2</sub> film photoanode was obtained after pre-heating at 80 °C and immersing in a 5 × 10<sup>-4</sup> M solution of N719 dye in acetonitrile/*tert*-butyl alcohol for 20 hours. The





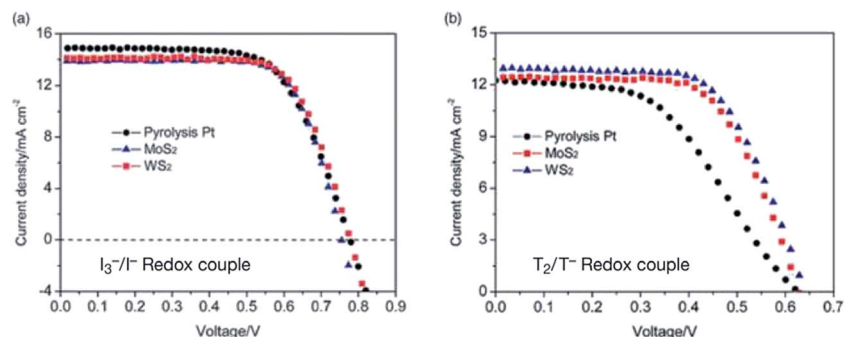


Fig. 5 (a) Photocurrent density–voltage ( $J$ – $V$ ) curves of the DSSCs having  $\text{MoS}_2$ ,  $\text{WS}_2$ , and Pt counter electrodes for triiodide to iodide ( $\text{I}_3^-/\text{I}^-$ ) reduction. (b)  $J$ – $V$  curves of the DSSCs using  $\text{MoS}_2$ ,  $\text{WS}_2$  and Pt CEs for redox couple of disulfide/thiolate ( $\text{T}_2/\text{T}^-$ ). Reprinted with permission from ref. 141, M. Wu, Y. Wang, X. Lin, N. Yu, L. Wang, L. Wang, A. Hagfeldt and T. Ma, economical and effective sulfide catalysts for dye-sensitized solar cells as counter electrodes. *Phys. Chem. Chem. Phys.*, 2011, **13**, 19298–19301. Copyright© Royal Society of Chemistry/Owner Societies.

triiodide/iodide ( $\text{I}_3^-/\text{I}^-$ ) electrolyte is made of 0.06 M of lithium iodide (LiI), 0.03 M of  $\text{I}_2$ , 0.5 M of 4-*tert*-butyl pyridine, 0.6 M of 1-butyl-3-methylimidazolium iodide, and 0.1 M of guanidinium thiocyanate in acetonitrile. The 5-mercapto-1-methyltetrazole di-5-(1-methyltetrazole) disulfide/*N*-tetramethylammonium salt ( $^+\text{NMe}_4\text{T}^-$ ) ( $\text{T}_2/\text{T}^-$ ) electrolyte consists of 0.4 M of  $^+\text{NMe}_4\text{T}^-$ , 0.05 M of  $\text{LiClO}_4$ , 0.4 M of di-5-(1-methyltetrazole) disulfide ( $\text{T}_2$ ), and 0.5 M 4-*tert*-butylpyridine in acetonitrile and ethylene carbonate solution. For both DSSCs, a spray-coating technique was used for fabricating  $\text{MoS}_2$  and  $\text{WS}_2$  CEs. The  $J$ – $V$  curves of the DSSCs having sulfide CEs and  $\text{T}_2/\text{T}^-$  electrolyte show PCE values of 4.97% for  $\text{MoS}_2$ , 5.24% for  $\text{WS}_2$ , and 3.70% for Pt CE. The PCE values were increased 36% for  $\text{MoS}_2$  and 41% for  $\text{WS}_2$  compared to the Pt CE, showing that DSSCs having  $\text{MoS}_2$  and  $\text{WS}_2$  are better than that of the Pt CE for the  $\text{T}_2/\text{T}^-$  redox couple.

The interfaced exfoliated  $\text{MoS}_2$  thin films with different porphyrin molecules, where the  $\text{MoS}_2$  was functionalized with zinc(II) porphyrin (ZnPP), showed a 10-fold increase in photocurrent compared to  $\text{MoS}_2$  films.<sup>142</sup> Exfoliated ultrathin porous  $\text{MoS}_2$  sheets prepared by a tetraethylorthosilicate (TEOS)-assisted hydrothermal method were used as CEs in DSSCs.<sup>143</sup> The cyclic voltammograms and electrochemical impedance spectroscopy showed low  $R_{\text{CT}}$  and high electro-catalytic activity for porous  $\text{MoS}_2$  sheets CEs in DSSCs, with a PCE of 6.35%, slightly better than that of Pt CEs ( $\eta = 6.19\%$ ) under similar experimental conditions. A CE created by spin-coating of  $\text{MoS}_2$  nanosheets followed by thermal treatment was also prepared.<sup>144</sup> DSSCs having  $\text{MoS}_2$  nanosheets thermally treated at 100 °C showed a PCE value of 7.35%, comparable to conventional a Pt CE (7.53%). When  $\text{MoS}_2$  nanosheets were thermally treated at 300 °C, the PCE value decreased significantly due to the transformation of  $\text{MoS}_2$  to  $\text{MoO}_3$ .  $\text{MoS}_2$  films deposited on FTO glass using an RF sputtering method were also used as CEs for  $\text{TiO}_2$ -based DSSCs.<sup>145</sup> CV, EIS, and Tafel polarization curve measurements conducted on the  $\text{MoS}_2$  CE showed high electrocatalytic activity, low charge-transfer resistance as well as the fast reaction kinetics for triiodide ( $\text{I}_3^-$ ) reduction. The  $\text{MoS}_2$  CE prepared after 5 minutes of sputtering showed a PCE of 6.0%, comparable to Pt CEs ( $\eta = 6.6\%$ ) in DSSCs. The PCE of DSSCs having  $\text{MoS}_2$  CEs sputtered for 1, 3, 5 and 7 minutes were 5.7,

5.8, 6.0, and 5.2%, respectively.  $\text{MoS}_2$  CEs were also developed by synthesizing  $\text{MoS}_2$  films at 70 °C using molybdenum(V) chloride and thioacetamide, followed by near-infrared laser-sintering for 1 minute to enhance crystallinity and inter-connectivity between the  $\text{MoS}_2$  particles.<sup>146</sup> The DSSC with laser-sintered  $\text{MoS}_2$  CE exhibited a PCE of 7.19%, much higher than heat-sintered  $\text{MoS}_2$  CE (5.96%) and comparable with a Pt CE ( $\eta = 7.42\%$ ). The laser-sintered  $\text{MoS}_2$  CE offers superior electrocatalytic activity for the triiodide ( $\text{I}_3^-$ ) to iodide ( $\text{I}^-$ ) redox couple. Also, a solution-phase process was used to grow  $\text{MoS}_2$  nanofilms on FTO glass as a CE for a DSSC, which showed a PCE of 8.3%.<sup>147</sup> Finally, exfoliated and annealed  $\text{MoS}_{2x}\text{Se}_2(1-x)$  as well as exfoliated- $\text{MoS}_2$  films were used as CEs.<sup>148</sup> The thickness and size of exfoliated  $\text{MoS}_2$  nanosheets were 0.9 by 1.2 nm and 0.2 by 2  $\mu\text{m}$ , corresponding to a single-layer. The  $\text{MoS}_2$  based CE showed a PCE of 6%, compared to 5.1% for the annealed  $\text{MoS}_2$  films.

**3.1.2  $\text{MoS}_2$ /graphene composites.** 2D TMDs based composites have been extensively investigated.<sup>149,150</sup> Like graphene,  $\text{MoS}_2$  can be mechanically exfoliated into nanosheets from its bulk crystals and used for studying electronics and photonic properties. These 2D layered materials can be combined into a single hybrid structure, so that both  $\text{MoS}_2$  and graphene components can synergistically enhance photovoltaic properties. The nanocomposites of  $\text{MoS}_2$  and graphene have been investigated as CEs for DSSCs.

To fabricate a Pt-free DSSC, Lin *et al.*<sup>151</sup> used a  $\text{MoS}_2$ /graphene nanosheet composite as a CE and nanocrystalline  $\text{TiO}_2$  as a photoanode. The redox electrolyte solution in the DSSC was made of 1 M 1,3-dimethylimidazolium iodide, 0.15 M iodine, 0.5 M 4-*tert*-butylpyridine and 0.1 M guanidine thiocyanate in 3-methoxypropionitrile. The  $\text{MoS}_2$ /graphene nanosheet based CE showed a PCE of 5.81%, in comparison to a PCE of 6.24% for the conventional sputtered Pt CE. Yue *et al.*<sup>152</sup> used a  $\text{MoS}_2$ /graphene flake composite film as the CEs for DSSCs with N719 dye for the reduction of triiodide ( $\text{I}_3^-$ ) to iodide ( $\text{I}^-$ ). The  $\text{MoS}_2$  powder (ARCOS, 99%) and 8 nm flakes of multi-layer graphene nanopowder (Uni-Onward Corp., 99.5%) were mixed in specific ratios to prepare the composites. The electrocatalytic activity increased after adding graphene flakes to the  $\text{MoS}_2$  film.



Charge-transfer resistances ( $R_{CT}$ ) of  $3.98 \Omega \text{ cm}^2$  for graphene,  $2.71 \Omega \text{ cm}^2$  for  $\text{MoS}_2$ ,  $2.09 \Omega \text{ cm}^2$  for  $\text{MoS}_2/\text{graphene}$ , and  $2.01 \Omega \text{ cm}^2$  for Pt CEs were measured. The current density of the  $\text{MoS}_2/\text{graphene}$  composite CE was recorded to be higher than that of the  $\text{MoS}_2$ , graphene and Pt CEs. The  $J$ - $V$  characteristics of the DSSCs having  $\text{MoS}_2/\text{graphene}$  as CEs and ranging in thickness from single-layer to six-layer were investigated and compared with conventional Pt CEs. The thickness of the  $\text{MoS}_2/\text{graphene}$  layers affected the PCE of the DSSCs, and  $J_{sc}$  and  $V_{oc}$  increased with increasing number of plaster layers from single to 3-layer, and, thereafter, a decrease was noticed for 4-layers and 5-layers. The effect of graphene content was also studied, where, the  $R_{CT}$  was found to decrease for the  $\text{MoS}_2/\text{graphene}$  CE, from 0.5 wt% to 1.5 wt% of graphene content. The PCE of the  $\text{MoS}_2/\text{graphene}$  composite CE having 1.5 wt% graphene was 5.98%, compared to the PCE of 6.23% for Pt CE. Yu *et al.*<sup>153</sup> used  $\text{MoS}_2$  nanosheets and graphene composites for fabricating CEs for the triiodide ( $\text{I}_3^-$ ) reduction. Graphene thin films were prepared by the chemical vapor deposition (CVD) technique in combination with a hydrothermal process.  $\text{MoS}_2$  nanosheets with 210 nm thickness were *in situ* grown on FTO glass substrate, and uniformly dispersed on the surface of a graphene film. Fig. 6 shows the morphology of the synthesized graphene- $\text{MoS}_2$  composites, using field-emission scanning electron microscopy (FESEM) and high-resolution transmission electron microscopy (HRTEM) with different magnifications. The thickness of the graphene film was found to be 2.48 nm by atomic force

microscopy, which corresponds to seven layers of graphene. The top-view FESEM images of graphene- $\text{MoS}_2$  hybrids showed fully covered graphene film with 5 to 20 nm thick  $\text{MoS}_2$  nanosheets. The nucleation and growth of  $\text{MoS}_2$  nanosheets depends upon the graphene film. Graphene films play an active role for higher electrical conductivity by speeding up the charge transfer process and generating active sites for dispersion and integration of  $\text{MoS}_2$  nanosheets. The presence of  $\text{MoS}_2$  nanosheets increases the electrode-electrolyte contact area, and therefore helps in improving the electrocatalytic activity. The low  $R_{CT}$  of  $1.5 \Omega \text{ cm}^2$  for  $\text{MoS}_2/\text{graphene}$  CE,  $1.7 \Omega \text{ cm}^2$  for  $\text{MoS}_2$ ,  $1.70 \Omega \text{ cm}^2$  for graphene, and a high  $R_{CT}$  of  $2.1 \Omega \text{ cm}^2$  for a Pt CE, indicates better interaction and contact formation of  $\text{MoS}_2$  nanosheets and graphene film with fluorine doped tin oxide (FTO) substrates and a fast charge transfer. The FF of graphene is 24% compared to a FF of 65% for  $\text{MoS}_2$ , however when both materials are combined into a composite system, the FF raises to 68%. Therefore,  $\text{MoS}_2$  nanosheet/graphene composite CEs resulted in a higher PCE of 7.1% because of the synergetic interactions between graphene and  $\text{MoS}_2$ , compared to the low PCE values of 2.8% for graphene and 5.6% for  $\text{MoS}_2$ , and a comparable PCE of 7.4% for Pt reference CEs.  $\text{MoS}_2/\text{graphene}$  based CEs in a DSSC offer higher electrocatalytic activity for triiodide ( $\text{I}_3^-$ ) reduction induced by the synergetic interactions. Fig. 7 represents the  $J$ - $V$  characteristics of DSSCs having graphene- $\text{MoS}_2$  as CEs with increasing number of layers<sup>152</sup> and



**Fig. 6** Field-emission scanning electron microscopy (FESEM) images of graphene- $\text{MoS}_2$  composites with different magnifications; (a) side-view, (b) and (c) top-view. (d) and (e) top-view FESEM images of flower-like  $\text{MoS}_2$  clusters without graphene film. (f) and (g) high-resolution transmission electron microscopy (HRTEM) images of as-prepared graphene- $\text{MoS}_2$  hybrids. Reprinted with permission from ref. 153, C. Yu, X. Meng, X. Song, S. Liang, Q. Dong, G. Wang, C. Hao, X. Yang, T. Ma, P. M. Ajayan and J. Qiu, graphene-mediated highly-dispersed  $\text{MoS}_2$  nanosheets with enhanced triiodide reduction activity for dye-sensitized solar cells. *Carbon*, 2016, **100**, 474–483. Copyright© Elsevier.



graphene-MoS<sub>2</sub> nanosheet based CE for the triiodide (I<sub>3</sub><sup>-</sup>) reduction.<sup>153</sup>

MoS<sub>2</sub> nanosheets/graphene electrodes were also studied by Lynch *et al.*<sup>154</sup> the PCE of 95% of the Pt electrode was achieved after adding 10 wt% MoS<sub>2</sub> nanosheets to a graphene film CE. This again confirms that the MoS<sub>2</sub> nanosheet/graphene composite ECs have higher catalytic activity than graphene CEs, though the graphene nanosheets contribute to higher electrical conductivity in the composite. An electrochemical strategy<sup>155</sup> was used for preparing MoS<sub>2</sub>/graphene composite as CEs of DSSCs, which included electro-deposition and electro-reduction of graphene oxide, and thereafter electro-deposition of MoS<sub>2</sub> on reduced graphene oxide (GO) layers. The MoS<sub>2</sub>/graphene composites were characterized by SEM, TEM and Raman spectroscopy. The MoS<sub>2</sub>/graphene CEs based DSSCs exhibited a PCE of 8.01%, comparable to a PCE of 8.21% for the Pt CE. In another study, nanocomposites of MoS<sub>2</sub> and nitrogen-doped graphene oxide (N-GO) were used as a CE for DSSCs.<sup>156</sup> The MoS<sub>2</sub>/N-GO nanocomposites were characterized by HRTEM, XPS, and Raman spectroscopy, and their electrochemical properties were evaluated by EIS, CV, and Tafel measurements. The MoS<sub>2</sub>/N-GO nanocomposite formation offered high specific surface area of N-GO and many edge sites of MoS<sub>2</sub>. The MoS<sub>2</sub>/N-GO nanocomposite based CE exhibited a PCE of 5.95%, lower than the standard Pt CE (PCE of 6.43%).

Composite films of MoS<sub>2</sub> with nitrogen-doped graphene (N-graphene) were prepared using a drop-coating method and used as a CE of DSSCs.<sup>157</sup> The N-graphene supported an increase in electrical conductivity, whereas MoS<sub>2</sub> increased the electrocatalytic activity in the composite thin film. The N-graphene/MoS<sub>2</sub> composite film showed a PCE of 7.82%, lower than the Pt CE ( $\eta = 8.25\%$ ) based DSSC. The electrocatalytic capability of N-graphene/MoS<sub>2</sub> composite films for the triiodide (I<sub>3</sub><sup>-</sup>) reduction was much higher compared with pristine N-graphene and MoS<sub>2</sub> thin films, as studied using CV, RDE, the Tafel polarization curve, and EIS. The graphene flakes (GF) into a nanosheet-like MoS<sub>2</sub> matrix were dispersed using an *in situ* hydrothermal

method, and used a MoS<sub>2</sub>/GF hybrid as a CE to fabricate Pt-free DSSCs.<sup>158</sup> The incorporation of GFs into the MoS<sub>2</sub> matrix was confirmed using scanning electron microscopy (SEM), transmission electron microscopy (TEM), XRD, and Raman spectroscopy. The electrochemical measurements showed improvement in the electrocatalytic activity after the GFs were integrated into the MoS<sub>2</sub> matrix, where the hybrid containing 1.5 wt% of graphene flakes exhibited the highest electrocatalytic activity. The DSSC with the MoS<sub>2</sub>/GF hybrid CE showed a PCE of 6.07%, which was 95% of the Pt CE ( $\eta = 6.41\%$ ).

**3.1.3 MoS<sub>2</sub>/carbon nanotubes composites.** Carbon nanotubes (CNTs) are one of the most interesting materials because they offer high optical transparency, high electrical conductivity, high mechanical strength, and high thermal stability, and therefore CNTs have been studied as CEs for DSSCs. It is of great interest to combine the unique properties of both MoS<sub>2</sub> and CNTs into a single hybrid system which could synergistically enhance the electrocatalytic activity of a DSSC system. Yue *et al.*<sup>159</sup> used a flower-like structure of MoS<sub>2</sub>/single-wall carbon nanotubes (MoS<sub>2</sub>/SWCNTs) as CE catalyst for DSSCs, synthesized using a glucose and PEDOT:PSS assisted (G-P-A) hydrothermal process. The flower-like structure and surface morphology of the (G-P-A) MoS<sub>2</sub>/SWCNTs was confirmed by SEM and TEM techniques. The DSSC having (G-P-A) MoS<sub>2</sub>/SWCNTs CE exhibits a lower  $R_{CT}$  of 1.46  $\Omega\text{ cm}^2$  compared to the  $R_{CT}$  of 2.44  $\Omega\text{ cm}^2$  for the Pt electrode. The PCE reached 8.14%, better than that of the Pt-based DSSC (7.78%) with the iodide/triiodide (I<sub>3</sub><sup>-</sup>) electrolyte. The speedy reduction of triiodide (I<sub>3</sub><sup>-</sup>) to iodide (I<sup>-</sup>) by the (G-P-A) MoS<sub>2</sub>/SWCNTs CE is attributed to the fast transport of the electrolyte *via* the flower-like structure. The MoS<sub>2</sub> and multi-walled carbon nanotube (MWCNTs) nanocomposites were employed as a CE in DSSCs for the reduction of triiodide (I<sub>3</sub><sup>-</sup>).<sup>160</sup> The microstructure of the MWCNTs@MoS<sub>2</sub> nanocomposite studied by transmission electron microscopy (TEM) confirmed the deposition of few-layers MoS<sub>2</sub> nanosheets on the MWCNTs surface. A MWCNTs@MoS<sub>2</sub> composite based CE resulted in higher



Fig. 7 (a) *J*-*V* characteristics of DSSCs having MoS<sub>2</sub>/graphene as counter electrodes with different thickness ranging from single-layer to six-layer and a comparison with sputtered Pt counter electrode (PEC of 6.23%). Reprinted with permission from ref. 152, G. Yue, J. Y. Lin, S. Y. Tai, Y. Xiao and J. Wu, A catalytic composite film of MoS<sub>2</sub>/graphene flake as a counter electrode for Pt-free dye-sensitized solar cells. *Electrochim. Acta*, 2012, **85**, 162–168. Copyright© Elsevier. (b) *J*-*V* curves of DSSCs based on Pt, graphene/MoS<sub>2</sub>, MoS<sub>2</sub>, and graphene CEs. Reprinted with permission from ref. 153, C. Yu, X. Meng, X. Song, S. Liang, Q. Dong, G. Wang, C. Hao, X. Yang, T. Ma, P. M. Ajayan and J. Qiu, graphene-mediated highly-dispersed MoS<sub>2</sub> nanosheets with enhanced triiodide reduction activity for dye-sensitized solar cells. *Carbon*, 2016, **100**, 474–483. Copyright© Elsevier.





cathodic current density than those of MWCNTs, MoS<sub>2</sub>, and Pt CEs. The MWCNTs@MoS<sub>2</sub> CE showed a low charge-transfer resistance of 1.69 Ω cm<sup>2</sup> and no degradation up to 100 repeated cyclic voltammogram tests. The DSSC having a MWCNTs@MoS<sub>2</sub> composite CE exhibited a PCE of 6.45%, slightly better than that of the DSSC having sputtered Pt CE ( $\eta$  = 6.41%). The MWCNT@MoS<sub>2</sub> based CE also showed improved catalytic activity for the reduction of I<sub>3</sub><sup>−</sup>.

The MoS<sub>2</sub> nanosheets anchored onto the CNT surfaces were used in Pt-free CEs for DSSCs.<sup>161</sup> The MoS<sub>2</sub> nanosheets offer edge-plane electrocatalytically active sites for the reduction of I<sub>3</sub><sup>−</sup>. The large surface area of CNTs supports the loading of MoS<sub>2</sub> nanosheets in order to increase the electrochemical activity. The CNTs deposited onto the FTO substrate promoted charge transport, leading to a higher exchange current density and also to the lower charge-transfer resistance. The MoS<sub>2</sub>/CNT hybrid based DSSCs achieved a PCE of 7.83%, which is 9.5% higher than that of the Pt CE ( $\eta$  = 7.15%) based DSSC.

Another research group<sup>162</sup> used flower-like MoS<sub>2</sub> and a multi-walled carbon nanotubes (MoS<sub>2</sub>/MWCNTs) hybrid as a CE for dye-sensitized solar cells. The flower-like MoS<sub>2</sub>/MWCNTs hybrid contains a large specific surface area and lamellar structure, as evidenced by field emission scanning electron microscopy (FESEM). The optimized MoS<sub>2</sub>/MWCNTs has a  $R_{CT}$  of 2.05 Ω cm<sup>2</sup> and series resistance ( $R_s$ ) of 1.13 Ω cm<sup>2</sup> as measured by electrochemical impedance spectroscopy. Cyclic voltammogram measurements showed larger current density for MoS<sub>2</sub>/MWCNTs based CEs than those of MoS<sub>2</sub>, MWCNTs, and Pt CEs.

MoS<sub>2</sub>/MWCNTs CE based DSSCs exhibited a PCE of 7.50%, comparable with the DSSC based on the Pt CE ( $\eta$  = 7.49%). A carbon nanotubes–MoS<sub>2</sub>–carbon (CNTs–MoS<sub>2</sub>–carbon) hybrid was prepared using wet impregnation and calcination with polyethylene glycol as a CE for DSSCs.<sup>163</sup> Spectroscopic characterization by Raman spectra, XRD, TEM, XPS, BET and thermal methods indicated a homogenous coating of CNTs with thin layers of MoS<sub>2</sub>, as a result of wetting and emulsification of polyethylene glycol 400. The CNTs–MoS<sub>2</sub>–carbon heterostructure was used as CEs for DSSCs, and showed high stability and electrocatalytic activity in the reduction of I<sub>3</sub><sup>−</sup> to I<sup>−</sup> because of low  $R_{CT}$ . Interestingly, a PCE of 7.23% achieved for the CNTs–MoS<sub>2</sub>–carbon CEs based DSSC was higher than Pt CEs ( $\eta$  = 6.19%).

In another study, nanocomposites of MoS<sub>2</sub> and CNTs using a glucose aided (G–A) hydrothermal method were prepared by Yue *et al.*<sup>164</sup> The (G–A)MoS<sub>2</sub>/CNTs nanocomposites obtained by adding 0.5, 1.0, 1.5, 2.0 and 2.5 wt% of acid-treated CNTs were deposited onto a FTO substrate and used as CEs in DSSCs for the reduction of triiodide (I<sub>3</sub><sup>−</sup>) to iodide (I<sup>−</sup>). The dye-sensitized TiO<sub>2</sub> anode was prepared by dipping the TiO<sub>2</sub> anode in 0.3 mM of dye N719 ethanol for 24 hours. Fig. 8 shows the SEM images of MoS<sub>2</sub> nanopowder and MoS<sub>2</sub>–MWCNTs composites,  $J$ – $V$  characteristics of the DSSCs fabricated with MoS<sub>2</sub>, MoS<sub>2</sub>/C, (G–A)MoS<sub>2</sub>/CNTs and Pt CEs, and the effect of CNT contents on the PCE of the DSSCs using (G–A)MoS<sub>2</sub>/CNTs. Scanning and transmission electron microscopy showed tentacle-like structures of the MoS<sub>2</sub>/CNTs composites, having large active surface area and



Fig. 8 Scanning electron microscopic image of MoS<sub>2</sub> nanopowder and MoS<sub>2</sub>–MWCNTs composites prepared by glucose aided (G–A) hydrothermal method. Photocurrent–voltage ( $J$ – $V$ ) characteristics of the DSSCs fabricated with MoS<sub>2</sub>, MoS<sub>2</sub>/C, (G–A)MoS<sub>2</sub>/CNTs and Pt CEs. Relationship between the contents of CNTs in (G–A)MoS<sub>2</sub>/CNTs CE and the PCE of DSSCs. Reprinted with permission from ref. 164, G. Yue, W. Zhang, J. Wu and Q. Jiang, glucose aided synthesis of molybdenum sulfide/carbon nanotubes composites as counter electrode for high performance dye-sensitized solar cells. *Electrochim. Acta*, 2013, **112**, 655–662. Copyright© Elsevier.



interconnected networks for fast transport for the electrolyte. The CNTs functionalized with a  $-\text{COOH}$  functional group were used and  $\text{MoS}_2$  was anchored onto the functionalized CNTs. The (G-A) $\text{MoS}_2/\text{CNTs}$  had specific surface area of  $411.7 \text{ m}^2 \text{ g}^{-1}$  and exhibited a small overpotential and better conductivity. The Nernst diffusion impedance ( $Z_w$ ) values of  $1.85 \Omega \text{ cm}^2$  for (G-A) $\text{MoS}_2/\text{CNTs}$  CEs and  $2.25 \Omega \text{ cm}^2$  for Pt CEs were measured, which indicates that the (G-A) $\text{MoS}_2/\text{CNTs}$  catalyst accelerated the reduction of triiodide ions ( $\text{I}_3^-$ ) to iodide ions ( $\text{I}^-$ ). The (G-A) $\text{MoS}_2/\text{CNTs}$  based CEs were found to exhibit enhanced electrocatalytic activity as evidenced by the CV, EIS, and Tafel polarization measurements. The photovoltaic performance of the DSSCs having  $\text{MoS}_2$ ,  $\text{MoS}_2/\text{C}$ , (G-A) $\text{MoS}_2/\text{CNTs}$ , and Pt CEs were compared. The photovoltaic performance of (G-A) $\text{MoS}_2/\text{CNTs}$  CEs were also studied as a function of the CNT contents. The PCE of the DSSCs increased as the contents of the CNTs increased from 0 to 1.5 wt%, however, further increase in CNT content leads to a decreased PCE. Likely, the maximum photovoltaic performance of the (G-A) $\text{MoS}_2/\text{CNTs}$  CE in the DSSCs was achieved for a film thickness of  $12 \mu\text{m}$ . The (G-A) $\text{MoS}_2/\text{CNTs}$  composite CE has a lower  $R_{\text{CT}}$  of  $1.77 \Omega \text{ cm}^2$  at the electrolyte/electrode interface than those of  $\text{MoS}_2$ ,  $\text{MoS}_2/\text{carbon}$  and conventional sputtered Pt CEs, and a PCE of 7.92% higher than the PCE of 7.11% for the Pt electrode in DSSCs for the triiodide/iodide ( $\text{I}_3^-/\text{I}^-$ ) system. Lin *et al.*<sup>165</sup> fabricated nanocomposites of  $\text{MoS}_2/\text{reduced graphene oxide (RGO)}$  with CNTs using electrophoretic deposition. The  $\text{MoS}_2/\text{RGO-CNTs}$  hybrid was then used as a CE in DSSCs. In this hybrid, CNTs offer conductive networks for electron transport to increase the rate of charge-transfer at the CE/electrolyte interface. The  $\text{MoS}_2/\text{RGO-CNTs}$  hybrid CEs show improved electrocatalytic activity

in comparison with the  $\text{MoS}_2/\text{RGO}$  alone. The DSSC having a  $\text{MoS}_2/\text{RGO-CNTs}$  hybrid CE achieved a PCE of 7.46%, exceeding PCE values of DSSCs containing  $\text{MoS}_2/\text{RGO}$  CE ( $\eta = 6.82\%$ ) and Pt CE ( $\eta = 7.23\%$ ). Thin films of  $\text{MoS}_2/\text{carbon}$  nanotube composites have also been applied as electrodes for lithium ion batteries.<sup>166</sup>

**3.1.4  $\text{MoS}_2/\text{TiO}_2$  composites.**  $\text{MoS}_2/\text{TiO}_2$  heterostructures were developed by Du *et al.*<sup>167</sup> by depositing few-layer  $\text{MoS}_2$  on mesoporous  $\text{TiO}_2$  by a chemical-bath method. Raman spectrum and HRTEM images indicated a few-layer structure of the  $\text{MoS}_2$ . After few-layer  $\text{MoS}_2$  deposition, the UV absorption spectra of the  $\text{TiO}_2$  photoanode showed enhanced absorption in the visible wavelength region and a PCE of 1.08% for the  $\text{MoS}_2/\text{TiO}_2$  based DSSC. Photovoltaic performance of the DSSC was found to be optimized by both thermal annealing and the thickness of the  $\text{MoS}_2$  sensitized layer. Jhang *et al.*<sup>168</sup> modified the interface of a  $\text{MoS}_2$  CE/electrolyte by incorporating  $\text{TiO}_2$  nanoparticles, in order to control the overpotential loss. Their  $\text{MoS}_2/\text{TiO}_2$  nanocomposite had a weight ratio of 5 : 1. Thermal annealing of the  $\text{MoS}_2$  and  $\text{MoS}_2/\text{TiO}_2$  CEs was performed at  $400^\circ\text{C}$  in vacuum for 2 hours. Fig. 9 shows the  $J-V$  curves for  $\text{MoS}_2$ ,  $\text{MoS}_2/\text{TiO}_2$ , and Pt CEs in the DSSCs. The addition of  $\text{TiO}_2$  nanoparticles into the  $\text{MoS}_2$  CE significantly increased the  $J_{\text{sc}}$  value from  $7.24 \text{ mA cm}^{-2}$  for the  $\text{MoS}_2$  CE to  $13.76 \text{ mA cm}^{-2}$  for the  $\text{MoS}_2/\text{TiO}_2$  CE. The  $\text{MoS}_2/\text{TiO}_2$  CE based DSSC ( $\eta = 5.08\%$ ) shows two times better photovoltaic performance compared with the  $\text{MoS}_2$  CE (2.54%) and comparable to the Pt CE (5.27%), because of an increased active surface area from the incorporated  $\text{TiO}_2$  nanoparticles and the low overpotential loss. Though the  $\text{MoS}_2/\text{TiO}_2$  CE exhibited high PCE, its electrical conductivity was found to be lower compared to the  $\text{MoS}_2$  CE, and, therefore, the high electrocatalytic activity was not related to its electrical conductivity.

The  $\text{MoS}_2/\text{TiO}_2$  based CE doped with different Co contents for the DSSCs were found to influence the PCE by improving electrocatalytic activity.<sup>169</sup> The Co content-optimized  $\text{MoS}_2/\text{TiO}_2$  CE had enhanced catalytic activity at the electrolyte interfaces. The Co 3d orbit plays a role in increasing in the reduction of  $\text{I}_3^-$  to  $\text{I}^-$ . The photoanodes were developed using  $\text{MoS}_2$  and  $\text{TiO}_2$  nanoparticles.<sup>170</sup> The DSSCs with  $\text{MoS}_2@\text{TiO}_2$  photoanode showed a PCE of 6.02%, 1.5 times higher than that of the  $\text{TiO}_2$  film photoanode ( $\eta = 4.43\%$ ).

**3.1.5  $\text{MoS}_2/\text{carbon}$  composites.** A very interesting study on  $\text{MoS}_2/\text{carbon}$  composites was conducted by Yue *et al.*<sup>171</sup> who developed DSSCs using  $\text{MoS}_2$  and carbon composites as a CE with different contents of carbon. Fig. 10 represents the SEM images of hydrothermally synthesized  $\text{MoS}_2$  and a porous  $\text{MoS}_2$ -carbon hybrid, a HRTEM image of  $\text{MoS}_2$ -carbon hybrid, an IPCE spectra, and  $J-V$  curves of the DSSCs with  $\text{MoS}_2$ ,  $\text{MoS}_2$ -carbon hybrid, and Pt CEs. The commercial  $\text{MoS}_2$  particles have lamellar structure with large surface area. The hydrothermally prepared  $\text{MoS}_2$  and  $\text{MoS}_2$ -carbon hybrid contains a large number of interlaced nanosheets. The intercalated nanosheets in the  $\text{MoS}_2$ -carbon hybrid are thinner compared with  $\text{MoS}_2$ , indicating an increase in the specific surface area, which is highly suitable for improving the electrocatalytic activity. The  $\text{MoS}_2$  and  $\text{MoS}_2$ -carbon hybrid CEs were characterized by CV,



Fig. 9 Photocurrent density–voltage ( $J-V$ ) characteristics curves of DSSCs with (a)  $\text{MoS}_2$ , (b)  $\text{MoS}_2/\text{TiO}_2$  and (c) Pt counter electrodes measured under the solar light illumination of  $100 \text{ mW cm}^{-2}$  (AM 1.5G). Reprinted with permission from ref. 168, W. H. Jhang and Y. J. Lin, interface modification of  $\text{MoS}_2$  counter electrode/electrolyte in dye-sensitized solar cells by incorporating  $\text{TiO}_2$  nanoparticles. *Curr. Appl. Phys.*, 2015, 15, 906–909. Copyright© Elsevier.





**Fig. 10** Scanning electron microscopy (SEM) images of (a) commercial MoS<sub>2</sub>, (b) hydrothermal route synthesized MoS<sub>2</sub>, (c) porous MoS<sub>2</sub>-carbon hybrid prepared by a hydrothermal route, (d) high-resolution TEM image of MoS<sub>2</sub>-carbon hybrid, (e) photocurrent-voltage (*J*-*V*) curves of the DSSCs with MoS<sub>2</sub>, MoS<sub>2</sub>-C and Pt CEs and (f) incident photon-to-current efficiency (IPCE) spectra of the DSSCs with MoS<sub>2</sub>, MoS<sub>2</sub>-C and Pt CEs. Reprinted with permission from ref. 171, G. Yue, J. Wu, Y. Xiao, M. Huang, J. Lin and J. Y. Lin, high performance platinum-free counter electrode of molybdenum sulfide-carbon used in dye-sensitized solar cells. *J. Mater. Chem. A*, 2013, 1, 1495–1501. Copyright© Royal Society of Chemistry.

EIS, and Tafel polarization curve measurements, and compared with the Pt CE. IPCE spectra of MoS<sub>2</sub>, MoS<sub>2</sub>-C, and Pt CEs in DSSCs measured in the 300–750 nm range show a similar photoelectric response. A strong photoelectric peak in the IPCE spectra appears at 340 nm. DSSCs with MoS<sub>2</sub> CE show the highest photoelectric response of 44.6% in the IPCE spectra at 520 nm, which is lower compared to a DSSC having a Pt CE (60.9%). Interestingly, in the IPCE spectra of the DSSC having porous MoS<sub>2</sub>-carbon CE, the highest photoelectric response of 67.3% is observed at 520 nm, which is higher than that of the Pt CE based DSSC. If one compares the  $R_{CT}$  values of 4.13  $\Omega\text{ cm}^2$  for MoS<sub>2</sub> and 2.29  $\Omega\text{ cm}^2$  for Pt electrodes, the MoS<sub>2</sub>/carbon electrode had a low  $R_{CT}$  value of 2.07  $\Omega\text{ cm}^2$ , appearing as a result of the high conductivity and large surface area for the MoS<sub>2</sub>/

carbon composite, which eventually contributes to enhanced electrocatalytic activity of the CE. The  $R_{CT}$  values of the MoS<sub>2</sub>/carbon electrode are also influenced by the carbon content, which decreases with the increase in carbon content, from 3.60  $\Omega\text{ cm}^2$  for 1.13 wt% carbon to 2.07  $\Omega\text{ cm}^2$  for 3.30 wt% carbon. Thereafter, the  $R_{CT}$  values increased from 2.40  $\Omega\text{ cm}^2$  for 4.35 wt% carbon content to 3.13  $\Omega\text{ cm}^2$  for 5.38 wt% carbon content. PCE values of 6.01, 7.03, 7.69, 7.33 and 5.76% were measured for MoS<sub>2</sub>-carbon electrodes having 1.13, 2.23, 3.30, 4.35 and 5.38 wt% of carbon content, respectively. The highest value of 7.69% was achieved at 3.30 wt% carbon content in a MoS<sub>2</sub>/carbon composite CE based DSSC for the  $\text{I}^-/\text{I}_3^-$  redox reaction, and exceeded the PCE value of 6.74% for a Pt CE under similar experimental conditions. PCE values of the DSSCs were also



**Table 2** Photovoltaic parameters of MoS<sub>2</sub> based counter electrodes (CEs) used for DSSCs. FTO glass is the common substrate used in assembling DSSCs with different CE materials. The measurements were conducted at a simulated solar light intensity of 100 mW cm<sup>-2</sup> (AM 1.5G) unless specified. The photovoltaic parameters short-circuit photocurrent density ( $J_{sc}$ ), open-circuit voltage ( $V_{oc}$ ), fill factor (FF), power conversion efficiency ( $\eta$ ), series resistance ( $R_s$ ), charge-transfer resistance ( $R_{CT}$ ), electrolyte and dye used of DSSCs of graphene/MoS<sub>2</sub> nano-composites are summarized and compared with standard Pt counter electrode<sup>a</sup>

| Counter electrodes                                   | Redox couple                                | Dye  | $J_{sc}$ (mA cm <sup>-2</sup> ) | $V_{oc}$ (V) | FF (%) | PCE ( $\eta$ , %) | $R_s$ ( $\Omega$ cm <sup>2</sup> ) | $R_{CT}$ ( $\Omega$ cm <sup>2</sup> ) | Ref. |
|--|---|------|---------------------------------|--------------|--------|-------------------|------------------------------------|---------------------------------------|------|
| 2H-MoS <sub>2</sub> (hydrothermal, 200 °C)           | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 6.78                            | 0.73         | 35     | 1.72              | 16                                 | 49                                    | 130  |
| 1T-MoS <sub>2</sub> (hydrothermal, 180 °C)           | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 8.76                            | 0.73         | 52     | 7.08              | 16                                 | 19                                    | 130  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 17.75                           | 0.702        | 58     | 7.25              | —                                  | —                                     | 130  |
| MoS <sub>2</sub> (CVD) vertically inclined           | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.2                            | 0.707        | 69.7   | 7.50              | 9.5                                | 3.10                                  | 131  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.6                            | 0.712        | 70.0   | 7.28              | 6.7                                | 5.36                                  | 131  |
| MoS <sub>2</sub> /graphite                           | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.64                           | 0.685        | 67     | 7.18              | —                                  | 8.05                                  | 132  |
| Graphite   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 11.62                           | 0.445        | 63     | 3.26              | —                                  | 15.70                                 | 132  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.84                           | 0.735        | 65     | 7.57              | —                                  | 6.35                                  | 132  |
| MoS <sub>2</sub> (multi-layer)                       | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.81                           | 0.745        | 25     | 2.92              | 27.3                               | 186.2                                 | 133  |
| MoS <sub>2</sub> (few-layer)                         | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.90                           | 0.744        | 16     | 1.74              | 35.8                               | 281.2                                 | 133  |
| MoS <sub>2</sub> (nanoparticle)                      | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.72                           | 0.745        | 49     | 5.41              | 26.9                               | 93.0                                  | 133  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.41                           | 0.754        | 65     | 6.58              | 34.2                               | 3.9                                   | 133  |
| MoS <sub>2</sub> (hydrothermal method)               | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 18.37                           | 0.698        | 57.8   | 7.41              | —                                  | 0.619                                 | 135  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.78                           | 0.722        | 58.8   | 7.13              | —                                  | 3.78                                  | 135  |
| MoS <sub>2</sub> (300 °C annealed)                   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.905                          | 0.727        | 51.7   | 6.351             | 23.89                              | 30.98                                 | 137  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 17.056                          | 0.724        | 55.7   | 6.929             | 27.17                              | 14.98                                 | 137  |
| MoS <sub>2</sub> (chemical deposition)               | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 18.46                           | 0.68         | 58     | 7.01              | 23.51                              | 18.50                                 | 138  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.80                           | 0.71         | 60     | 7.31              | 26.73                              | 22.88                                 | 138  |
| MoS <sub>2</sub> (non-annealed)                      | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 5.24                            | 0.74         | 27     | 1.0               | 28                                 | —                                     | 139  |
| MoS <sub>2</sub> (vacuum-annealed)                   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 7.95                            | 0.74         | 29     | 1.7               | 22                                 | —                                     | 139  |
| MoS <sub>2</sub> (N <sub>2</sub> -annealed)          | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 4.35                            | 0.67         | 27     | 0.8               | 44                                 | —                                     | 139  |
| MoS <sub>2</sub> /Mo ( <i>in situ</i> sulfurization) | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 22.6                            | 0.74         | 50     | 8.4               | —                                  | —                                     | 140  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 21.9                            | 0.735        | 53.4   | 8.7               | —                                  | —                                     | 140  |
| MoS <sub>2</sub> (hydrothermal method)               | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.84                           | 0.76         | 73     | 7.59              | 20.8                               | 0.5                                   | 141  |
| WS <sub>2</sub> (hydrothermal method)                | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.13                           | 0.78         | 70     | 7.73              | 19.4                               | 0.3                                   | 141  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.89                           | 0.78         | 66     | 7.64              | 12.7                               | 3.0                                   | 141  |
| MoS <sub>2</sub> (hydrothermal method)               | T <sub>2</sub> /T <sup>-</sup>              | N719 | 12.52                           | 0.63         | 63     | 4.97              | —                                  | —                                     | 141  |
| WS <sub>2</sub> (hydrothermal method)                | T <sub>2</sub> /T <sup>-</sup>              | N719 | 12.99                           | 0.64         | 64     | 5.24              | —                                  | —                                     | 141  |
| Pt reference   | T <sub>2</sub> /T <sup>-</sup>              | N719 | 12.23                           | 0.63         | 48     | 3.70              | —                                  | —                                     | 141  |
| MoS <sub>2</sub> (porous sheets)                     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.40                           | 0.763        | 53     | 6.35              | 7.95                               | 1.73                                  | 143  |
| MoS <sub>2</sub> (flower-shaped)                     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.73                           | 0.700        | 52     | 5.23              | 7.89                               | 2.67                                  | 143  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.34                           | 0.745        | 51     | 6.19              | 8.06                               | 1.82                                  | 143  |
| MoS <sub>2</sub> (sputtering, 5 min)                 | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.17                           | 0.71         | 64     | 6.6               | 30.1                               | 2.2                                   | 145  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.70                           | 0.71         | 66     | 6.0               | 3.1                                | 1.5                                   | 145  |
| MoS <sub>2</sub> (as-prepared)                       | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 11.92                           | 0.656        | 35     | 2.74              | —                                  | 1.01 × 10 <sup>4</sup>                | 146  |
| MoS <sub>2</sub> (heat-sintered)                     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.01                           | 0.705        | 65     | 5.96              | —                                  | 18.50                                 | 146  |
| MoS <sub>2</sub> (laser-sintered)                    | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.94                           | 0.718        | 67     | 7.19              | —                                  | 15.29                                 | 146  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.30                           | 0.741        | 70     | 7.42              | —                                  | 3.99                                  | 146  |
| MoS <sub>2</sub> (growth time, 5 h)                  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.15                           | 0.76         | 52     | 5.96              | 50.9                               | 118.8                                 | 147  |
| MoS <sub>2</sub> (growth time, 10 h)                 | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.94                           | 0.71         | 63     | 7.14              | 50.4                               | 21.2                                  | 147  |
| MoS <sub>2</sub> (growth time, 15 h)                 | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.96                           | 0.74         | 66     | 8.28              | 38.8                               | 12.9                                  | 147  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.77                           | 0.74         | 74     | 7.53              | 36.3                               | 13.1                                  | 147  |
| MoS <sub>2</sub> (exfoliated)                        | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 11.54                           | 0.80         | 65     | 6.0               | 29.60                              | 19.60                                 | 148  |
| MoS <sub>2</sub> (annealed)                          | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 10.92                           | 0.80         | 58     | 5.1               | 28.10                              | 121.10                                | 148  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | —                               | —            | —      | —                 | —                                  | —                                     | 148  |
| MoS <sub>2</sub>                                     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.92                           | 0.701        | 46     | 4.15              | 11.69                              | 3.65                                  | 151  |
| Graphene nanosheet                                   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 11.99                           | 0.754        | 30     | 2.68              | 9.31                               | 6.24                                  | 151  |
| MoS <sub>2</sub> -graphene nanosheet                 | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.79                           | 0.773        | 59     | 5.81              | 9.52                               | 2.34                                  | 151  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.12                           | 0.763        | 62     | 6.24              | 9.11                               | 1.79                                  | 151  |
| MoS <sub>2</sub> /graphene                           | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.41                           | 0.71         | 68     | 5.98              | 24.42                              | 4.94                                  | 152  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.43                           | 0.73         | 67     | 6.23              | 24.72                              | 4.74                                  | 152  |
| MoS <sub>2</sub> (CVD)                               | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.0                            | 0.62         | 65     | 5.6               | 1.5                                | 2.3                                   | 153  |
| MoS <sub>2</sub> /graphene (CVD)                     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.1                            | 0.66         | 67     | 7.1               | 1.7                                | 1.6                                   | 153  |
| Graphene   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.9                            | 0.68         | 24     | 2.8               | 1.7                                | 2.8                                   | 153  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 17.2                            | 0.72         | 60     | 7.4               | 2.1                                | 1.8                                   | 153  |
| MoS <sub>2</sub>                                     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 9.14                            | 0.589        | 47     | 2.53              | —                                  | —                                     | 154  |
| Graphene   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 10.7                            | 0.652        | 51.9   | 3.62              | —                                  | —                                     | 154  |
| MoS <sub>2</sub> : graphene (10 : 90)                | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 11.91                           | 0.646        | 56.5   | 4.35              | —                                  | —                                     | 154  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.39                           | 0.657        | 50     | 4.40              | —                                  | —                                     | 154  |



Table 2 (Contd.)

| Counter electrodes                                      | Redox couple                                | Dye  | $J_{sc}$ (mA cm <sup>-2</sup> ) | $V_{oc}$ (V) | FF (%) | PCE ( $\eta$ , %) | $R_s$ ( $\Omega$ cm <sup>2</sup> ) | $R_{CT}$ ( $\Omega$ cm <sup>2</sup> ) | Ref. |
|---|---|------|---------------------------------|--------------|--------|-------------------|------------------------------------|---------------------------------------|------|
| MoS <sub>2</sub> /graphene oxide (N <sub>2</sub> doped) | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.98                           | 0.70         | 53     | 5.95              | 25.7                               | 5.4                                   | 156  |
| Graphene oxide (N <sub>2</sub> doped)                   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.66                           | 0.71         | 38     | 3.95              | 25.7                               | 21.3                                  | 156  |
| MoS <sub>2</sub>  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.39                           | 0.69         | 39     | 4.09              | 26.0                               | 10.1                                  | 156  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.14                           | 0.70         | 57     | 6.43              | 26.3                               | 4.3                                   | 156  |
| MoS <sub>2</sub> (drop-coating)                         | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.46                           | 0.79         | 58     | 6.20              | 21.14                              | 24.93                                 | 157  |
| Nitrogen-doped graphene (NGr)                           | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.72                           | 0.68         | 64     | 5.50              | 16.31                              | 30.17                                 | 157  |
| MoS <sub>2</sub> /NGr (8 wt%)                           | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.36                           | 0.77         | 66     | 7.82              | 15.60                              | 16.73                                 | 157  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.71                           | 0.77         | 68     | 8.25              | 15.23                              | 10.15                                 | 157  |
| MoS <sub>2</sub>  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 10.56                           | 0.67         | 58     | 4.10              | —                                  | —                                     | 158  |
| Graphene flake (GF)                                     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 10.96                           | 0.69         | 48     | 3.63              | —                                  | —                                     | 158  |
| MoS <sub>2</sub> (GF is 0.5 wt%)                        | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.09                           | 0.69         | 59     | 4.85              | —                                  | —                                     | 158  |
| MoS <sub>2</sub> (GF is 1 wt%)                          | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.68                           | 0.74         | 59     | 5.35              | —                                  | —                                     | 158  |
| MoS <sub>2</sub> (GF is 1.5 wt%)                        | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.27                           | 0.75         | 61     | 6.07              | —                                  | —                                     | 158  |
| MoS <sub>2</sub> (GF is 2 wt%)                          | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.95                           | 0.74         | 58     | 5.56              | —                                  | —                                     | 158  |
| MoS <sub>2</sub> (GF is 2.5 wt%)                        | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.63                           | 0.70         | 58     | 5.04              | —                                  | —                                     | 158  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.95                           | 0.75         | 66     | 6.41              | —                                  | —                                     | 158  |
| MoS <sub>2</sub>  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 11.25                           | 0.72         | 61     | 4.99              | 11.37                              | 2.43                                  | 160  |
| Multi-walled CNT (MWCNT)                                | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 9.11                            | 0.65         | 58     | 3.53              | 9.91                               | 8.59                                  | 160  |
| MoS <sub>2</sub> /MWCNT                                 | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.69                           | 0.73         | 65     | 6.45              | 10.22                              | 1.69                                  | 160  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.24                           | 0.74         | 66     | 6.41              | 9.06                               | 1.91                                  | 160  |
| MoS <sub>2</sub>  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.44                           | 0.74         | 64     | 6.81              | —                                  | —                                     | 161  |
| Carbon nanotubes  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.33                           | 0.75         | 62     | 6.15              | —                                  | —                                     | 161  |
| MoS <sub>2</sub> /carbon nanotubes                      | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.65                           | 0.74         | 66     | 7.83              | —                                  | —                                     | 161  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.83                           | 0.74         | 65     | 7.15              | —                                  | —                                     | 161  |
| MoS <sub>2</sub> /CNTs                                  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.93                           | 0.65         | 47     | 4.51              | 8.42                               | 4.35                                  | 163  |
| CNTs/MoS <sub>2</sub> /carbon                           | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.44                           | 0.79         | 57     | 7.23              | 8.14                               | 1.73                                  | 163  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.40                           | 0.75         | 55     | 6.19              | 8.31                               | 1.95                                  | 163  |
| MoS <sub>2</sub> /CNTs (G-A)                            | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.82                           | 0.77         | 65     | 7.92              | 5.20                               | 1.77                                  | 164  |
| MoS <sub>2</sub> /carbon                                | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.52                           | 0.76         | 64     | 7.06              | 5.24                               | 2.35                                  | 164  |
| MoS <sub>2</sub>  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.33                           | 0.72         | 61     | 5.42              | 5.33                               | 4.16                                  | 164  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.82                           | 0.75         | 64     | 7.11              | 5.06                               | 2.22                                  | 164  |
| MoS <sub>2</sub> /reduced graphene oxide (RGO)          | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.31                           | 0.76         | 63     | 6.82              | 20.58                              | 4.42                                  | 165  |
| MoS <sub>2</sub> /RGO-CNTs                              | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.59                           | 0.76         | 67     | 7.46              | 20.37                              | 3.31                                  | 165  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.53                           | 0.77         | 65     | 7.23              | 20.13                              | 4.06                                  | 165  |
| MoS <sub>2</sub> (spin-coating)                         | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 7.24                            | 0.70         | 49     | 2.54              | 59.5                               | —                                     | 168  |
| MoS <sub>2</sub> /TiO <sub>2</sub> (5 : 1 wt ratio)     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.76                           | 0.82         | 45     | 5.08              | 56.5                               | —                                     | 168  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.06                           | 0.78         | 52     | 5.27              | —                                  | —                                     | 168  |
| MoS <sub>2</sub> /TiO <sub>2</sub>                      | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 4.67                            | 0.68         | 44     | 1.4               | —                                  | —                                     | 169  |
| MoS <sub>2</sub> /TiO <sub>2</sub> /Co                  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 9.21                            | 0.70         | 50     | 3.2               | —                                  | —                                     | 169  |
| MoS <sub>2</sub> /carbon (C is 2.23 wt%)                | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.98                           | 0.74         | 68     | 7.03              | 5.87                               | 2.67                                  | 171  |
| MoS <sub>2</sub> /carbon (C is 3.30 wt%)                | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.07                           | 0.75         | 68     | 7.69              | 5.77                               | 2.07                                  | 171  |
| MoS <sub>2</sub> /carbon (C is 4.35 wt%)                | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.37                           | 0.75         | 68     | 7.33              | 5.83                               | 2.40                                  | 171  |
| MoS <sub>2</sub>  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 11.66                           | 0.73         | 63     | 5.36              | 5.87                               | 4.13                                  | 171  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.98                           | 0.73         | 66     | 6.74              | 5.79                               | 2.29                                  | 171  |
| MoS <sub>2</sub> /PEDOT-PSS                             | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.55                           | 0.68         | 58     | 5.7               | —                                  | —                                     | 174  |
| PEDOT-PSS   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.6                            | 0.68         | 26     | 2.5               | —                                  | —                                     | 174  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.26                           | 0.73         | 59     | 6.6               | —                                  | —                                     | 174  |

<sup>a</sup> Disulfide/thiolate (T<sub>2</sub>/T<sup>-</sup>) redox couple. In the case of  $R_s$  and  $R_{CT}$ : some of the authors used  $\Omega$  instead of  $\Omega$  cm<sup>2</sup> for the resistances without mentioning the size of the electrode.

found to vary as a function of the thickness of MoS<sub>2</sub>/carbon CE. PCE values of 5.10, 6.89, 7.69, 7.01 and 4.85% were measured for the CE thicknesses of 4, 8, 12, 16 and 20  $\mu$ m for the MoS<sub>2</sub>/carbon CE. EIS, CV, and Tafel curve analysis showed low  $R_{CT}$ , high electrocatalytic activity, and faster reduction of triiodide (I<sub>3</sub><sup>-</sup>) to iodide (I<sup>-</sup>) for the MoS<sub>2</sub>/carbon CE compared to that of the Pt CE.

In yet another study, MoS<sub>2</sub>/carbon fibers were used as CEs for DSSCs.<sup>172</sup> Both electrocatalytic activity and the PCE (3.26%) of

the MoS<sub>2</sub>/carbon fiber based CE was found to be better than that of Pt/carbon fiber CE ( $\eta$  = 2.93%). In another study, composites of flower-like MoS<sub>2</sub> microspheres and carbon materials such as vulcan carbon, acetylene black, MWCNTs, carbon nanofibers (CNFs), and rice husk ash were studied as cost-effective Pt-free CEs for DSSCs.<sup>173</sup> The electrolyte used in the DSSC was a phthaloylchitosan-based polymer. The carbon materials/MoS<sub>2</sub> CEs showed low  $R_{CT}$  at the CE/electrolyte interface and high electro-catalytic activity for I<sub>3</sub><sup>-</sup> reduction. The DSSC with MoS<sub>2</sub>/



CNF CE showed a PCE of 3.17%, compared to a PCE of 1.04% for the pure MoS<sub>2</sub> CE.

Another study used MoS<sub>2</sub> and PEDOT:PSS composites as CEs for DSSCs.<sup>174</sup> The MoS<sub>2</sub>/PEDOT:PSS composite CE exhibits a PCE of 5.7% and FF of 58%, comparable to the Pt CE. The high PCE of the MoS<sub>2</sub>/PEDOT:PSS CE originated from high electrocatalytic activity of the MoS<sub>2</sub> active sites for triiodide (I<sub>3</sub><sup>−</sup>) reduction and high conductivity of PEDOT:PSS. The inorganic/organic MoS<sub>2</sub>/PEDOT:PSS composite may be useful as a low-cost Pt-free CEs for DSSCs. Another study used Bi<sub>5</sub>FeTi<sub>3</sub>O<sub>15</sub> (BFTO) nanofibers of 40–100 nm diameter developed by a sol-gel aided electrospinning method.<sup>175</sup> The MoS<sub>2</sub>/BFTO nanocomposite-based CE for DSSCs was prepared by uniformly dispersing MoS<sub>2</sub> nanoparticles into the BFTO matrix. The optical bandgap of the MoS<sub>2</sub>/BFTO nanocomposites was found to decrease with increasing MoS<sub>2</sub> contents. The DSSC with a MoS<sub>2</sub>/BFTO nanocomposite-based CE showed a PCE of 5.20%, 24 times higher than that of the pure BFTO nanofiber based CE. Table 2 summarizes the electrochemical and photovoltaic properties of all types of MoS<sub>2</sub> based CEs discussed in this section above, and a comparison is made with conventional Pt CEs for DSSCs.

### 3.2 WS<sub>2</sub> counter electrodes

Tungsten disulfide (WS<sub>2</sub>), traditionally used as a lubricant, is a semiconductor having van der Waals bonding which forms 2D layered-structures similar to other TMDs. WS<sub>2</sub> can form atomically thin nanosheets,<sup>176,177</sup> nanorods,<sup>178</sup> and nanotubes,<sup>179,180</sup> which have been actively studied for potential applications.

Carbon-coated WS<sub>2</sub> CEs have been fabricated for DSSCs at low temperature and characterized using FESEM, XRD, and Raman spectroscopy.<sup>181</sup> The electrocatalytic activity of the WS<sub>2</sub> CEs was studied using CV and EIS. The DSSCs with carbon-coated WS<sub>2</sub> CEs show a PCE of 5.5%, comparable to that of Pt CE based DSSCs ( $\eta = 5.6\%$ ). A DSSC having plastic WS<sub>2</sub> CEs exhibited a PCE of 5.0%. Carbon-coated WS<sub>2</sub> seems promising to develop low cost Pt-free CEs for DSSCs. The WS<sub>2</sub> films were

deposited by radio frequency (RF) sputtering and a sulfurization process as CE for DSSCs.<sup>182</sup> The WS<sub>2</sub> films were characterized using XRD, FESEM, Raman spectroscopy, and XPS techniques. The transparent WS<sub>2</sub> CEs demonstrated high electrocatalytic activity and fast reduction of triiodide, (I<sub>3</sub><sup>−</sup>) as characterized using CV, EIS, and Tafel polarization curve. WS<sub>2</sub> CE sputtered for 10 minutes showed a PCE of 6.3%, slightly lower than the Pt-based CE ( $\eta = 6.64\%$ ) used in the DSSC. The *J*-*V* characteristics as a function of sputtering time used to prepare WS<sub>2</sub> films as a CE were also studied. WS<sub>2</sub> film CEs prepared at sputtering time of 5, 10 and 15 minutes showed PCEs of 5.4%, 6.3% and 5.8%, respectively.

Another research team<sup>183</sup> used edge-oriented WS<sub>2</sub> based CEs for DSSCs. Edge-oriented WS<sub>2</sub> was obtained from mesoporous interconnected WO<sub>3</sub> structures using a high temperature sulfurization process. The DSSCs with edge-oriented WS<sub>2</sub> CEs show a PCE of 8.85%, higher compared to the Pt CE ( $\eta = 7.20\%$ ). The large number of active edge sites in edge-oriented WS<sub>2</sub> is responsible for high electrocatalytic activity for the reduction of triiodide (I<sub>3</sub><sup>−</sup>) in the DSSCs. The WS<sub>2</sub> films were fabricated by the doctor-blade method (or tape casting method; a method removing excessive liquid material using a moving blade for uniform coating) to use as CEs for DSSCs.<sup>184</sup> The TiO<sub>2</sub> (P25) and carbon nanoparticles were introduced into WS<sub>2</sub> films to increase electrical conductivity and bonding strength. The electrochemical catalytic activity of WS<sub>2</sub>/P25/C CEs was compared with Pt for the triiodide (I<sub>3</sub><sup>−</sup>) to iodide (I<sup>−</sup>) electrolyte system using CV and EIS measurements. The DSSC developed with WS<sub>2</sub>/P25/C CE was shown to yield a PCE of 4.56%.

Yue *et al.*<sup>185</sup> prepared WS<sub>2</sub> decorated multi-walled carbon nanotubes (MWCNTs) by applying a hydrothermal method, for use as a low-cost Pt-free CE for DSSCs. The contents of MWCNTs in MWCNTs-WS<sub>2</sub> CEs varied from 1 to 10 wt%. PCE values of 5.20, 5.45, 6.41, 5.53 and 5.22% were measured in the DSSCs for CEs having 1, 3, 5, 7 and 10 wt% contents of MWCNTs, respectively. CV and EIS showed high electrocatalytic activity for the MWCNTs-WS<sub>2</sub> CE for the triiodide (I<sub>3</sub><sup>−</sup>) reduction. The *R*<sub>CT</sub>



Fig. 11 (Left) SEM images of (a) WS<sub>2</sub>, (b) MWCNTs, and (c and d) WS<sub>2</sub>/MWCNTs composites. (Right) photocurrent–voltage (*J*–*V*) curves of the DSSCs with Pt, WS<sub>2</sub>, MWCNTs, WS<sub>2</sub>/MWCNTs\* (prepared without glucose aid), and (G–A)WS<sub>2</sub>/MWCNTs counter electrodes under a simulated solar illumination of 100 mW cm<sup>−2</sup>. Reprinted with permission from ref. 186, J. Wu, G. Yue, Y. Xiao, M. Huang, J. Lin, L. Fan, Z. Lan and J. Y. Lin, glucose aided preparation of tungsten sulfide/multi-wall carbon nanotube hybrid and use as counter electrode in dye-sensitized solar cells. *ACS Appl. Mater. Interfaces*, 2012, 4, 6530–6536. Copyright© American Chemical Society.





of MWCNTs-WS<sub>2</sub> CE having 1, 3, 7, and 10 wt% contents of MWCNTs were 4.54, 3.47, 3.24, and 4.59  $\Omega\text{ cm}^2$ , respectively. The  $R_{\text{CT}}$  of the MWCNTs-WS<sub>2</sub> CE with 5 wt% contents of MWCNTs shows 2.53  $\Omega\text{ cm}^2$ , comparable to the  $R_{\text{CT}}$  of 2.74  $\Omega\text{ cm}^2$  for a Pt CE. The DSSCs based on WS<sub>2</sub>/MWCNTs CEs showed a PCE of 6.41% for 5 wt% MWCNTs, comparable to the PCE of 6.56% for Pt CE under a simulated AM 1.5 solar illumination (100  $\text{mW cm}^{-2}$ ). The low  $R_{\text{CT}}$  of WS<sub>2</sub>/MWCNTs CEs at the electrolyte/electrode interface contributed to the higher PCEs.

The WS<sub>2</sub> based CEs prepared by a hydrothermal method was also used for DSSC by Wu *et al.*,<sup>141</sup> which exhibited a PCE of 7.73%. The same research team<sup>186</sup> also synthesized WS<sub>2</sub>/MWCNTs hybrids by a glucose-aided (G-A) hydrothermal route, which is discussed here in detail. Fig. 11 presents the SEM images of WS<sub>2</sub>, MWCNTs, and (G-A)WS<sub>2</sub>/MWCNTs composites, and  $J$ - $V$  curves of the DSSCs with WS<sub>2</sub>, MWCNTs, WS<sub>2</sub>/MWCNTs\* (prepared without the aid of glucose), WS<sub>2</sub>/MWCNTs, and Pt CEs, under a simulated solar illumination of 100  $\text{mW cm}^{-2}$ . The WS<sub>2</sub> exhibits graphene-like lamellar structure, whereas the MWCNTs have a fiber-like structure, indicating both materials have a large specific surface area. The specific surface area of the (G-A)WS<sub>2</sub>/MWCNTs composite was estimated to be 230  $\text{m}^2\text{ g}^{-1}$  by the Brunauer-Emmett-Teller (BET) technique, indicating high electrochemical activity as well as photovoltaic efficiency for CEs. The cathodic peak potentials of the WS<sub>2</sub>, WS<sub>2</sub>/MWCNTs, and WS<sub>2</sub>/MWCNTs\* CEs showed cathodic peak potentials of -0.14, -0.13 and -0.17 V, respectively, which implies that the MWCNTs help in improving the electrocatalytic activity, and a lower cathodic peak potential observed for (G-A)WS<sub>2</sub>/MWCNTs as opposed to WS<sub>2</sub>/MWCNTs\* results from the large specific surface area generated by glucose aided preparation. The EIS measurements yielded an  $R_{\text{CT}}$  of 2.49  $\Omega\text{ cm}^2$  and  $R_s$  of 2.54  $\Omega\text{ cm}^2$  for the WS<sub>2</sub>/MWCNTs hybrid CE, which is smaller compared with WS<sub>2</sub> CE, and indicates the synergistic effect between WS<sub>2</sub> and MWCNTs that enhanced the electrical conductivity of the hybrid. The (G-A)WS<sub>2</sub>/MWCNT CE based DSSC resulted in a PCE of 7.36%, comparable to WS<sub>2</sub> CE (5.32%), MWCNTs CE (4.34%), and the Pt CE (7.54%). The  $J_{\text{sc}}$  and PCE values increased with increasing content of MWCNTs, up to 5 wt% in the WS<sub>2</sub>/MWCNT hybrid CEs, and thereafter started decreasing with further increases in MWCNTs content. The (G-A)WS<sub>2</sub>/MWCNT (5 wt%) film also exhibits a smaller transmission between 320 to 800 nm than Pt film, therefore the WS<sub>2</sub>/MWCNT film absorbs more incident light, which also further improves photovoltaic performance. The glucose aided (G-A)WS<sub>2</sub>/MWCNTs (5 wt%) CE in the DSSC had low  $R_{\text{CT}}$  and high electrocatalytic activity for the reduction of triiodide ( $\text{I}_3^-$ ), due to the synergistic effects induced by glucose.

### 3.3 TiS<sub>2</sub> counter electrodes

Titanium disulfide (TiS<sub>2</sub>) is a metallic thermoelectric material which attains unique morphologies such as nanotubes, nanoclusters and nanodisks, and exhibits interesting physical properties.<sup>187–198</sup> Meng *et al.*<sup>199</sup> has prepared 2D TiS<sub>2</sub> nanosheets decorated on graphene using a ball milling method and followed by high-temperature annealing. The electroactive surface



Fig. 12 A comparison of photocurrent density-voltage ( $J$ - $V$ ) curves of DSSCs having TiS<sub>2</sub>-graphene hybrid and Pt counter electrodes. Reprinted with permission from ref. 199, X. Meng, C. Yu, B. Lu, J. Yang and J. Qiu, dual integration system endowing two-dimensional titanium disulfide with enhanced triiodide reduction performance in dye-sensitized solar cells. *Nano Energy*, 2016, 22, 59–69. Copyright© Elsevier.

areas of 1.70  $\text{cm}^2$  for TiS<sub>2</sub>-graphene and 0.232  $\text{cm}^2$  for Pt electrodes, measured by CV, indicate more active sites for the hybrid. Fig. 12 compares  $J$ - $V$  curves of DSSCs having TiS<sub>2</sub>-graphene and Pt/FTO CEs. The CEs based on TiS<sub>2</sub>-graphene hybrids exhibited higher electrocatalytic activity for the reduction of triiodide ( $\text{I}_3^-$ ) to iodide ( $\text{I}^-$ ) in electrolyte with a PCE of 8.80%, which is higher than the Pt CE ( $\eta = 8.00\%$ ). The  $R_s$  of TiS<sub>2</sub>-graphene CEs (2.32  $\Omega\text{ cm}^2$ ) was found to be smaller compared to the Pt CEs (6.90  $\Omega\text{ cm}^2$ ), showing better contact between the hybrid CE and FTO glass. Furthermore, the  $R_{\text{CT}}$  of TiS<sub>2</sub>-graphene CE (0.63  $\Omega\text{ cm}^2$ ) was also lower than the Pt CE (1.32  $\Omega\text{ cm}^2$ ), which again indicates a higher electrocatalytic activity for the reduction of triiodide ( $\text{I}_3^-$ ). Also, the  $Z_n$  of TiS<sub>2</sub>-graphene CE (10.52  $\Omega\text{ cm}^2$ ) was found to be higher than the Pt CE (6.89  $\Omega\text{ cm}^2$ ). The high electrocatalytic activity of the TiS<sub>2</sub>-graphene hybrids is attributed to the highly electroactivity of TiS<sub>2</sub> and enhanced transport facilitated by the graphene conductive network.

Li *et al.*<sup>200</sup> deposited composite films of TiS<sub>2</sub>/PEDOT:PSS on ITO substrates by drop coating, to study CEs of DSSCs. The wt% of TiS<sub>2</sub> particles in TiS<sub>2</sub>/PEDOT:PSS composite films varied from 5 to 15 wt%. TiS<sub>2</sub> particles were dispersed in a PEDOT:PSS matrix to be used as an electrocatalyst for the  $\text{I}^-/\text{I}_3^-$  redox reaction. In the composite, conducting polymer PEDOT:PSS plays the role of a binder for the TiS<sub>2</sub> nanoparticles, as well as a linking agent between TiS<sub>2</sub> particles and the ITO substrate, and also facilitates electron transfer. The TiO<sub>2</sub> photoanode for a DSSC was prepared by immersing it in N719 dye solution for 24 hours at room temperature. Fig. 13 shows the photocurrent density-voltage curves and IPCE curves of the DSSCs with Pt, bare TiS<sub>2</sub>, bare PEDOT:PSS, and 10 wt% TiS<sub>2</sub>/PEDOT:PSS composite CEs. The TiS<sub>2</sub>/PEDOT:PSS composite CE offered a large surface area, yielding a high PCE of 7.04%. The CEs of bare TiS<sub>2</sub>, bare PEDOT:PSS, the TiS<sub>2</sub>/PEDOT:PSS composite, and Pt were characterized by AFM, SEM, and EDX. AFM images indicated a roughness of 45 nm for PEDOT:PSS and of 378 nm for TiS<sub>2</sub>/PEDOT:PSS composite film; therefore, the higher





Fig. 13 (a) Photocurrent density–voltage curves of DSSCs with Pt, bare TiS<sub>2</sub>, bare PEDOT:PSS, and 10 wt% TiS<sub>2</sub>/PEDOT:PSS composite based CEs recorded under light illumination of 100 mW cm<sup>-2</sup> (AM 1.5). (b) Incident photon-to-current conversion efficiency (IPCE) curves of the DSSCs with similar CEs. Reprinted with permission from ref. 200, C. T. Li, C. P. Lee, Y. Y. Li, M. H. Yeh and K. C. Ho, a composite film of TiS<sub>2</sub>/PEDOT:PSS as the electrocatalyst for the counter electrode in dye-sensitized solar cells. *J. Mater. Chem. A*, 2013, 1, 14888–14896. Copyright© Royal Society of Chemistry.

roughness could lead to a larger active surface area and consequently to the higher electrocatalytic activity for the TiS<sub>2</sub>/PEDOT:PSS composite thin. The electrocatalytic properties of the DSSCs using the CEs of bare TiS<sub>2</sub>, bare PEDOT:PSS, the TiS<sub>2</sub>/PEDOT:PSS composite, and Pt were evaluated by CV, RDE, EIS, and Tafel polarization measurements. The high PCE of the TiS<sub>2</sub>/PEDOT:PSS composite CE based DSSC was also measured by IPCE curves. The maximum of the IPCE spectra at 520 nm increased from 52% to 63% as the content of TiS<sub>2</sub> particles increased from 0 to 10 wt%, respectively, and similar characteristics were observed for the  $J_{sc}$  values from the  $J$ - $V$  curves of the DSSCs. The 10 wt% TiS<sub>2</sub>/PEDOT:PSS composite film based CE shows a higher redox current density compared with bare TiS<sub>2</sub> and PEDOT:PSS CEs, therefore, it possesses high

electrocatalytic activity for triiodide (I<sub>3</sub><sup>-</sup>) reduction, and it also exhibits high electrochemical stability after 100 consecutive cycles in the I<sup>-</sup>/I<sub>3</sub><sup>-</sup> redox electrolyte.

### 3.4 NiS<sub>2</sub> counter electrodes

Nickel disulfide (NiS<sub>2</sub>) is a semiconducting material with pyrite structure which acquires unique morphologies such as hollow prisms, nano/microspheres, nanocubes, nanosheets, nanoparticles, and also exhibits interesting electrical, optical, magnetic, and catalytic properties.<sup>201–205</sup> Depending upon the synthesis procedures, the stoichiometric composition of nickel sulfide varies to a great extent (NiS, NiS<sub>2</sub>, Ni<sub>3</sub>S<sub>2</sub>, Ni<sub>3</sub>S<sub>4</sub>, Ni<sub>6</sub>S<sub>5</sub>, Ni<sub>7</sub>S<sub>6</sub>, Ni<sub>9</sub>S<sub>8</sub>, etc.).

In one study, hierarchical NiS<sub>2</sub> hollow microspheres on a FTO substrate were prepared by a hydrothermal method to use as a CE for a DSSC.<sup>206</sup> The NiS<sub>2</sub> hollow microspheres were partially broken, offering more active sites for electrocatalysis and electrolyte adsorptions. The IPCE values of 81.3% for the NiS<sub>2</sub> microspheres CE and 76.6% for the Pt CEs at 500 nm were observed. The peak current density of the NiS<sub>2</sub> microspheres CE was found to be higher than the Pt CE, whereas the peak-to-peak separation ( $E_{pp}$ ) value was lower by 10 mV compared to Pt CE, which suggests a high electrocatalytic activity for the NiS<sub>2</sub> microspheres CE in the reduction of triiodide (I<sub>3</sub><sup>-</sup>) in the electrolyte. The NiS<sub>2</sub> hollow microspheres CE based DSSC showed a PCE of 7.84%, equal to the Pt CE (7.89%), indicating their potential as low-cost CEs for DSSCs. The NiS/NiS<sub>2</sub> composite hollow spheres prepared by a solvothermal method exhibited a low  $R_{CT}$  of 0.34  $\Omega$  cm<sup>-2</sup> at the CE/electrolyte interface, and a PCE of 7.66%, outperforming the Pt CE (7.01%), and showed high electrocatalytic activity for I<sub>3</sub><sup>-</sup> reduction, and also better electrochemical stability.<sup>207</sup> The NiS and NiS<sub>2</sub> hollow spheres were synthesized through a solvothermal process.<sup>208</sup> The Ni/S molar ratio controlled the different stoichiometric ratios of nickel sulfides. The NiS<sub>2</sub> CE based DSSC showed a higher electrocatalytic activity than that of the NiS CE for I<sub>3</sub><sup>-</sup> reduction. The DSSC with NiS<sub>2</sub> CE yielded a PCE value of 7.13% in comparison to 6.49% for NiS CE.

NiS<sub>2</sub> polyhedrons were studied as CEs for DSSCs by Zheng *et al.*<sup>209</sup> Fig. 14 shows SEM, TEM, and selected area electron diffraction (SAED) images of NiS<sub>2</sub> octahedrons and NiS<sub>2</sub> cubes, and electrochemical characteristics of DSSCs having NiS<sub>2</sub> octahedrons, NiS<sub>2</sub> cubes and Pt CEs, under simulated AM1.5G solar light. The average size of NiS<sub>2</sub> octahedrons and cubes were about 250 nm. The electrochemical performance of NiS<sub>2</sub> octahedron and cube based CEs were evaluated using CV,  $J$ - $V$  characteristics, EIS, and the Tafel polarization method. The NiS<sub>2</sub> octahedron CEs showed peak current density of 1.40 mA cm<sup>-2</sup>, compared to 1.22 mA cm<sup>-2</sup> for the NiS<sub>2</sub> cubes, indicating better electrocatalytic activity. The NiS<sub>2</sub> octahedron CEs also exhibited a higher  $J_{sc}$  of 13.55 mA cm<sup>-2</sup> and FF of 62%, higher than that of the NiS<sub>2</sub> cube CE ( $J_{sc}$  of 12.62 mA cm<sup>-2</sup> and FF of 60%), giving rise to a higher PCE. Octahedral NiS<sub>2</sub> nanocrystals based CEs incorporated into DSSCs exhibited a PCE of 5.98%, slightly higher than that of the NiS<sub>2</sub> cube nanocrystals ( $\eta$  = 5.43%). The NiS<sub>2</sub> octahedron CE had a PCE of up to 91% of the





**Fig. 14** SEM, TEM, and SAED images of NiS<sub>2</sub> octahedrons (a–c) and NiS<sub>2</sub> cubes (d–f). SAED patterns of NiS<sub>2</sub> octahedrons (c) and NiS<sub>2</sub> cubes (f) were recorded from the corresponding particles depicted (b) and (e), respectively. (g) C–V curves of DSSCs having counter electrodes of NiS<sub>2</sub> octahedrons, NiS<sub>2</sub> cubes and Pt for the reduction of tri-iodide (h) J–V curves of DSSCs with NiS<sub>2</sub> octahedrons, NiS<sub>2</sub> cubes and Pt CEs under simulated AM1.5G solar light. Nyquist plots (i) and Tafel polarization curves (j) of DSSCs having NiS<sub>2</sub> octahedrons, NiS<sub>2</sub> cubes and Pt CEs. Reprinted with permission from ref. 209, J. Zheng, W. Zhou, Y. Ma, W. Cao, C. Wang and L. Guo, facet-dependent NiS<sub>2</sub> polyhedrons on counter electrodes for dye-sensitized solar cells. *Chem. Commun.*, 2015, 51, 12863–12866. Copyright© Royal Society of Chemistry.

conventional Pt CE in DSSCs ( $\eta = 6.55\%$ ). The  $R_s$  of the NiS<sub>2</sub> octahedron based CE was  $13.14 \Omega \text{ cm}^2$ , somewhat lower than that of the NiS<sub>2</sub> cube CE ( $R_s$  of  $14.98 \Omega \text{ cm}^2$ ), indicating higher

electrical conductivity of the NiS<sub>2</sub> octahedron based CE. The  $R_{CT}$  of the NiS<sub>2</sub> octahedron CE was measured as  $9.86 \Omega \text{ cm}^2$ , also lower than that of the NiS<sub>2</sub> cube CE ( $R_{CT}$  of  $13.17 \Omega \text{ cm}^2$ ), which







Fig. 15 (a) Photocurrent density–voltage ( $J$ – $V$ ) curves of DSSCs with bare  $\text{NiS}_2$ ,  $\text{NiS}_2$ @RGO nanocomposites, bare RGO, and Pt CEs measured under light illumination of  $100 \text{ mW cm}^{-2}$  (AM 1.5). Reprinted with permission from ref. 210, Z. Li, F. Gong, G. Zhou and Z. S. Wang,  $\text{NiS}_2$ /reduced graphene oxide nanocomposites for efficient dye-sensitized solar cells. *J. Phys. Chem. C*, 2013, **117**, 6561–6566. Copyright© American Chemical Society.

demonstrates that the  $\text{NiS}_2$  octahedrons with  $\{111\}$  facets possesses better electrocatalytic activity than the  $\text{NiS}_2$  cubes with  $\{100\}$  facets.

The electrocatalytic performance of  $\text{NiS}_2$  nanoparticles and their nanocomposites with RGO were compared by Li *et al.*<sup>210</sup> In a hydrothermal process, graphene oxide was transformed to RGO, and then  $\text{NiS}_2$ @RGO nanocomposites were formed by depositing  $\text{NiS}_2$  nanoparticles on the surface of RGO. CEs for DSSCs were fabricated by drop-casting solutions of  $\text{NiS}_2$ ,  $\text{NiS}_2$ @RGO, and RGO nanocomposites on FTO-coated glass substrate. The surface areas measured by the BET method were  $11.4$ ,  $9.4$ , and  $8.6$ , and  $5.8 \text{ m}^2 \text{ g}^{-1}$  for  $\text{NiS}_2$ @RGO,  $\text{NiS}_2$ , and RGO, respectively. Fig. 15 shows  $J$ – $V$  curves of DSSCs with bare  $\text{NiS}_2$ ,  $\text{NiS}_2$ @RGO nanocomposites, bare RGO, and Pt CEs. The  $\text{NiS}_2$ @RGO nanocomposites based CE showed a PCE of  $8.55\%$  ( $J_{\text{sc}} = 16.55 \text{ mA cm}^{-2}$ ,  $V_{\text{oc}} = 0.749 \text{ V}$ , and  $\text{FF} = 0.69$ ), much higher than that of the  $\text{NiS}_2$  CE ( $\eta = 7.02\%$ ), RGO CE ( $\eta = 3.14\%$ ), or standard Pt CE ( $\eta = 8.15\%$ ) for the DSSCs under the same experimental conditions. The larger  $R_{\text{CT}}$  values of  $100.2 \Omega \text{ cm}^2$  for RGO and  $8.8 \Omega \text{ cm}^2$  for  $\text{NiS}_2$  also suggest the low electrocatalytic activity. On the other hand, the smaller  $R_{\text{CT}}$  value of  $2.9 \Omega \text{ cm}^2$  for the  $\text{NiS}_2$ @RGO nanocomposite indicates much higher electrocatalytic activity for the reduction of triiodide ( $\text{I}_3^-$ ) in electrolyte due the cooperative synergetic effect and the increased conductivity from the RGO nanosheets. This study demonstrates that  $\text{NiS}_2$ @RGO nanocomposites are a promising alternate CE to conventional Pt CE for DSSC devices.

### 3.5 $\text{FeS}_2$ based counter electrodes

Pyrite iron disulfide ( $\text{NiS}_2$ ) acquires unique morphological structures including nanocrystals, nanowires, nanosheets, nanocubes, and exhibits interesting electrical, photovoltaic, and catalytic properties.<sup>211–220</sup> An interesting comparative study was done by Shukla *et al.*<sup>221</sup> on pyrite iron disulfide ( $\text{FeS}_2$ ) as a CE material in comparison with Pt and PEDOT CEs in DSSCs.

The  $\text{FeS}_2$  film CEs were fabricated on a FTO glass substrate by a spray pyrolysis method and used in  $\text{I}_3^-/\text{I}^-$  and  $\text{Co(III)}/\text{Co(II)}$  electrolyte-mediated DSSCs. N719 dye was used for the DSSC with  $\text{I}_3^-/\text{I}^-$  redox electrolyte and C128 dye for the  $[\text{Co}(\text{bpy})_3]^{2+/3+}$  redox electrolyte. The  $\text{I}_3^-/\text{I}^-$  redox electrolyte contained  $1.0 \text{ mM}$  of 1,3-dimethylimidazolium iodide,  $50 \text{ mM}$  of  $\text{LiI}$ ,  $30 \text{ mM}$  of  $\text{I}_2$ ,  $0.5 \text{ mM}$  of *tert*-butylpyridine, and  $0.1 \text{ mM}$  of guanidinium thiocyanate in a acetonitrile and valeronitrile (v/v, 85/15) mixed solution. The cobalt electrolyte was made up of  $0.22 \text{ M}$  of  $\text{Co}(\text{bpy})_3(\text{TFSI})_2$ , ( $\text{bpy} = 2,2'$ -bipyridine and  $\text{TFSI} = [\text{bis}(\text{trifluoromethane})\text{-sulfonimide}]$ ),  $0.05 \text{ M}$  of  $\text{Co}(\text{bpy})_3(\text{TFSI})_3$ ,  $0.1 \text{ M}$  of lithium *bis*(trifluoromethanesulfonyl)imide ( $\text{LiTFSI}$ ), and  $0.2 \text{ M}$  of *tert*-butylpyridine (*tBP*) in acetonitrile. Fig. 16 shows the  $J$ – $V$  curves and IPCE of the DSSCs with  $\text{FeS}_2$  and Pt CEs in  $\text{I}_3^-/\text{I}^-$  electrolyte, and DSSCs with  $\text{FeS}_2$  and PEDOT CEs in the  $\text{Co(III)}/\text{Co(II)}$  electrolyte. The catalytic activity of the  $\text{FeS}_2$  film CEs was found to be comparable to the Pt and PEDOT CEs, which were both in  $\text{I}_3^-/\text{I}^-$  and  $\text{Co}^{2+}/\text{Co}^{3+}$  electrolytes, respectively. With the  $\text{I}_3^-/\text{I}^-$  electrolyte, a PCE of  $7.97\%$  was observed for the  $\text{FeS}_2$  film CE and a PCE of  $7.54\%$  for the Pt CE in the  $\text{I}_3^-/\text{I}^-$  electrolyte, whereas the PCEs were almost the same ( $6.3\%$ ) for the  $\text{FeS}_2$  film and PEDOT CEs in the  $[\text{Co}(\text{bpy})_3]^{2+/3+}$  redox-mediated DSSCs. The performance of the DSSCs with  $\text{FeS}_2$  and Pt CEs was studied by varying solar light illumination intensities between 1 Sun and 0.1 Sun. The current density was observed to be higher for the  $\text{FeS}_2$  CE ( $15.20 \text{ mA cm}^{-2}$ ) than for the Pt CE ( $14.77 \text{ mA cm}^{-2}$ ) at 1 Sun light intensity. When the solar light intensity was reduced to 0.5 and 0.1 Sun, the difference in current density between the  $\text{FeS}_2$  and Pt CEs was not noticeable, with the  $J_{\text{sc}}$  values being  $8.97$  and  $8.91 \text{ mA cm}^{-2}$  at 0.5 Sun, and  $1.75$  and  $1.74 \text{ mA cm}^{-2}$  at 0.1 Sun for the Fe and Pt CEs, respectively. The PCE values for the  $\text{FeS}_2$  and Pt CEs were  $9.27\%$  and  $8.92\%$  at 0.5 Sun, and  $8.68\%$  and  $8.32\%$  at 0.1 Sun, respectively. The excellent performance of  $\text{FeS}_2$  film in both electrolyte systems makes it very interesting for applications in DSSCs.

In an interesting study,  $\text{FeS}_2$  nanorod arrays were fabricated on a FTO substrate after sulfurizing  $\text{FeO}(\text{OH})$  nanorods, and used as a CE for DSSCs.<sup>222</sup> The  $\text{FeS}_2$  nanorods exhibited better electrocatalytic activity than  $\text{FeS}_2$  films and Pt-based CEs due to more active sites, which resulted in high  $J_{\text{sc}}$  value of the DSSCs. The  $\text{FeS}_2$  nanorods-based CEs showed lower interface resistance compared with  $\text{FeS}_2$  thin films, which leads to a higher FF and hence a higher PCE comparable to Pt CE based DSSCs. The electrochemical stability of the  $\text{FeS}_2$  nanorod arrays-based CE measured in  $\text{I}_3^-/\text{I}^-$  electrolyte showed a slight change in CV plots up to 10 consecutive days of aging time. In another study,  $\text{FeS}_2$  powder prepared through a hydrothermal method was used as a CE for fabricating DSSCs.<sup>223</sup> The effect of NaOH addition on  $\text{FeS}_2$  crystal size and electrocatalytic activities was then studied. It was observed that the size of  $\text{FeS}_2$  nanoparticles decreased after adding NaOH, and the resulting photovoltaic performance and electrocatalytic activity of DSSC with  $\text{FeS}_2$  powder significantly increased, achieving a PCE of  $5.78\%$  under simulated sunlight irradiation of 1 Sun.

A chemically prepared  $\text{FeS}_2$  nanocrystal ink was used to fabricate a CE for a DSSC, which showed a PCE of  $7.31\%$  after





Fig. 16 (a) Photocurrent density–voltage ( $J$ – $V$ ) curves and (b) IPCE of the DSSCs with  $FeS_2$  and Pt counter electrodes using N719 dye in  $I_3^-/I^-$  electrolyte. (c)  $J$ – $V$  curve and (d) IPCE of the DSSCs with  $FeS_2$  and PEDOT counter electrodes using C128 dye in  $Co^{3+}/Co^{2+}$  electrolyte. Reprinted with permission from ref. 221, S. Shukla, N. H. Loc, P. P. Boix, T. M. Koh, R. R. Prabhakar, H. K. Mulmudi, J. Zhang, S. Chen, C. F. Ng, C. H. A. Huan and N. Mathews, iron pyrite thin film counter electrodes for dye-sensitized solar cells: high efficiency for iodine and cobalt redox electrolyte cells. *ACS Nano*, 2014, 8, 10597–10605. Copyright© American Chemical Society.

ethanedithiol (EDT) treatment.<sup>224</sup>  $FeS_2$  nanocrystal ink casted on a flexible ITO/PET substrate exhibited a  $J_{sc}$  of  $14.93\text{ mA cm}^{-2}$ ,  $V_{oc}$  of 0.71 V, FF of 0.60, and a PCE of 6.36%. The semi-transparent  $FeS_2$  nanocrystal/ITO glass CE has an optical transmittance of 50–70% between 300 to 800 nm in comparison to 15% transmittance for the reference Pt/ITO glass CE. When the DSSC with the  $FeS_2$  nanocrystal CE was illuminated from the rear side, it showed a PCE of 4.17%, which was 57% of the front illumination value, whereas opaque Pt CE had a PCE of 1.06% from the rear side. Semi-transparent  $FeS_2$  nanocrystal CEs offer bifacial DSSCs utilizing incident light from both front and rear sides, and thus could be cost-effective for energy production. The  $FeS_2$  nanocrystal ink also demonstrated high electrocatalytic activity and electrochemical stability. Additionally, MWCNT/ $TiO_2$  hybrid and pure  $TiO_2$  mesoporous photoanodes with  $FeS_2$  thin films as CEs were studied for DSSCs by Kilic *et al.*<sup>225</sup> In the MWCNT/ $TiO_2$  hybrid photoanode, CNT played an important role of increasing the optical absorption and shifting it toward a longer wavelength region, where the bandgap of 3.15 eV for mesoporous  $TiO_2$  shifted to 2.5 eV for the MWCNT/ $TiO_2$  hybrid. The DSSC with the MWCNT/ $TiO_2$  hybrid photoanode and the Pt CE showed values of  $J_{sc}$  of  $15.96\text{ mA cm}^{-2}$ ,  $V_{oc}$  of 0.77 V, FF of 0.57 and a PCE of 7.0%. The DSSC with the pure mesoporous  $TiO_2$  photoanode and the Pt CE both resulted in

PCEs of 6.51%. The enhancement in PCE value of the hybrid photoanode is associated with MWCNTs, which offer an electrical conduction pathway for speedy electron transport. The MWCNT/ $TiO_2$  hybrid photoanode also showed an increase in IPCE in the 350–600 nm wavelength range compared to the mesoporous  $TiO_2$  photoanode. When  $FeS_2$  thin films were used as a CE with a MWCNT/ $TiO_2$  hybrid photoanode, the PCE of the DSSC increased to 7.27% under 1 Sun. The DSSC with a  $FeS_2$  CE and a pure  $TiO_2$  photoanode both yielded a PCE of 6.65%. The  $FeS_2$  thin films showed an optical bandgap of 1.27 eV and large effective surface area, which contribute to more light absorption and increased electrocatalytic activity for the reduction of triiodide ( $I_3^-$ ).

### 3.6 $CoS_2$ counter electrodes

Cobalt disulfide ( $CoS_2$ ) is a semiconducting material that exhibits interesting magnetic, electrical, and catalytic properties for energy storage applications.<sup>226–231</sup> The properties of  $CoS_2$  nanocrystalline thin films prepared by a hydrothermal method were reported by Jin *et al.*<sup>232</sup>  $CoS_2$  powder was dispersed in ethanol in order to prepare a nanoink ( $40\text{ mg mL}^{-1}$ ) for fabricating a CE. The  $CoS_2$  nanoink ( $10\text{ }\mu\text{L}$ ) was drop-cast on an FTO glass or flexible ITO/PET substrate, followed by ethanol



evaporation. The self-assembled CoS<sub>2</sub> film CE has a thickness of 2.5 μm which can be controlled by the nanoink content. DSSCs were assembled by using a N719 dye-sensitized TiO<sub>2</sub> photoanode as the working electrode, a CoS<sub>2</sub> nanocrystal film or a Pt as the CE, and an electrolyte solution containing LiI (0.1 M), I<sub>2</sub> (0.05 M), 1,2-dimethyl-3-*n*-propylimidazolium iodide (DMPII, 0.6 M), and 4-*tert*-butylpyridine (TBP, 0.5 M) in acetonitrile. The morphology and structure of the CoS<sub>2</sub> self-assemblies were studied by SEM and TEM techniques. Fig. 17 shows an SEM image of a self-assembled CoS<sub>2</sub> nanocrystal film, a photographic image of CoS<sub>2</sub> nanoink, a self-assembled CoS<sub>2</sub> CE, and *J*-*V* curves of the DSSCs, fabricated with the CoS<sub>2</sub> nanocrystal thin film and a Pt CE on the FTO and flexible ITO/polyethylene terephthalate (PET) substrate. The CoS<sub>2</sub> nanoparticles were stabilized with poly(vinylpyrrolidone) (PVP) to form an oriented structure. The DSSC with self-assembled CoS<sub>2</sub> CE shows a *J*<sub>sc</sub> of 14.62 mA cm<sup>-2</sup>, *V*<sub>oc</sub> of 0.71 V, and a FF of 0.64, resulting in a PCE of 6.78%, which is comparable to a Pt CE with a value of 7.38%. The PCE was found to decrease when the thickness of the self-assembled CoS<sub>2</sub> film was either higher or lower than 2.5 μm. The CoS<sub>2</sub> shows a *R*<sub>s</sub> value of 34.20 Ω cm<sup>2</sup>, slightly higher compared to Pt (27.13 Ω cm<sup>2</sup>), indicating comparable electrical conductivity. The *R*<sub>CT</sub> value of 7.21 Ω cm<sup>2</sup> for the CoS<sub>2</sub> CE indicates higher electrocatalytic activity for the reduction of triiodide (I<sub>3</sub><sup>-</sup>). The CoS<sub>2</sub> CE has a high chemical capacitance (*C*<sub>μ</sub>) of 27.57 μF, compared to 2.76 μF for the Pt CE, which also is evidence of a high surface area for CoS<sub>2</sub> CE which is beneficial to electrocatalysis. The DSSCs with CoS<sub>2</sub> deposited on a flexible ITO/PET substrate showed a *J*<sub>sc</sub> of 13.17 mA cm<sup>-2</sup>, *V*<sub>oc</sub> of 0.70 V,

FF of 0.68 and a PCE of 6.40%. The fabrication of a CoS<sub>2</sub> CE is low-cost and solution processable at room temperature, which could make it an alternative to Pt CEs for flexible DSSCs.

Another study used mesoporous CoS<sub>2</sub> nanotube arrays deposited on an FTO glass substrate and used as a CE for a DSSC.<sup>233</sup> The CoS<sub>2</sub> nanotube arrays were characterized by SEM, TEM, and XRD techniques for their morphology and crystal structures. The electrocatalytic properties of the CoS<sub>2</sub> nanotube arrays were measured using CV and Tafel polarization curve measurements. The DSSCs having CoS<sub>2</sub> CEs achieved a PCE of 6.13%, comparable to that of sputtered Pt CE (6.04%). The *R*<sub>CT</sub> of the mesoporous CoS<sub>2</sub> nanotube array CE was found to be 3.51 Ω cm<sup>2</sup> and comparable to the Pt CE (5.78 Ω cm<sup>2</sup>). The CoS<sub>2</sub> nanotube array based CEs have large active surface area due to the mesoporous nanotube structure. The CoS<sub>2</sub> nanotube array CE also exhibits electrocatalytic activities comparable to Pt CE. Tsai *et al.*<sup>234</sup> also prepared CoS<sub>2</sub> nanoflake arrays from Co(OH)<sub>2</sub> nanoflake arrays through an ion exchange reaction to develop CEs for DSSCs. The CoS<sub>2</sub> nanoflakes were found to be composed of CoS<sub>2</sub> single crystals as well as their aggregates. The DSSC with CoS<sub>2</sub> nanoflake arrays as a CE showed a PCE of 5.20%, comparable to a sputtered Pt CE (5.34%).

Different types of cobalt sulfide (CoS) have been used as CEs for DSSCs. The CoS nanoparticles deposited onto FTO glass substrates showed good transparency and high electrocatalytic activity for the I<sup>-</sup>/I<sub>3</sub><sup>-</sup> redox couple for a DSSC.<sup>235</sup> CoS nanoparticle CEs showed a low *R*<sub>CT</sub> value of 1.3 Ω cm<sup>2</sup>, less than that of Pt on FTO glass (*R*<sub>CT</sub> of 2.3 Ω cm<sup>2</sup>) and achieved a PCE of 6.6%. An optimized CoS nanoparticle CE was also studied for



Fig. 17 (a) SEM image of a self-assembled CoS<sub>2</sub> nanocrystal film on FTO glass substrate, (b) cross-sectional SEM image of the CoS<sub>2</sub> counter electrode (CE), (c) photographic image of CoS<sub>2</sub> nanoink, and (d) self-assembled CoS<sub>2</sub> CE. (e) Photocurrent density–voltage (*J*-*V*) curves of the DSSCs with CoS<sub>2</sub> nanocrystal thin film and Pt CEs. (f) *J*-*V* curves of the DSSCs with CoS<sub>2</sub> deposited on a flexible ITO/PET substrate. Reprinted with permission from ref. 232, J. Jin, X. Zhang and T. He, self-assembled CoS<sub>2</sub> nanocrystal film as an efficient counter electrode for dye-sensitized solar cells. *J. Phys. Chem. C*, 2014, **118**, 24877–24883. Copyright© American Chemical Society.







Fig. 18 (Left) illustration depicting preparation of tin sulfide nanoparticles/reduced graphene oxide (SnS<sub>2</sub>@RGO) nanocomposites. (Right) photocurrent density–photovoltage ( $J$ – $V$ ) curves for DSSCs having Pt, RGO, SnS<sub>2</sub>, and SnS<sub>2</sub>@RGO composite CEs. Reprinted with permission from ref. 250, B. Yang, X. Zuo, P. Chen, L. Zhou, X. Yang, H. Zhang, G. Li, M. Wu, Y. Ma, S. Jin and X. Chen, nanocomposite of tin sulfide nanoparticles with reduced graphene oxide in high-efficiency dye-sensitized solar cells. *ACS Appl. Mater. Interfaces*, 2015, 7, 137–143. Copyright© American Chemical Society.

a ferrocene-based liquid electrolyte. The rose-petal like CoS<sub>2</sub> was deposited on an FTO as CE using a chemical bath deposition method.<sup>236</sup> The DSSC assembled with a CoS<sub>2</sub> CE achieved a PCE of 5.32%, higher than that of a Pt CE (5.02%). The PCEs of CoS<sub>2</sub> CEs depend on the deposition parameters including the concentrations of urea and thioacetamide, and the deposition time of the CEs. Also, CoS<sub>2</sub> embedded carbon nanocages were fabricated as CEs for DSSCs through a zeolitic imidazolate framework-67, Co(2-methylimidazole)<sub>2</sub> template.<sup>237</sup> The performance of the CoS<sub>2</sub> CE in a DSSC was optimized *via* a sulfurization process, where CoS<sub>2</sub> nanoparticles with embedded carbon nanocages were sulfurized for a period of 4 hours, and showed the highest PCE of 8.20%, even higher than Pt-based CE (7.88%). The synergic effect of CoS<sub>2</sub> nanoparticles and the carbon matrix resulted in the CE having high electrical conductivity and catalytic activity. Kim *et al.*<sup>238</sup> deposited CoS<sub>2</sub>, nickel sulfide (NiS), and Ni-doped CoS<sub>2</sub> nanoparticles on a FTO substrate as CEs for DSSCs *via* a chemical bath deposition method. The surface morphology of the thin films was analyzed by SEM. Electrochemical properties of Ni-doped CoS<sub>2</sub> thin films evaluated by EIS, CV, and Tafel polarization curves indicated increased electrocatalytic activity for the reduction of I<sub>3</sub><sup>−</sup> in the DSSCs compared to Pt CEs. The Ni-doped CoS<sub>2</sub> CE (15% Ni) showed a PCE of 5.50% under 1 Sun illumination, exceeding the PCE of the Pt CE ( $\eta$  = 5.21%). PCE and  $R_{CT}$  values of the DSSCs were found to depend on the amount of Ni-doping of the CoS<sub>2</sub> nanoparticles. These yielded PCEs of 4.81, 5.17, 5.50, and 4.12%, for  $R_{CT}$  values of 279.7, 36.63, 8.53 and 82.72  $\Omega$  cm<sup>2</sup>, at 5, 10, 15 and 20% Ni contents in the CoS<sub>2</sub> CE, respectively. Comparatively, DSSCs with bare CoS<sub>2</sub> and NiS CEs showed poor electrocatalytic activity of I<sub>3</sub><sup>−</sup> reduction.

In another study, CoS<sub>2</sub>/graphene composites were prepared *via* a hydrothermal method using Co ions with thiourea in the presence of graphene oxide (GO).<sup>239</sup> The distribution and size of the CoS<sub>2</sub> nanoparticles deposited onto a flexible graphene sheet was controlled in order to optimize the electrocatalytic activity for I<sub>3</sub><sup>−</sup> reduction. A CoS<sub>2</sub> nanoparticles/graphene sheet (CoS<sub>2</sub>/G<sub>50</sub>) CE was prepared by incorporating 50 mg graphene oxide,

and exhibited the lowest electrolyte diffusion resistance and the highest electrocatalytic activity. The DSSC with CoS<sub>2</sub>/G<sub>50</sub> CE achieved a PCE of 6.55%, higher than bare CoS<sub>2</sub> or graphene CEs or a conventional Pt CE ( $\eta$  = 6.20%). Also, CoS<sub>2</sub>/RGO composite films for a CE of a DSSC were prepared using the layer-by-layer (LbL) assembly method, followed by thermal annealing.<sup>240</sup> The photovoltaic parameters of the CoS<sub>2</sub>/RGO CE based DSSCs were found to depend upon the deposition times of graphene oxide. PCE values of 2.6, 4.1, 5.4, 2.9 and 1.4% were measured for 2, 4, 6, 8 and 10 deposition times of graphene oxide, respectively. It appeared that the lowest  $R_{CT}$  of 4.8  $\Omega$  cm<sup>2</sup> was observed for a CoS<sub>2</sub>/RGO CE prepared with 6 deposition times.

### 3.7 SnS<sub>2</sub> counter electrodes

Tin disulfide (SnS<sub>2</sub>) attains morphological structures which include nanocrystals, nanosheets, nanowires, nanobelts, and these show potential for field-effect transistors, gas sensors, photocatalysts, and solar cells.<sup>241–248</sup> In one study, semi-transparent SnS<sub>2</sub> nanosheets were prepared as a CE to develop a Pt-free DSSC for the reduction of I<sub>3</sub><sup>−</sup>.<sup>249</sup> The SnS<sub>2</sub>-based CE with 300 nm thickness showed high electrocatalytic activity, with a PCE of 7.64% compared to a PCE of 7.71% for a Pt CE based DSSC. When SnS<sub>2</sub> nanosheets were functionalized with carbon nanoparticles, the CE exhibited a PCE of 8.06%, a better electrocatalytic performance than a Pt CE. SnS<sub>2</sub> nanosheets could therefore be used as a low cost electrocatalytic electrode material for DSSCs. Yang *et al.*<sup>250</sup> prepared SnS<sub>2</sub> nanoparticles and a RGO nanocomposite as a Pt-free CE for a DSSC. The SnS<sub>2</sub> nanoparticles dispersed onto RGO sheets exhibited improved electrocatalytic activity for reducing I<sub>3</sub><sup>−</sup>, and also increased conductivity. Fig. 18 illustrates the preparation of SnS<sub>2</sub>@RGO nanocomposites and compares  $J$ – $V$  curves for DSSCs having Pt, RGO, SnS<sub>2</sub>, and SnS<sub>2</sub>@RGO composite CEs. The DSSC with SnS<sub>2</sub>@RGO nanocomposite CE showed a PCE of 7.12%, much higher than that of the RGO sheet alone (3.73%) and SnS<sub>2</sub> nanoparticles (5.58%), and a comparable PCE value to Pt CE (6.79%). The  $Z_N$  values were 0.64, 4.36, 5.01 and 0.95  $\Omega$  for the





**Table 3** Photovoltaic parameters of WS<sub>2</sub>, NiS<sub>2</sub>, TiS<sub>2</sub>, FeS<sub>2</sub>, CoS<sub>2</sub>, and SnS<sub>2</sub> based CEs used in DSSCs. FTO glass is the common substrate used in assembling DSSCs with different CE materials. The measurements were conducted at a simulated solar light intensity of 100 mW cm<sup>-2</sup> (AM 1.5G) unless specified. The photovoltaic parameters short-circuit photocurrent density ( $J_{sc}$ ), open-circuit voltage ( $V_{oc}$ ), fill factor (FF), and power conversion efficiency ( $\eta$ ), series resistance ( $R_s$ ), charge-transfer resistance ( $R_{CT}$ ), electrolyte and dye used for DSSCs are summarized and compared with standard Pt counter electrode<sup>a</sup>

| Counter electrodes                                   | Redox couples                               | Dye  | $J_{sc}$ (mA cm <sup>-2</sup> ) | $V_{oc}$ (V) | FF (%) | PCE ( $\eta$ , %) | $R_s$ ( $\Omega$ cm <sup>2</sup> ) | $R_{CT}$ ( $\Omega$ cm <sup>2</sup> ) | Ref. |
|--|---|------|---------------------------------|--------------|--------|-------------------|------------------------------------|---------------------------------------|------|
| WS <sub>2</sub>                                      | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.1                            | 0.662        | 55     | 4.4               | —                                  | —                                     | 181  |
| WS <sub>2</sub> (glucose solution, 0.3 M)            | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.8                            | 0.658        | 63     | 5.3               | —                                  | —                                     | 181  |
| WS <sub>2</sub> (glucose solution, 0.6 M)            | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.1                            | 0.670        | 62     | 5.5               | —                                  | —                                     | 181  |
| WS <sub>2</sub> (glucose solution, 1.2 M)            | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.4                            | 0.675        | 63     | 5.3               | —                                  | —                                     | 181  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.2                            | 0.668        | 63     | 5.6               | —                                  | —                                     | 181  |
| WS <sub>2</sub> (sputtering time, 10 min)            | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.43                           | 0.71         | 66     | 6.3               | —                                  | —                                     | 182  |
| WS <sub>2</sub> (sputtering time, 15 min)            | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.01                           | 0.69         | 55     | 5.8               | —                                  | —                                     | 182  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.50                           | 0.66         | 61     | 6.8               | —                                  | —                                     | 182  |
| WS <sub>2</sub> (hydrothermal method)                | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 11.28                           | 0.72         | 59     | 4.79              | 4.86                               | 5.13                                  | 185  |
| WS <sub>2</sub> /MWCNTs (3 wt%)                      | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.65                           | 0.73         | 59     | 5.45              | 3.75                               | 3.47                                  | 185  |
| WS <sub>2</sub> /MWCNTs (5 wt%)                      | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.51                           | 0.73         | 65     | 6.41              | 3.01                               | 2.53                                  | 185  |
| WS <sub>2</sub> /MWCNTs (10 wt%)                     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.09                           | 0.72         | 60     | 5.22              | 4.17                               | 4.59                                  | 185  |
| MWCNTs   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 10.77                           | 0.66         | 61     | 4.34              | 6.52                               | 6.60                                  | 185  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.23                           | 0.74         | 67     | 6.56              | 2.26                               | 2.74                                  | 185  |
| WS <sub>2</sub> (hydrothermal method)                | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 11.72                           | 0.72         | 63     | 5.32              | 2.86                               | 4.60                                  | 186  |
| WS <sub>2</sub> /MWCNTs (1 wt%)                      | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 11.95                           | 0.73         | 63     | 5.50              | 2.80                               | 3.86                                  | 186  |
| WS <sub>2</sub> /MWCNTs (5 wt%)                      | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.63                           | 0.75         | 72     | 7.36              | 2.54                               | 2.49                                  | 186  |
| WS <sub>2</sub> /MWCNTs (7 wt%)                      | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.75                           | 0.75         | 68     | 6.50              | 2.67                               | 2.94                                  | 186  |
| WS <sub>2</sub> /MWCNTs (10 wt%)                     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.47                           | 0.74         | 68     | 6.27              | 2.78                               | 3.46                                  | 186  |
| WS <sub>2</sub> /MWCNTs*                             | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.65                           | 0.73         | 59     | 5.45              | 2.85                               | 3.47                                  | 186  |
| MWCNTs   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 10.77                           | 0.66         | 61     | 4.34              | 2.95                               | 6.60                                  | 186  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.23                           | 0.76         | 75     | 7.54              | 2.27                               | 2.74                                  | 186  |
| TiS <sub>2</sub> nanosheets                          | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 17.48                           | 0.73         | 60.3   | 7.66              | —                                  | —                                     | 199  |
| TiS <sub>2</sub> /graphene hybrid                    | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 17.76                           | 0.72         | 68.5   | 8.80              | 2.32                               | 0.63                                  | 199  |
| Graphene   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.41                           | 0.71         | 48.4   | 5.33              | —                                  | —                                     | 199  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.93                           | 0.72         | 65.6   | 8.00              | 6.90                               | 1.32                                  | 199  |
| TiS <sub>2</sub> (drop coating method)               | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 11.27                           | 0.565        | 51     | 3.24              | 16.12                              | —                                     | 200  |
| TiS <sub>2</sub> /PEDOT:PSS (5 wt%)                  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.81                           | 0.686        | 62     | 5.91              | —                                  | —                                     | 200  |
| TiS <sub>2</sub> /PEDOT:PSS (10 wt%)                 | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.78                           | 0.681        | 66     | 7.04              | 15.78                              | 4.78                                  | 200  |
| PEDOT:PSS  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.74                           | 0.664        | 46     | 3.91              | 14.92                              | 7.27                                  | 200  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.83                           | 0.716        | 68     | 7.65              | 14.29                              | 3.02                                  | 200  |
| NiS <sub>2</sub> -hollow microspheres                | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 17.48                           | 0.712        | 63     | 7.84              | 10.56                              | 9.68                                  | 206  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 17.04                           | 0.747        | 62     | 7.89              | 12.78                              | 8.76                                  | 206  |
| NiS <sub>2</sub> -octahedron                         | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.55                           | 0.712        | 62     | 5.98              | 13.14                              | 9.86                                  | 209  |
| NiS <sub>2</sub> -cube                               | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.62                           | 0.715        | 60     | 5.43              | 14.98                              | 13.17                                 | 209  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.37                           | 0.718        | 63     | 6.55              | 2.24                               | 6.25                                  | 209  |
| NiS <sub>2</sub> (hydrothermal method)               | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.42                           | 0.738        | 66     | 7.02              | 5.1                                | 8.8                                   | 210  |
| NiS <sub>2</sub> /RGO                                | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.55                           | 0.749        | 69     | 8.55              | 6.4                                | 2.9                                   | 210  |
| Reduced graphene oxide (RGO)                         | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 10.98                           | 0.716        | 40     | 3.14              | 14.2                               | 100.2                                 | 210  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.75                           | 0.739        | 70     | 8.15              | 2.2                                | 0.5                                   | 210  |
| FeS <sub>2</sub> (spray pyrolysis)                   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.20                           | 0.79         | 65     | 7.97              | —                                  | —                                     | 221  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.77                           | 0.78         | 66     | 7.54              | —                                  | —                                     | 221  |
| FeS <sub>2</sub>                                     | Co <sup>2+</sup> /Co <sup>3+</sup>          | C128 | 11.57                           | 0.78         | 69     | 6.34              | 4.9                                | 7.2                                   | 221  |
| PEDOT  | Co <sup>2+</sup> /Co <sup>3+</sup>          | C128 | 10.83                           | 0.79         | 75     | 6.31              | 6.0                                | 3.9                                   | 221  |
| FeS <sub>2</sub> films                               | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.56                           | 0.658        | 57.8   | 4.78              | 9.60                               | 213.1                                 | 222  |
| FeS <sub>2</sub> nanorods                            | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.68                           | 0.653        | 65.7   | 5.88              | 9.61                               | 11.0                                  | 222  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.36                           | 0.685        | 68.2   | 6.23              | 5.62                               | 9.2                                   | 222  |
| FeS <sub>2</sub> (without NaOH)                      | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 10.20                           | 0.70         | 66     | 4.76              | 3.73                               | 13.6                                  | 223  |
| FeS <sub>2</sub> (with NaOH)                         | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.08                           | 0.74         | 64     | 5.78              | 2.91                               | 5.99                                  | 223  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 11.58                           | 0.74         | 69     | 5.93              | 3.09                               | 1.16                                  | 223  |
| FeS <sub>2</sub> (with ethanedithiol)                | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.14                           | 0.71         | 68     | 7.31              | —                                  | 1.60                                  | 224  |
| FeS <sub>2</sub> (without ethanedithiol)             | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.63                           | 0.71         | 64     | 5.74              | —                                  | 4.45                                  | 224  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.37                           | 0.71         | 69     | 7.52              | —                                  | 1.47                                  | 224  |
| FeS <sub>2</sub> (MWCNT/TiO <sub>2</sub> photoanode) | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.86                           | 0.77         | 56     | 7.27              | —                                  | —                                     | 225  |
| FeS <sub>2</sub> (TiO <sub>2</sub> photoanode)       | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.16                           | 0.77         | 57     | 6.65              | —                                  | —                                     | 225  |
| Pt (MWCNT/TiO <sub>2</sub> photoanode)               | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.96                           | 0.77         | 57     | 7.00              | —                                  | —                                     | 225  |
| Pt (TiO <sub>2</sub> photoanode)                     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.68                           | 0.77         | 54     | 6.51              | —                                  | —                                     | 225  |
| CoS <sub>2</sub> nanocrystals                        | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.62                           | 0.71         | 64     | 6.78              | 34.20                              | 7.21                                  | 232  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.78                           | 0.72         | 68     | 7.38              | 27.13                              | 4.57                                  | 232  |



Table 3 (Contd.)

| Counter electrodes                                   | Redox couples                               | Dye  | $J_{sc}$ (mA cm <sup>-2</sup> ) | $V_{oc}$ (V) | FF (%) | PCE ( $\eta$ , %) | $R_s$ ( $\Omega$ cm <sup>2</sup> ) | $R_{CT}$ ( $\Omega$ cm <sup>2</sup> ) | Ref. |
|--|---|------|---------------------------------|--------------|--------|-------------------|------------------------------------|---------------------------------------|------|
| CoS <sub>2</sub> nanotube (NT1)                      | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 5.26                            | 0.765        | 52.5   | 2.13              | —                                  | —                                     | 233  |
| CoS <sub>2</sub> nanotube (NT2)                      | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 10.68                           | 0.794        | 64.6   | 5.48              | —                                  | —                                     | 233  |
| CoS <sub>2</sub> nanotube (NT3)                      | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 11.70                           | 0.797        | 65.5   | 6.11              | —                                  | —                                     | 233  |
| CoS <sub>2</sub> nanotube (NT4)                      | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 11.58                           | 0.804        | 65.8   | 6.13              | —                                  | —                                     | 233  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.28                           | 0.770        | 63.9   | 6.04              | —                                  | —                                     | 233  |
| CoS <sub>2</sub> nanoflakes                          | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 10.13                           | 0.747        | 68.8   | 5.20              | —                                  | —                                     | 234  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 10.04                           | 0.767        | 69.4   | 5.34              | —                                  | —                                     | 234  |
| CoS(50) (chloroform, 50 mM)                          | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N3   | 8.48                            | 0.703        | 53.1   | 3.4               | —                                  | —                                     | 235  |
| CoS(25) (chloroform, 25 mM)                          | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N3   | 9.23                            | 0.700        | 51.3   | 3.5               | —                                  | —                                     | 235  |
| CoS(25)A (annealed for 240 min)                      | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N3   | 3.86                            | 0.560        | 23.2   | 0.5               | —                                  | —                                     | 235  |
| CoS(12.5) (chloroform, 12.5 mM)                      | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N3   | 6.08                            | 0.701        | 54.1   | 2.3               | —                                  | —                                     | 235  |
| CoS(2.5) (chloroform, 2.5 mM)                        | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N3   | 4.32                            | 0.700        | 47.9   | 1.4               | —                                  | —                                     | 235  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N3   | 9.05                            | 0.702        | 56.4   | 3.6               | —                                  | —                                     | 235  |
| CoS(25) (chloroform, 25 mM)                          | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.15                           | 0.703        | 66.7   | 6.6               | —                                  | —                                     | 235  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.90                           | 0.692        | 62.4   | 6.0               | —                                  | —                                     | 235  |
| CoS <sub>2</sub> rose-petal structure                | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.14                           | 0.64         | 68     | 5.32              | 9.88                               | 3.52                                  | 236  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.35                           | 0.61         | 61     | 5.02              | 9.09                               | 3.65                                  | 236  |
| CoS <sub>2</sub> (chemical bath deposition)          | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 8.41                            | 0.628        | 73.6   | 4.01              | 12.02                              | 326.6                                 | 238  |
| CoS <sub>2</sub> (Ni-doped, 15%)                     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.12                           | 0.649        | 69.8   | 5.50              | 9.21                               | 8.53                                  | 238  |
| NiS nanoparticles                                    | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 9.54                            | 0.592        | 67.8   | 3.83              | —                                  | —                                     | 238  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.33                           | 0.649        | 65.0   | 5.21              | 10.4                               | 14.18                                 | 238  |
| CoS <sub>2</sub>                                     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 6.25                            | 0.58         | 51     | 1.86              | 9.7                                | 3.4                                   | 239  |
| CoS <sub>2</sub> -G <sub>20</sub> (GO powder, 20 mg) | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.38                           | 0.71         | 57     | 5.86              | 7.7                                | 2.3                                   | 239  |
| CoS <sub>2</sub> -G <sub>50</sub> (GO powder, 50 mg) | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.12                           | 0.73         | 60     | 6.55              | 7.6                                | 1.3                                   | 239  |
| CoS <sub>2</sub> -G <sub>80</sub> (GO powder, 80 mg) | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.11                           | 0.71         | 52     | 4.83              | 7.9                                | 2.7                                   | 239  |
| Graphene   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 3.68                            | 0.65         | 58     | 1.37              | 7.6                                | 4.0                                   | 239  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.69                           | 0.73         | 58     | 6.20              | 7.2                                | 1.9                                   | 239  |
| CoS <sub>2</sub> /reduced graphene oxide             | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | Z907 | 12.87                           | 0.67         | 63     | 5.4               | 22.5                               | 4.8                                   | 240  |
| SnS <sub>2</sub> (350 °C, 30 min)                    | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.63                           | 0.725        | 55.3   | 6.27              | 21.5                               | 8.3                                   | 249  |
| SnS <sub>2</sub> (400 °C, 30 min)                    | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.96                           | 0.743        | 60.7   | 7.64              | 18.6                               | 5.6                                   | 249  |
| C/SnS <sub>2</sub> (400 °C, 30 min)                  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 17.47                           | 0.745        | 61.9   | 8.06              | 17.4                               | 5.2                                   | 249  |
| SnS <sub>2</sub> (450 °C, 30 min)                    | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.37                           | 0.734        | 62.6   | 6.14              | 20.8                               | 10.6                                  | 249  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.53                           | 0.730        | 63.9   | 7.71              | 16.2                               | 6.7                                   | 249  |
| SnS <sub>2</sub> @RGO hybrid                         | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.80                           | 0.718        | 67.02  | 7.12              | 17.96                              | 7.24                                  | 250  |
| SnS <sub>2</sub>                                     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.60                           | 0.770        | 53.28  | 5.58              | 39.73                              | 11.24                                 | 250  |
| RGO  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 10.08                           | 0.661        | 52.29  | 3.73              | 34.20                              | 50.25                                 | 250  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.00                           | 0.720        | 67.36  | 6.79              | 24.21                              | 5.08                                  | 250  |

<sup>a</sup> WS<sub>2</sub>/MWCNTs\* prepared without glucose aid. In the case of  $R_s$  and  $R_{CT}$ : some of the authors used  $\Omega$  instead of  $\Omega$  cm<sup>2</sup> for the resistances without mentioning the size of the electrode.

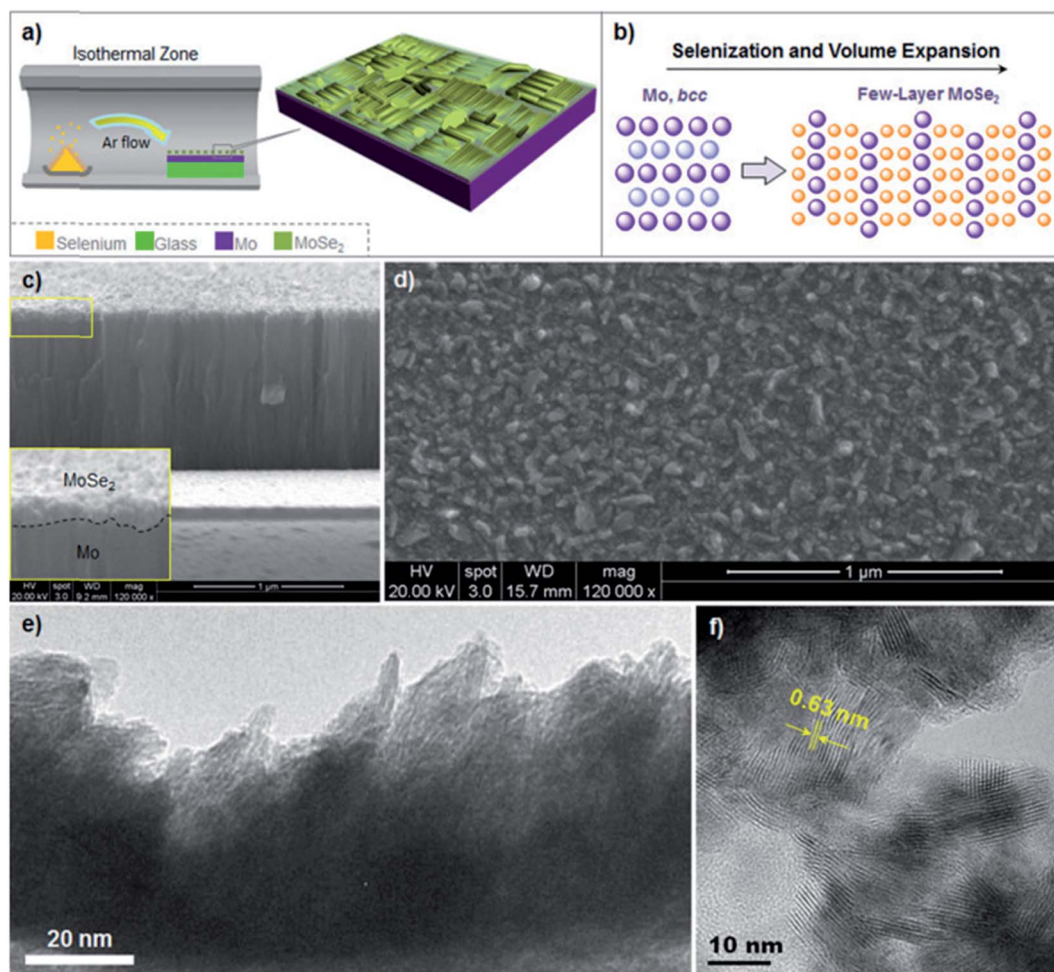
SnS<sub>2</sub>@RGO nanocomposite, SnS<sub>2</sub>, RGO and Pt CEs, respectively. The RGO and SnS<sub>2</sub> CEs have larger  $R_{CT}$  values, hence lower electrocatalytic ability among these CEs, whereas the SnS<sub>2</sub>@RGO composite has a lower  $R_{CT}$  value, leading to a higher electrocatalytic activity. The role of the RGO sheets is to facilitate the conduction pathway. The  $E_{pp}$  of the SnS<sub>2</sub>@RGO nanocomposite CE is 593 mV, similar to a Pt CE ( $E_{pp}$  of 605 mV). This indicates that the electrocatalytic activity of the SnS<sub>2</sub>@RGO nanocomposite CE is similar to that of a conventional Pt CE. The electrochemical stability of the SnS<sub>2</sub>@RGO nanocomposite CE was analyzed up to 25 cycles of CV curves, where no drastic change was noticed in peak current density, confirming that SnS<sub>2</sub>@RGO nanocomposite CEs are stable for electrocatalysis of I<sub>3</sub><sup>-</sup> in the electrolyte. The SnS<sub>2</sub>@RGO nanocomposite CEs are as promising as Pt CEs in DSSCs. Table 3 lists a summary of the photovoltaic parameters of WS<sub>2</sub>, NiS<sub>2</sub>, TiS<sub>2</sub>, FeS<sub>2</sub>, CoS<sub>2</sub>, and SnS<sub>2</sub> based CEs for DSSCs and their comparison with a standard Pt CE.

## 4. Transition-metal diselenides based counter electrodes

### 4.1 MoSe<sub>2</sub> counter electrodes

Molybdenum dichalcogenides, such as MoS<sub>2</sub>, MoSe<sub>2</sub>, and MoTe<sub>2</sub>, are a very interesting class of materials that has attracted a great attention because of their unique properties.<sup>251–257</sup> Molybdenum diselenide (MoSe<sub>2</sub>) is a semiconductor that has been studied for device applications.<sup>92,258,259</sup> The nanosheets of MoSe<sub>2</sub> have weak van der Waals forces, therefore, poorly adhere to the surface of substrates. To resolve this problem, Lee *et al.*<sup>260</sup> and Chen *et al.*<sup>261</sup> applied a CVD technique to grow catalytic MoSe<sub>2</sub> films on Mo foils. Lee *et al.*<sup>260</sup> used few-layer MoSe<sub>2</sub> in a DSSC as CE for the reduction of I<sub>3</sub><sup>-</sup> to I<sup>-</sup>. Fig. 19 shows a schematic representation for the preparation of few-layer MoSe<sub>2</sub>, and their SEM and TEM images. The few-layer MoSe<sub>2</sub> on Mo film was developed by selenizing the Mo-coated soda-lime glass in a tube furnace. X-ray diffraction analysis exhibits





**Fig. 19** (a) Schematic representation for the selenization of Mo-coated soda-lime glass in a tube furnace for few-layer MoSe<sub>2</sub>; (b) schematic illustration showing the formation of few-layer MoSe<sub>2</sub> from body-centered cubic (bcc) crystal structures of Mo (c) cross-sectional SEM image of the MoSe<sub>2</sub> on Mo surface, inset shows the borderline between MoSe<sub>2</sub> and Mo substrate; (d) SEM image of the as-synthesized MoSe<sub>2</sub> nanostructures; (e) HRTEM image of the few-layer MoSe<sub>2</sub>; (f) high magnification HRTEM image of the few-layer MoSe<sub>2</sub> with interlayer spacing of 0.63–0.64 nm. Reprinted with permission from ref. 260, L. T. L. Lee, J. He, B. Wang, Y. Ma, K. Y. Wong, Q. Li, X. Xiao and T. Chen, few-layer MoSe<sub>2</sub> possessing high catalytic activity towards iodide/tri-iodide redox shuttles. *Sci. Rep.*, 2014, **4**, 4063–4069. Copyright© Nature Publishing Group.

body-centered cubic (bcc) crystal structures of the Mo film. The Mo film thickness was 1  $\mu\text{m}$  and selenization was performed at 550  $^{\circ}\text{C}$  for 5 minutes, and produced the best performance for the DSSC. The MoSe<sub>2</sub> layer was about 70 nm as confirmed by the cross-sectional SEM image. The surface of the selenized Mo/glass contains nanoparticles, and the HRTEM image shows the few-layer structures. The interlayer spacing was measured as 0.63–0.64 nm. The few-layer MoSe<sub>2</sub> was prepared by surface selenization of Mo-coated soda-lime glass, which yielded a PCE of 9.0%, compared to a PCE of 8.68% for the Pt/FTO-based photoanode, thus showing the Pt/FTO free MoSe<sub>2</sub> CE outperformed the conventional CE. An MoSe<sub>2</sub>/Mo combination as a CE in a DSSC shows a PCE of 8.69%. Fig. 20 shows a comparison of  $J$ - $V$  curves of the DSSCs having MoSe<sub>2</sub>/Mo and MoS<sub>2</sub>/Mo CEs with different temperatures and times of selenization and sulfurization, and the Pt/FTO CE. The PCE of the DSSCs decreased from 7.14% for MoSe<sub>2</sub> CEs selenized at 580  $^{\circ}\text{C}$

for 60 minutes, to a PCE of 4.26% for 120 minutes. The edge sites were also found to be important for the high catalytic activity. The Mo substrate plays an important role in significantly reducing the sheet resistance of the CE, which eventually leads to a high DSSC performance. The low sheet resistance of 0.29  $\Omega\text{sq}^{-1}$  for MoSe<sub>2</sub>/Mo, compared to 12.60  $\Omega\text{sq}^{-1}$  for Pt/FTO, indicates that MoSe<sub>2</sub>/Mo is better as a CE in a DSSC than a Pt/FTO. The  $R_{\text{CT}}$  of 0.87  $\Omega\text{cm}^2$  for MoSe<sub>2</sub> and 0.61  $\Omega\text{cm}^2$  for MoS<sub>2</sub> is lower compared to Pt (6.26  $\Omega\text{cm}^2$ ) due to high conductivity of the Mo substrate, therefore the Mo substrate seems superior to the FTO substrate. Chen *et al.*<sup>261</sup> also used a MoSe<sub>2</sub>/Mo based CE in a DSSC to develop a Pt/FTO-free CE, which showed a PCE of 8.13%, slightly higher than the Pt/FTO CE (PCE of 8.06%). The  $R_s$  and  $R_{\text{CT}}$  values of the MoSe<sub>2</sub>/Mo CEs were found to be 16.5% and 3.35% of the Pt/FTO CE, indicating a higher electrocatalytic activity of the MoSe<sub>2</sub>/Mo.





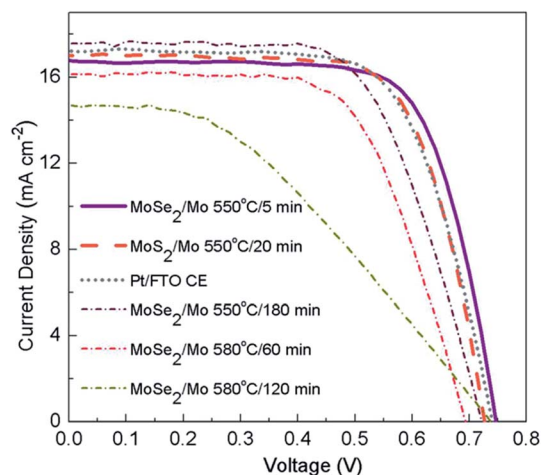


Fig. 20 Photocurrent density–voltage ( $J$ – $V$ ) curves of DSSCs having  $\text{MoSe}_2/\text{Mo}$  and  $\text{MoSe}_2/\text{Mo}$  counter electrodes with different temperatures and time of selenization and sulfurization and a comparison with conventional Pt/FTO counter electrodes. Reprinted with permission from ref. 260, L. T. L. Lee, J. He, B. Wang, Y. Ma, K. Y. Wong, Q. Li, X. Xiao and T. Chen, few-layer  $\text{MoSe}_2$  possessing high catalytic activity towards iodide/tri-iodide redox shuttles. *Sci. Rep.*, 2014, **4**, 4063–4069. Copyright© Nature Publishing Group.

Thin films of the metal selenides  $\text{NiSe}_2$ ,  $\text{CoSe}_2$ , and  $\text{MoSe}_2$  were used as CEs for DSSCs for  $\text{I}_3^-$  reduction by Ji *et al.*<sup>262</sup>  $\text{NiSe}_2$  was found to be equally efficient to conventional Pt CEs. In comparison,  $\text{NiSe}_2$  also showed a higher PCE than its sulfide analog ( $\text{NiS}_2$ ) due to lower resistance to charge transfer. Fig. 21 shows SEM images of  $\text{NiSe}_2$ ,  $\text{CoSe}_2$ , and  $\text{MoSe}_2$ , and Tafel polarization curves and  $J$ – $V$  curves of the metal selenides  $\text{NiSe}_2$ ,  $\text{CoSe}_2$ ,  $\text{MoSe}_2$ ,  $\text{WSe}_2$ ,  $\text{Bi}_2\text{Se}_3$ ,  $\text{MnSe}$ ,  $\text{PbSe}$ , as well as Pt based CEs used in DSSCs. The metal selenides were deposited on FTO glass. The  $\text{NiSe}_2$ ,  $\text{CoSe}_2$ , and  $\text{MoSe}_2$  showed higher exchange current densities compared to other selenides. The  $J$ – $V$  curve measurements of the DSSCs indicated better performance of the  $\text{NiSe}_2$  CE than that of the Pt CE, however the performance of DSSCs having  $\text{CoSe}_2$  and  $\text{MoSe}_2$  CEs was lower compared to the Pt CE.

In another study,  $\text{MoSe}_2$  nanosheets were prepared using a solvothermal method which shows microsphere hierarchical architecture.<sup>263</sup>  $\text{MoSe}_2$  nanosheets used as CE in fabricating a DSSC device showed a PCE of 9.80%, exceeding the PCE of a Pt CE based DSSC ( $\eta = 8.17\%$ ) for the triiodide/iodide ( $\text{I}_3^-/\text{I}^-$ ) redox reaction. Bi *et al.*<sup>264</sup> anchored fullerene-structured  $\text{MoSe}_2$  hollow spheres on highly nitrogen-doped graphene (HNG) as a CE for a DSSC. Diethylenetriamine (DETA) was used as a dopant for nitrogen of graphene. The hollow spheres consisted of 12–15 layers of  $\text{MoSe}_2$  which formed the conductive network for facilitating rapid electron transfer in the DSSC. The  $\text{MoSe}_2$  hollow spheres of 60–100 nm diameter and 8–12 nm thickness were dispersed on a HNG surface. The HNG– $\text{MoSe}_2$  hybrid has 52.4 wt% of  $\text{MoSe}_2$  content. The N content increased from 2.5% in  $\text{MoSe}_2/\text{graphene}$  hybrid to 12.5% in the HNG– $\text{MoSe}_2$  hybrid, which also showed high stability after 200 consecutive cycles of CV measurements. The HNG– $\text{MoSe}_2$

hybrid CE showed a PCE of 10.01%, slightly lower than a Pt CE ( $\eta = 10.55\%$ ) under similar conditions, while the  $\text{MoSe}_2/\text{graphene}$  hybrid CE had a PCE of 7.34% arising from a poor fill factor of 0.60.

Composites of  $\text{MoSe}_2$  nanosheets (NS) and poly(3,4 ethylenedioxythiophene):poly(styrenesulfonate) were investigated as the CE of a DSSC by Huang *et al.*<sup>265</sup>  $\text{MoSe}_2$  NS acts as an electrocatalyst, while the PEDOT:PSS plays a role of a conductive binder to facilitate electron transfer between the  $\text{MoSe}_2$  and the substrate. The weight ratios of  $\text{MoSe}_2$  and PEDOT:PSS (MP) in the composites varied from 0.25 to 2.00. Each composite film contained 50 mg of  $\text{MoSe}_2$  powder and 200 mg, 100 mg, 50 mg, and 25 mg of PEDOT:PSS, which are respectively referred to as MP-0.25, MP-0.50, MP-1.00, and MP-2.00, as per the ratios. The DSSC with a MP-1.00 composite film (equal weights of  $\text{MoSe}_2$  and PEDOT:PSS) CE exhibits the highest electrocatalytic activity for the reduction of  $\text{I}_3^-$ . The DSSC containing the  $\text{MoSe}_2$  NS/PEDOT:PSS composite film based CE shows a PCE of 7.58%, compared to the Pt CE exhibiting a PCE of 7.81% under similar experimental conditions. When  $\text{MoSe}_2$  NS/PEDOT:PSS composite films coated on a titanium (Ti) foil flexible substrate was used as CE, the DSSC showed a PCE of 8.51%, compared to a PCE of 8.21% for the Pt-coated Ti foil CE. The CEs in the DSSCs show the relative order of the electrocatalytic activity as Pt > MP-1.00 > bare  $\text{MoSe}_2$  > bare PEDOT:PSS, which is the same as observed by the IPCE spectra. The MP-1.00 composite film shows larger values of the heterogeneous rate constant, and the effective catalytic surface area as compared to bare  $\text{MoSe}_2$  and bare PEDOT:PSS, because of  $\text{MoSe}_2$  NS contents. The  $R_{\text{CT-Tafel}}$  values of  $3.23 \Omega \text{ cm}^2$  for Pt,  $181.46 \Omega \text{ cm}^2$  for bare PEDOT:PSS,  $3.77 \Omega \text{ cm}^2$  for MP-1.00, and  $3.11 \Omega \text{ cm}^2$  for bare  $\text{MoSe}_2$  were observed. The electrocatalytic ability of the CEs follow a trend seen in the  $R_{\text{CT}}$  values measured from Tafel polarization curves and EIS. The  $\text{MoSe}_2$  NS/PEDOT:PSS composite film based CEs thus show potential to replace a costly Pt electrode.

A cobalt selenide ( $\text{Co}_{0.85}\text{Se}$ )/ $\text{MoSe}_2$ /molybdenum oxide ( $\text{MoO}_3$ ) ternary hybrid was evaluated as a CE for DSSCs.<sup>266</sup>  $\text{Co}_{0.85}\text{Se}/\text{MoSe}_2/\text{MoO}_3$  ternary hybrids consist of nanorods, nanosheets, and nanoparticles, as confirmed by FESEM. CV showed larger current density for the  $\text{Co}_{0.85}\text{Se}/\text{MoSe}_2/\text{MoO}_3$  hybrid compared with a sputtered Pt CE. The  $\text{Co}_{0.85}\text{Se}/\text{MoSe}_2/\text{MoO}_3$  CE based DSSCs showed a PCE of 7.10%, much higher than that of a DSSC with a Pt CE ( $\eta = 6.03\%$ ). For comparison, the  $\text{Co}_{0.85}\text{Se}$  hollow nanoparticles as a CE for DSSCs showed a PCE of 6.03%, lower compared to the Pt CE based DSSC ( $\eta = 6.45\%$ ).<sup>267</sup> The transparent CEs using metal selenides alloys (M-Se; M = Co, Ni, Cu, Fe, Ru) were studied for the electrocatalytic activity for DSSCs and triiodide ( $\text{I}_3^-$ ) reduction.<sup>268</sup> The DSSCs containing CEs consisting of a metal selenide alloy showed PCEs of 8.30% for  $\text{Co}_{0.85}\text{Se}$ , 7.85% for  $\text{Ni}_{0.85}\text{Se}$ , 6.43% for  $\text{Cu}_{0.50}\text{Se}$ , 7.64% for  $\text{FeSe}$ , and 9.22% for  $\text{Ru}_{0.33}\text{Se}$ . A Pt CE based DSSC exhibited PCE of 6.18%. Also, a nickel cobalt sulfide ( $\text{NiCo}_2\text{S}_4$ ) nanoneedle array<sup>269</sup> used as a CE for a DSSC showed a PCE value of 6.9%, which is comparable to a Pt CE ( $\eta = 7.7\%$ ).



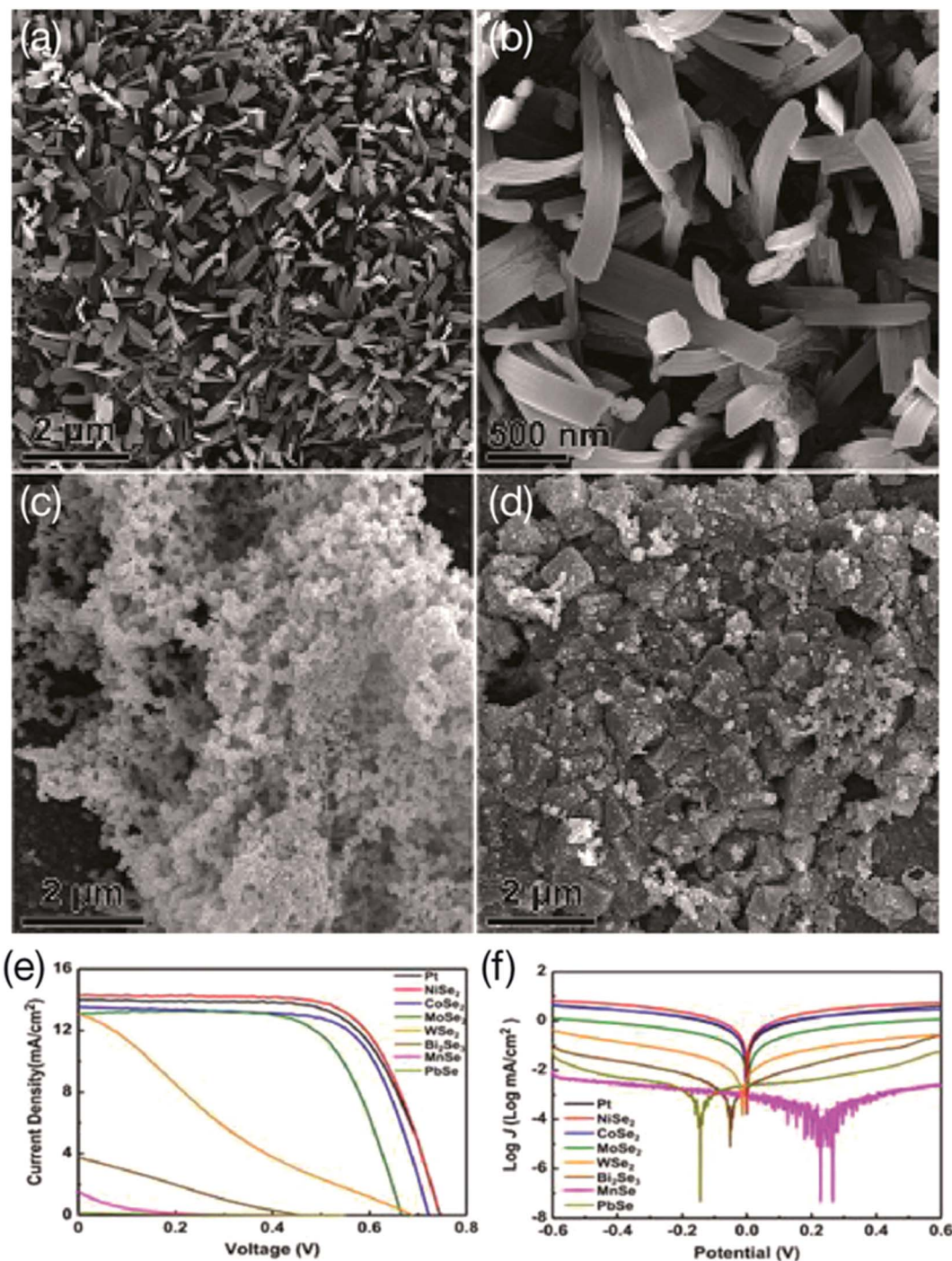


Fig. 21 SEM images of NiSe<sub>2</sub> (a, b) and SEM images of CoSe<sub>2</sub> (c) and MoSe<sub>2</sub> (d). J–V characteristic curves (e) and Tafel polarization curves (f) of DSSCs based on CEs of made of metal selenides; NiSe<sub>2</sub>, CoSe<sub>2</sub>, MoSe<sub>2</sub>, WSe<sub>2</sub>, Bi<sub>2</sub>Se<sub>3</sub>, MnSe, PbSe, and Pt. Reprinted with permission from ref. 262, I. A. Ji, H. M. Choi and J. H. Bang, metal selenide films as the counter electrode in dye-sensitized solar cell. *Mater. Lett.*, 2014, **123**, 51–54. Copyright© Elsevier.

#### 4.2 NbSe<sub>2</sub> counter electrodes

Niobium diselenide (NbSe<sub>2</sub>) has attracted attention due to its superconducting properties<sup>270–275</sup> and can be easily processed into nanosheets, nanoflakes, nanowires and nanotubes usable for applications in field-effect transistors,<sup>99a</sup> light-emitting diodes,<sup>276</sup> superconductors,<sup>277</sup> and lithium batteries.<sup>278</sup>

NbSe<sub>2</sub> nanosheets, nanorods, and NbSe<sub>2</sub>/C composites were used as CEs for DSSCs.<sup>279</sup> The morphology and structure of the NbSe<sub>2</sub> materials were characterized by SEM, TEM, and XRD while their electrochemical properties were evaluated by CV, EIS, and Tafel polarization curve measurements. The CEs based on NbSe<sub>2</sub> nanorods and NbSe<sub>2</sub> nanosheets showed lower charge



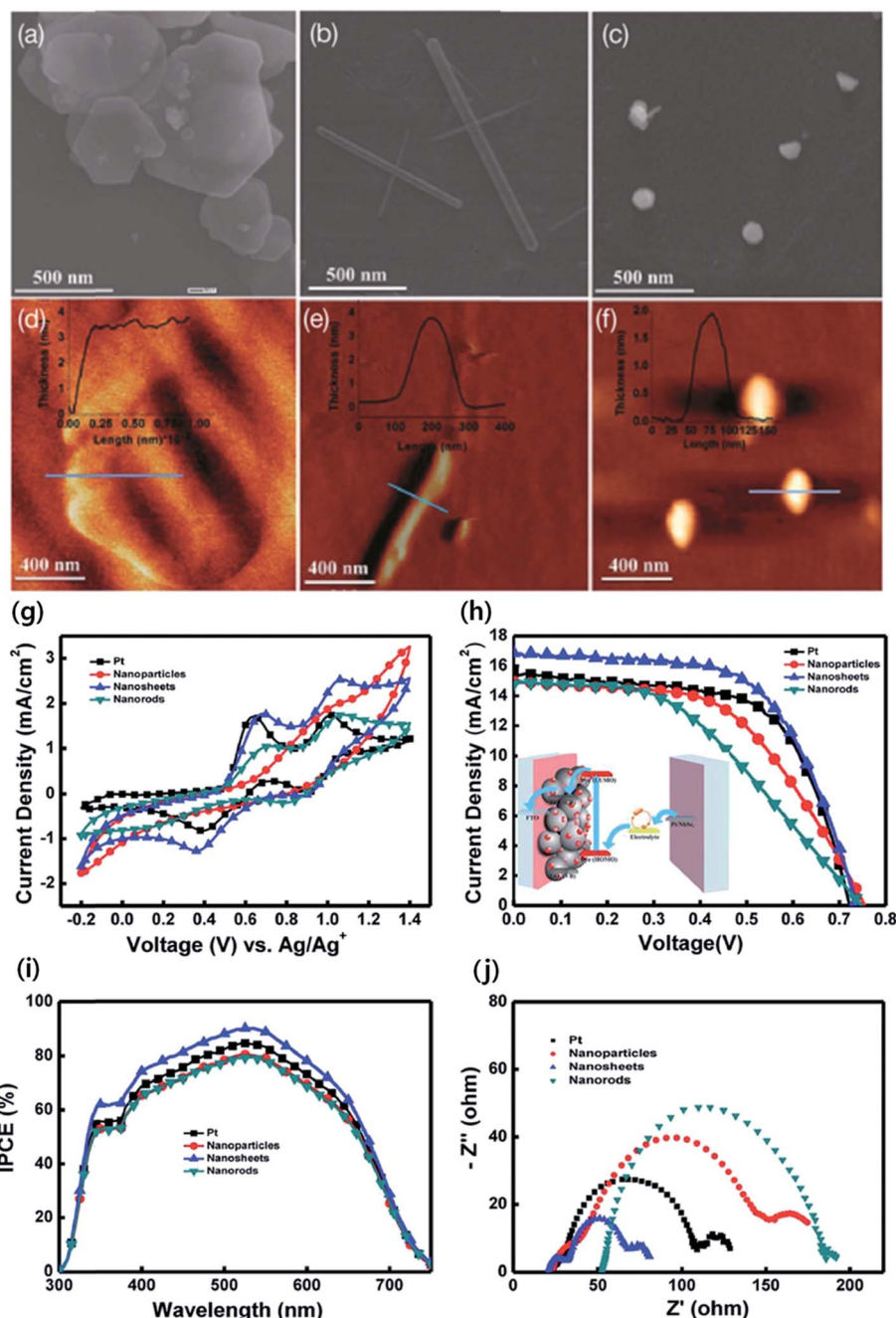


Fig. 22 SEM images of NbSe<sub>2</sub> nanostructures that include nanosheets (a), nanorods (b), and nanoparticles (c), (d–f) AFM height images of NbSe<sub>2</sub> nanosheets (d), nanorods (e), and nanoparticles (f). The insets show height profiles measured by AFM images. (g) Cyclic voltammograms (CV) of Pt CE and NbSe<sub>2</sub> nanostructures based CEs. (h) *J*–*V* curves of Pt and NbSe<sub>2</sub> nanostructures. The inset represents DSSC structure with an energy level diagram of the materials. (i) Photon-to-current conversion efficiency (IPCE) curves of Pt and NbSe<sub>2</sub> nanostructures, and (j) EIS Nyquist plots of Pt and NbSe<sub>2</sub> nanostructures based CEs used in DSSCs. Reprinted with permission from ref. 280, M. A. Ibrahim, W. C. Huang, T. W. Lan, K. M. Boopathi, Y. C. Hsiao, C. H. Chen, W. Budiawan, Y. Y. Chen, C. S. Chang, L. J. Li, C. H. Tsai, C. C. Chu, controlled mechanical cleavage of bulk niobium diselenide to nanoscaled sheet, rod, and particle structures for Pt-free dye-sensitized solar cells. *J. Mater. Chem. A*, 2014, 2, 11382–11390. Copyright© Royal Society of Chemistry.

transfer resistance and ionic diffusion. DSSCs having NbSe<sub>2</sub> nanosheet-based CEs achieved a PCE of 7.34%, which further increased to 7.80% for the NbSe<sub>2</sub>/C composite-based CEs due to reduced series resistance, which is a PCE of 98.7% of the conventional Pt-based CEs ( $\eta = 7.90\%$ ). Also, NbSe<sub>2</sub>

nanostructures deposited *via* spray-coating were used to develop Pt-free CEs for DSSCs by Ibrahim *et al.*<sup>280</sup> Fig. 22 shows SEM images and AFM height profiles of NbSe<sub>2</sub> nanosheets, nanorods, and nanoparticles, CV, *J*–*V* curves, IPCE spectra, and EIS (presented in Nyquist plots) of Pt and NbSe<sub>2</sub> nanostructures





based CEs used in DSSCs. The morphology of the synthesized NbSe<sub>2</sub> nanostructures was analyzed by SEM and AFM techniques. SEM analysis indicated the pristine NbSe<sub>2</sub> 2D sheets were 100  $\mu\text{m}$  thick. The separate NbSe<sub>2</sub> nanosheets were between 100–500 nm in lateral dimension. The length of NbSe<sub>2</sub> nanorods were up to 1.2  $\mu\text{m}$  with diameters ranging between 20 to 100 nm. The average size of the NbSe<sub>2</sub> nanoparticles was between 50–100 nm. The AFM images revealed an average thickness of <8 nm for the NbSe<sub>2</sub> nanosheets, <5 nm for the NbSe<sub>2</sub> nanorods, and <3 nm for the NbSe<sub>2</sub> nanoparticles. HRTEM of the NbSe<sub>2</sub> nanosheets on their edge showed a spacing of 6.3 Å. HRTEM revealed the crystalline nature of individual NbSe<sub>2</sub> nanorods and nanoparticles. The NbSe<sub>2</sub>

nanosheets, nanorods and nanoparticles were studied as CEs in DSSCs as a replacement to a conventional Pt CE. The dye-absorbed TiO<sub>2</sub> electrodes were prepared by dipping electrodes into ruthenium dye 719 solution for 24 hours at room temperature. The dye solution contained 0.5 mM dye N719, [*cis*-di(thiocyanato)-*N*-N0-*bis*(2,20-bipyridyl-4-carboxylic acid-40-tetrabutyl-ammonium carboxylate) ruthenium(II)], and 0.5 mM chenodeoxycholic acid in a 1 : 1 mixture of *tert*-butanol and acetonitrile. The electrolyte solution was composed of 1-butyl-3-methylimidazolium iodide (BMII, 0.6 M), 4-*tert*-butylpyridine (0.5 M), iodine (0.03 M), and guanidinium thiocyanate (0.1 M) in a acetonitrile–valeronitrile mixture. The NbSe<sub>2</sub> nanosheet CEs achieved a PCE of 7.73%, compared to a PCE of 7.01% for

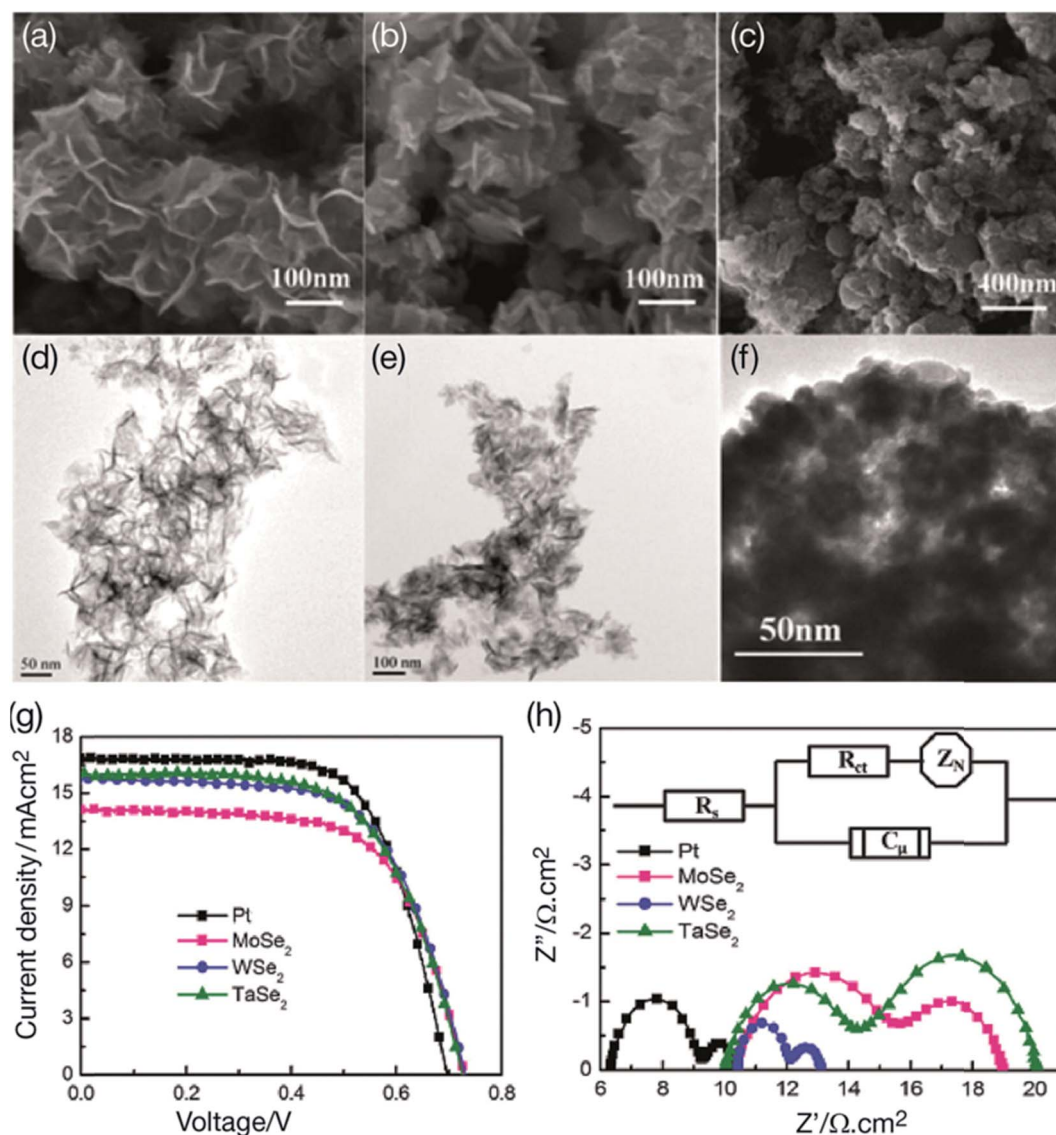


Fig. 23 SEM and TEM images of MoSe<sub>2</sub> (a and d), WSe<sub>2</sub> (b and e), and TaSe<sub>2</sub> (c and f). (g) Photocurrent–voltage (*J*–*V*) curves of the DSSCs based on MoSe<sub>2</sub>, WSe<sub>2</sub>, and Pt CEs, measured under simulated sunlight illumination (100 mW cm<sup>-2</sup>, 1.5 AM G). (h) Nyquist plots of electrochemical impedance spectroscopy (EIS) measurements for DSSCs fabricated with two identical electrodes in the triiodide/iodide (I<sub>3</sub><sup>-</sup>/I<sup>-</sup>) redox couple in the electrolyte. The inset represents equivalent circuit of DSSCs for fitting Nyquist plots. Reprinted with permission from ref. 281, J. Guo, S. Liang, Y. Shi, C. Hao, X. Wang and T. Ma, transition metal selenides as efficient counter-electrode materials for dye-sensitized solar cells. *Phys. Chem. Chem. Phys.*, 2015, 17, 28985–28992. Copyright© Royal Society of Chemistry/Owner Societies.



Pt-based CEs for DSSCs. The DSSCs with NbSe<sub>2</sub> nanoparticles and nanorods based CEs show PCE values of 6.27% and 5.05%, respectively, due to low FF arising from relatively smaller surface areas, as well as low exposure on the FTO glass substrates. DSSCs having NbSe<sub>2</sub> nanosheets based CE show the best IPCE spectral response, where the peak increases from 84% for a Pt CE to 89% for a NbSe<sub>2</sub> nanosheets based CE. On the other hand, lower IPCE peak values were observed for NbSe<sub>2</sub> nanoparticles and nanorods based CEs. The charge-transfer processes at the interface of TiO<sub>2</sub>/dye/electrolyte were analyzed by EIS. The NbSe<sub>2</sub> nanosheet based CEs for the DSSCs shows a middle-frequency semicircle, implying it had the highest electro-catalytic activity for the reduction of triiodide ions (I<sub>3</sub><sup>−</sup>), and efficient generation of electrons, therefore, occurring of larger electrons at the TiO<sub>2</sub>/dye/electrolyte interface. This study suggests that NbSe<sub>2</sub> nanosheets could be used as alternative CEs to conventional Pt CEs in DSSCs because of their large surface area.

### 4.3 TaSe<sub>2</sub> counter electrodes

Three transition-metal selenides (MoSe<sub>2</sub>, WSe<sub>2</sub>, and TaSe<sub>2</sub>) were prepared by Guo *et al.*<sup>281</sup> and compared as potential CEs for fabricating DSSC devices using a solvothermal method. These transition-metal selenides show high electrocatalytic activity for the reduction of triiodide (I<sub>3</sub><sup>−</sup>), except for MoSe<sub>2</sub>, due to low adsorption and charge-transfer. Fig. 23 shows SEM and TEM images of MoSe<sub>2</sub> (a and d), WSe<sub>2</sub> (b and e), and TaSe<sub>2</sub>; the Nyquist plots of EIS measurements recorded at −0.75 V bias of the DSSCs based on MoSe<sub>2</sub>, WSe<sub>2</sub>, and Pt CEs for the triiodide/iodide (I<sub>3</sub><sup>−</sup>/I<sup>−</sup>) redox couple in the electrolyte; and their *J*–*V* curves measured under simulated sunlight illumination. The MoSe<sub>2</sub> nanosheets had thickness of about 10 nm with lateral dimensions ranging 100–150 nm. WSe<sub>2</sub> consists of interlaced nanoplates with 15 nm average thickness and a width varying between 60 and 100 nm. The SEM image of TaSe<sub>2</sub> shows fluffy nanoparticles with a wide size distribution. The HRTEM images of MoSe<sub>2</sub>, WSe<sub>2</sub>, and TaSe<sub>2</sub> indicated spacings of 0.282 nm, 0.283 nm, and 0.291 nm, respectively. The WSe<sub>2</sub> shows a pore size distribution (PSD) curve at about 43 nm, MoSe<sub>2</sub> at 30 nm, and TaSe<sub>2</sub> at 10 nm. The mesoporous structure of WSe<sub>2</sub> facilitates the adsorption of triiodide (I<sub>3</sub><sup>−</sup>) and transport during the electrocatalytic activity. The BET surface areas were 95.6, 104.4 and 78.8 m<sup>2</sup> g<sup>−1</sup>, and the total pore volumes were 0.32 cm<sup>3</sup> g<sup>−1</sup>, 0.41 cm<sup>3</sup> g<sup>−1</sup> and 0.14 cm<sup>3</sup> g<sup>−1</sup>, for WSe<sub>2</sub>, MoSe<sub>2</sub>, TaSe<sub>2</sub>, respectively. The significant difference in BET surface area and the pore size distribution led to different adsorption properties and electrocatalytic activity of the DSSCs. The *R*<sub>CT</sub> of the transition-metal selenides at the electrolyte/electrode interface indicates the level of electrocatalytic activity. The *R*<sub>CT</sub> value of 0.78 Ω cm<sup>2</sup> for the WSe<sub>2</sub> CE is smaller compared with a Pt CE (1.32 Ω cm<sup>2</sup>) and a TaSe<sub>2</sub> (1.89 Ω cm<sup>2</sup>) CE, while the *R*<sub>CT</sub> value of the MoSe<sub>2</sub> (2.43 Ω cm<sup>2</sup>) CE was larger than that of the Pt CE. Therefore, WSe<sub>2</sub> shows better electrocatalytic activity for triiodide (I<sub>3</sub><sup>−</sup>) reduction. The ionic *Z*<sub>N</sub> value of WSe<sub>2</sub> is 1.15 Ω cm<sup>2</sup>, lower than that of the MoSe<sub>2</sub>, and TaSe<sub>2</sub> CEs, and comparable to the Pt CE, which demonstrates a larger diffusion coefficient for

triiodide (I<sub>3</sub><sup>−</sup>) within the CEs. The conductivities measured by linear sweep voltammetry decrease in the relative order TaSe<sub>2</sub> > MoSe<sub>2</sub> > WSe<sub>2</sub>. The DSSCs based on TaSe<sub>2</sub> and WSe<sub>2</sub> CEs showed larger *J*<sub>sc</sub> than that of MoSe<sub>2</sub> CE. WSe<sub>2</sub> has larger pores and high electrocatalytic activity suitable for fast regeneration and transfer of triiodide (I<sub>3</sub><sup>−</sup>). PCE values of 7.32% for TaSe<sub>2</sub> and 7.48% for WSe<sub>2</sub> were measured, which are comparable to a sputtered Pt CE (*η* = 7.91%). The lower PCE value of 6.70% for MoSe<sub>2</sub> arises from a lower *V*<sub>oc</sub> and *J*<sub>sc</sub> for the DSSC.

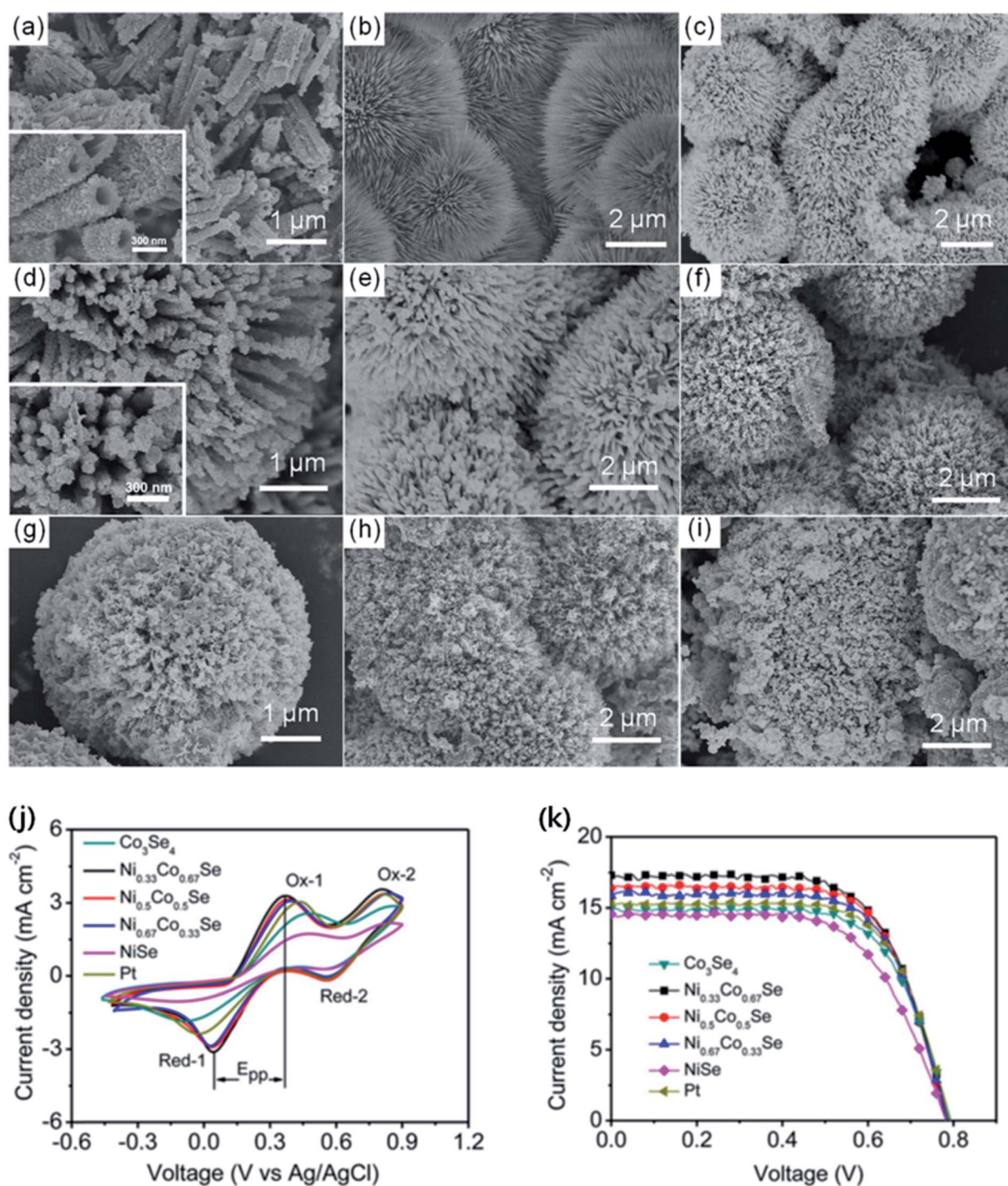
### 4.4 NiSe<sub>2</sub> counter electrodes

Nickel diselenide (NiSe<sub>2</sub>) has been studied as a CE of DSSCs for the reduction of I<sub>3</sub><sup>−</sup>, which yielded higher PCE of 8.69% than that of a conventional Pt CE (8.04%) under the same experimental conditions.<sup>282</sup> Zhang *et al.*<sup>283</sup> developed two types of NiSe<sub>2</sub> CEs on RGO; namely, microsphere NiSe<sub>2</sub>/RGO, and octahedron NiSe<sub>2</sub>/RGO through a hydrothermal process. The microsphere NiSe<sub>2</sub>/RGO CE exhibited higher electrocatalytic performance than a Pt CE for the reduction of triiodide (I<sub>3</sub><sup>−</sup>) because of better carrier transfer induced by graphene nanosheets.

CEs of ternary Ni–Co compounds having different morphological structures such as nanoparticles, nanotubes, nanowires, nanoflakes, flower-like, and urchin-like have been studied for DSSCs.<sup>284,285</sup> For example, the CE made of flower-like NiCo<sub>2</sub>S<sub>4</sub>/NiS microspheres<sup>286</sup> exhibited a PCE of 8.8%, much higher than a standard Pt CE (*η* = 8.1%). A similar concept was employed by Qian *et al.*<sup>287</sup> for developing a very interesting class of CEs for DSSCs from nickel cobalt (Ni–Co) selenides having different morphological structures, due to the tuning of the Ni/Co molar ratios. The morphological structure and electrocatalytic performance of ternary Ni–Co selenides was optimized by using different Ni/Co molar ratios. Fig. 24 shows the SEM images of Co<sub>3</sub>Se<sub>4</sub>, Ni<sub>0.33</sub>Co<sub>0.67</sub>Se precursor, Ni<sub>0.33</sub>Co<sub>0.67</sub>Se, Ni<sub>0.5</sub>Co<sub>0.5</sub>Se, Ni<sub>0.67</sub>Co<sub>0.33</sub>Se, and NiSe, and also shows CV and *J*–*V* curves of their DSSCs. The different morphological structures were obtained by tuning the Ni/Co molar ratio, Ni<sub>x</sub>Co<sub>1−x</sub>Se, where, *x* was 0, 0.33, 0.5, 0.67, and 1.0. The 3D dandelion-like precursor of Ni<sub>0.33</sub>Co<sub>0.67</sub>Se assembled into nanotubes having about 100 nm diameter, Ni<sub>0.5</sub>Co<sub>0.5</sub>Se into a floccus-like microsphere structure with a diameter of 4 microns, Ni<sub>0.67</sub>Co<sub>0.33</sub>Se microspheres compiled into nanosheets, and Co<sub>3</sub>Se<sub>4</sub> built up rough-surface nanotubes. The specific surface areas determined from the BET method were 5.0, 10.1, 26.1, 28.9, and 35.6 m<sup>2</sup> g<sup>−1</sup>, for NiSe, Co<sub>3</sub>Se<sub>4</sub>, Ni<sub>0.5</sub>Co<sub>0.5</sub>Se, Ni<sub>0.67</sub>Co<sub>0.33</sub>Se and Ni<sub>0.33</sub>Co<sub>0.67</sub>Se, respectively. Among all metal selenides, Ni<sub>0.33</sub>Co<sub>0.67</sub>Se has the highest specific surface area, which is favorable for providing more active sites for catalysis and increasing the contact area between its CE and the electrolyte, which results in better electrochemical and photovoltaic properties of its DSSCs. The *R*<sub>CT</sub> values of CEs follows the relative order of NiSe > Co<sub>3</sub>Se<sub>4</sub> > Pt > Ni<sub>0.67</sub>Co<sub>0.33</sub>Se > Ni<sub>0.5</sub>Co<sub>0.5</sub>Se > Ni<sub>0.33</sub>Co<sub>0.67</sub>Se, which implies that the electrocatalytic activity increases in a reverse order. Thus, NiSe was of the lowest activity and Ni<sub>0.33</sub>Co<sub>0.67</sub>Se was of the highest catalytic activity for the reduction of triiodide (I<sub>3</sub><sup>−</sup>). Therefore, higher contents of Ni in the Ni–Co selenides CEs are







**Fig. 24** SEM images of (a)  $\text{Co}_3\text{Se}_4$ , (b)  $\text{Ni}_{0.33}\text{Co}_{0.67}\text{Se}$  precursor, (c–e)  $\text{Ni}_{0.33}\text{Co}_{0.67}\text{Se}$ , (f and g)  $\text{Ni}_{0.5}\text{Co}_{0.5}\text{Se}$ , (h)  $\text{Ni}_{0.67}\text{Co}_{0.33}\text{Se}$ , and (i)  $\text{NiSe}$ . (j) CVs of DSSCs with  $\text{Co}_3\text{Se}_4$ ,  $\text{Ni}_{0.33}\text{Co}_{0.67}\text{Se}$ ,  $\text{Ni}_{0.5}\text{Co}_{0.5}\text{Se}$ ,  $\text{Ni}_{0.67}\text{Co}_{0.33}\text{Se}$ ,  $\text{NiSe}$ , and Pt-based CEs at a scan rate of  $50 \text{ mV s}^{-1}$ . (k) Photocurrent density–voltage ( $J-V$ ) curves of DSSCs with  $\text{Co}_3\text{Se}_4$ ,  $\text{Ni}_{0.33}\text{Co}_{0.67}\text{Se}$ ,  $\text{Ni}_{0.5}\text{Co}_{0.5}\text{Se}$ ,  $\text{Ni}_{0.67}\text{Co}_{0.33}\text{Se}$ ,  $\text{NiSe}$ , and Pt CEs under AM 1.5G illumination. Reprinted with permission from ref. 287, X. Qian, H. Li, L. Shao, X. Jiang and L. Hou, morphology-tuned synthesis of nickel cobalt selenides as highly efficient Pt-free counter electrode catalysts for dye-sensitized solar cells. *ACS Appl. Mater. Interfaces*, 2016, **8**, 29486–29495. Copyright© American Chemical Society.

not favorable for electrocatalytic activity. The values of cathodic peak current density (red-1) and the  $E_{pp}$  can also help understand the electrocatalytic activities of these CEs. The authors noted the following relative order of cathodic peak current

density:  $\text{NiSe}$  ( $1.044 \text{ mA cm}^{-2}$ ) <  $\text{Co}_3\text{Se}_4$  ( $1.849 \text{ mA cm}^{-2}$ ) < Pt ( $2.373 \text{ mA cm}^{-2}$ ) <  $\text{Ni}_{0.67}\text{Co}_{0.33}\text{Se}$  ( $2.878 \text{ mA cm}^{-2}$ ) <  $\text{Ni}_{0.5}\text{Co}_{0.5}\text{Se}$  ( $2.917 \text{ mA cm}^{-2}$ ) <  $\text{Ni}_{0.33}\text{Co}_{0.67}\text{Se}$  ( $3.120 \text{ mA cm}^{-2}$ ). They also noted  $E_{pp}$  values of  $\text{NiSe}$  (602 mV) >  $\text{Co}_3\text{Se}_4$  (565 mV) > Pt (460



mV) > Ni<sub>0.67</sub>Co<sub>0.33</sub>Se (365 mV) > Ni<sub>0.5</sub>Co<sub>0.5</sub>Se (349 mV) > Ni<sub>0.33</sub>Co<sub>0.67</sub>Se (329 mV), which were in an agreement with EIS measurements of the CEs. The 3D dandelion-like Ni<sub>0.33</sub>S<sub>0.67</sub>Se microspheres based CEs exhibited the highest PCE of 9.01%, exceeding that of the Pt CE ( $\eta$  = 8.30%). The DSSC with a Co<sub>3</sub>Se<sub>4</sub> CE showed a PCE of 7.95%, higher than that of NiSe CE ( $\eta$  = 7.23%). These results support the notion that the ternary Ni-Co selenides possess higher electrocatalytic activities and photovoltaic properties than those of binary selenides NiSe and Co<sub>3</sub>Se<sub>4</sub> as well as Pt CEs for the triiodide (I<sub>3</sub><sup>−</sup>) reduction, due to their unique morphology and chemical composition.

#### 4.5 FeSe<sub>2</sub> counter electrodes

Iron diselenide (FeSe<sub>2</sub>) can be processed into nanosheets, nanocubes, flower-like structures, and nanorods, rod clusters, and microspheres,<sup>288–294</sup> and has applications in catalysis,<sup>295</sup> batteries,<sup>296,297</sup> and photovoltaic devices.<sup>298</sup> The first-row (3d) transition metal dichalcogenides (MX<sub>2</sub>) with pyrite structure (where, M = Fe, Co, Ni, and X = S, Se) also exhibit electronic, optoelectronic, and magnetic properties comparable to other TMDs.<sup>299–302</sup> Huang *et al.*<sup>302</sup> used 2D FeSe<sub>2</sub> nanosheets with 7 nm average thickness as a CE for a DSSC. Fig. 25 shows the SEM and TEM images of the synthesized FeSe<sub>2</sub> nanosheets. The thickness of FeSe<sub>2</sub> nanosheets was found to be in the 4–7 nm range, as evaluated by TEM images. High-resolution TEM (HRTEM) indicated the crystalline nature of the nanosheets, having 0.168 nm interplanar spacing. The FeSe<sub>2</sub> nanosheets had specific surface area of 35.02 m<sup>2</sup> g<sup>−1</sup> as calculated by the BET analysis. The FeSe<sub>2</sub> nanosheets exhibit a low charge-transfer resistance ( $R_{CT}$ ) and a high electrocatalytic activity for triiodide (I<sub>3</sub><sup>−</sup>) reduction in DSSCs. The FeSe<sub>2</sub> nanosheets CE based DSSC showed a PCE of 7.53%, comparable to a Pt CE, while the PCE of FeSe<sub>2</sub> microparticles CE based DSSC was slightly lower ( $\eta$

= 6.88%). The large surface area of the FeSe<sub>2</sub> nanosheets contributed to a higher PCE by providing more active sites for electrocatalytic activity, as well as a larger electrode/electrolyte interface that of the FeSe<sub>2</sub> microparticles. The electrochemical stability of the CEs of FeSe<sub>2</sub> nanosheets and Pt were investigated with sequential CV scanning. The current densities of the FeSe<sub>2</sub> CE showed no change after 1000 cycles, confirming corrosion resistance to the electrolyte. The PCEs of FeSe<sub>2</sub> nanosheets under nitrogen protection (N-FeSe<sub>2</sub>) and exposure to air for one week (O-FeSe<sub>2</sub>) were also studied. The  $R_{CT}$  of the N-FeSe<sub>2</sub> CE (0.53  $\Omega$  cm<sup>2</sup>) was much lower than the O-FeSe<sub>2</sub> CE (10.13  $\Omega$  cm<sup>2</sup>) and a Pt CE (1.68  $\Omega$  cm<sup>2</sup>), indicating poorer electrocatalytic activity of the O-FeSe<sub>2</sub> CE compared to the N-FeSe<sub>2</sub> and Pt CEs. The Tafel polarization curves decreased in the order N-FeSe<sub>2</sub> > Pt > O-FeSe<sub>2</sub>, having the same order as of exchange current density, CV and EIS measurements. The O-FeSe<sub>2</sub> nanosheets CE based DSSC has a PCE of 6.15%, much lower than that of the N-FeSe<sub>2</sub> ( $\eta$  = 7.53%) CE and Pt CE ( $\eta$  = 7.47%) under similar conditions.

3D hierarchical FeSe<sub>2</sub> microspheres using a hot-injection method were prepared and studied by Huang *et al.*<sup>303</sup> The morphologies of the FeSe<sub>2</sub> nanomaterials was controlled by the use of alkyl thiols; 1-dodecanethiol (1-DDT) or *tert*-dodecanethiol (*t*-DDT) and their contents were used in synthesis, which varied from irregular FeSe<sub>2</sub> micro/nanoparticles to 3D hierarchical FeSe<sub>2</sub> microspheres and consisted of ultrathin FeSe<sub>2</sub> nanosheets or urchin-like microspheres made of crystalline FeSe<sub>2</sub> nanorods having an average diameter of 650 nm. The FeSe<sub>2</sub> nanomaterials were used as CEs for DSSCs. 3D hierarchical FeSe<sub>2</sub> microspheres made of ultrathin FeSe<sub>2</sub> nanosheets showed the lowest  $R_{CT}$  of 0.49  $\Omega$  cm<sup>2</sup> at the electrolyte/electrode interface, a lower  $Z_N$  value of 0.39  $\Omega$  cm<sup>2</sup>, and faster reaction kinetics for the reduction of I<sub>3</sub><sup>−</sup> to I<sup>−</sup> than that of a Pt CE ( $R_{CT}$  of 1.15  $\Omega$  cm<sup>2</sup> and  $Z_N$  value of 0.91  $\Omega$  cm<sup>2</sup>).  $R_{CT}$  values followed the relative order of FeSe<sub>2</sub> microparticles < FeSe<sub>2</sub> nanorods < Pt < FeSe<sub>2</sub> nanosheets, as supported by EIS measurements. A DSSC with a FeSe<sub>2</sub> nanosheets CE exhibited a PCE of 8.39%, slightly better than that of a Pt CE (8.20%) under simulated solar illumination of 100 mW cm<sup>−2</sup> (AM 1.5). FeSe<sub>2</sub> nanorods showed a PCE value of 8.03%, higher than that of FeSe<sub>2</sub> microparticles (7.68%). The PCE value of DSSCs is morphology dependent, where the FeSe<sub>2</sub> nanosheets CE has a high electrocatalytic activity and a larger specific surface area (30.03 m<sup>2</sup> g<sup>−1</sup>) than that of FeSe<sub>2</sub> nanorods (19.82 m<sup>2</sup> g<sup>−1</sup>). The FeSe<sub>2</sub> nanosheets CE based DSSC retained 99.5% of its initial photocurrent density, compared to 98.3% retained by the Pt CE, after simulated solar illumination of 100 mW cm<sup>−2</sup> for 1 hour, and this indicates better stability of the FeSe<sub>2</sub> nanosheets CE than that of standard Pt CE. Also, the 3D flower-like and sphere-shaped FeSe<sub>2</sub> films were used as CEs for DSSCs.<sup>304</sup> The 3D flower-like FeSe<sub>2</sub>-based CE exhibited a comparable PCE to a Pt CE ( $\eta$  = 8.00% *versus* 7.87%).

#### 4.6 CoSe<sub>2</sub> counter electrodes

Cobalt diselenide (CoSe<sub>2</sub>) has been extensively studied as a catalyst for oxygen reduction reactions.<sup>305–308</sup> The CoSe<sub>2</sub>

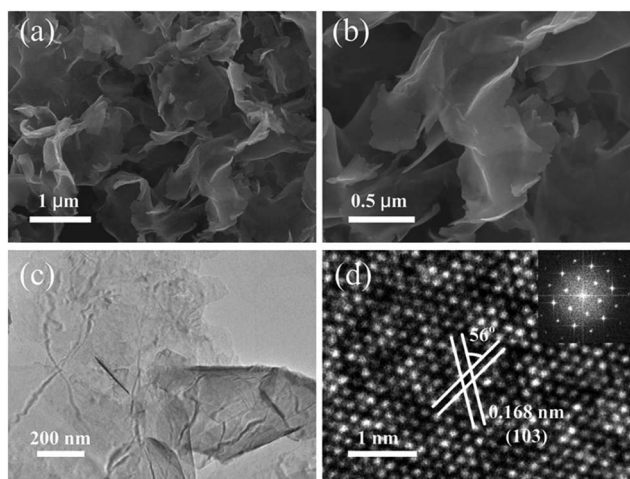


Fig. 25 (a, b) SEM images and (c) TEM image of the as-synthesized FeSe<sub>2</sub> nanosheets, and (d) HRTEM image of a small portion of FeSe<sub>2</sub> nanosheet (inset shows SAED pattern of the FeSe<sub>2</sub> nanosheets). Reprinted with permission from ref. 302, S. Huang, Q. He, W. Chen, Q. Qiao, J. Zai and X. Qian, ultrathin FeSe<sub>2</sub> nanosheets: controlled synthesis and application as a heterogeneous catalyst in dye-sensitized solar cells. *Chem.–Eur. J.*, 2015, **21**, 4085–4091. Copyright© Wiley-VCH.



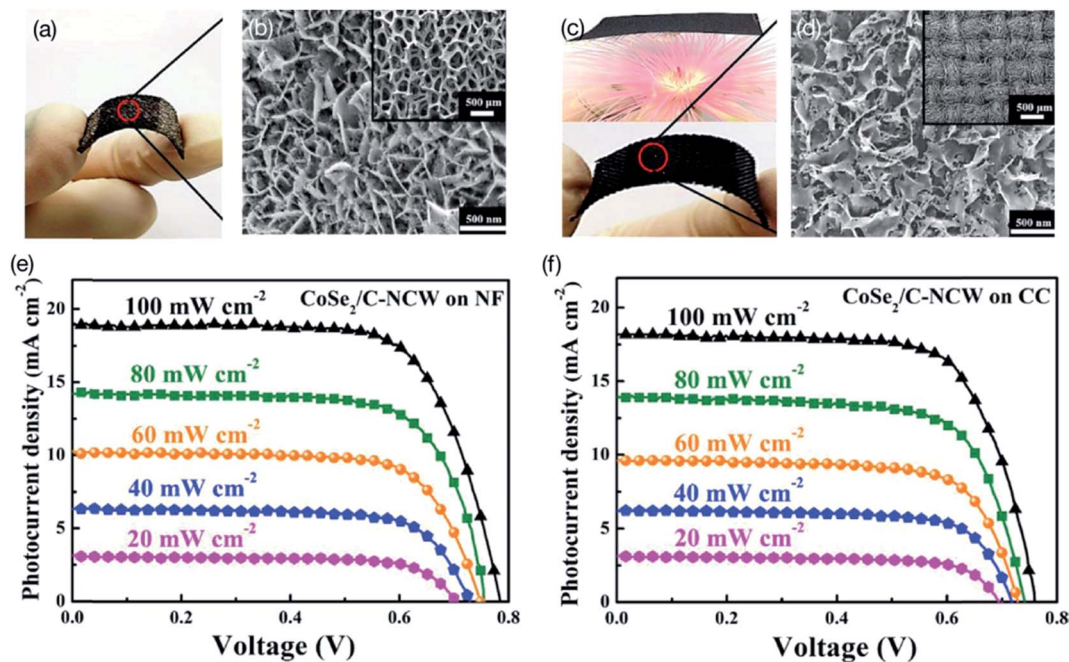


Fig. 26 (a) Photograph of the nickel foam (NF) and (b) SEM image of  $\text{CoSe}_2/\text{C-NCW}$  film on the nickel foam (NF). (c) Photograph of the carbon cloth (CC) and thin CC substrate on a soft flower having needle-like petals and (d) SEM image of  $\text{CoSe}_2/\text{C-NCW}$  film on carbon cloth (CC). Inset shows field-emission scanning electron microscopy (FE-SEM) images in a magnified version. (e) Photocurrent–voltage ( $J$ – $V$ ) curves of the DSSCs with  $\text{CoSe}_2/\text{C-NCW}$  on flexible nickel foam (NF) CE, measured at light intensities varying from  $20 \text{ mW cm}^{-2}$  (0.2 Sun) to  $100 \text{ mW cm}^{-2}$  (1 Sun). (f) Photocurrent–voltage ( $J$ – $V$ ) curves of the DSSCs with  $\text{CoSe}_2/\text{C-NCW}$  on flexible carbon cloth (CC) CE, under similar light intensities. Reprinted with permission from ref. 310, I. T. Chiu, C. T. Li, C. P. Lee, P. Y. Chen, Y. H. Tseng, R. Vittal and K. C. Ho, nanoclimbing-wall-like  $\text{CoSe}_2$ /carbon composite film for the counter electrode of a highly efficient dye-sensitized solar cell: a study on the morphology control. *Nano Energy*, 2016, 22, 594–606. Copyright© Elsevier.

nanorods synthesized by a hydrothermal method was studied as CEs for DSSCs.<sup>309</sup> FESEM revealed a  $\text{CoSe}_2$  nanorod morphology of the  $\text{CoSe}_2$ , which supports carrier transport from the surface of the nanorods to the redox electrolyte. The  $\text{CoSe}_2$  CE also exhibited larger current density compared with a Pt CE, as measured by CV. EIS shows an  $R_s$  of  $8.034 \Omega \text{ cm}^2$  and a low  $R_{CT}$  of  $0.097 \Omega \text{ cm}^2$  for the  $\text{CoSe}_2$  CE. The DSSC with a  $\text{CoSe}_2$  CE showed a PCE value of 8.38%, higher than the DSSC based on a Pt CE ( $\eta = 7.83\%$ ), under simulated sunlight illumination of  $100 \text{ mW cm}^{-2}$  (AM 1.5G).

A comprehensive and detailed study was conducted by Chiu *et al.*<sup>310</sup> on composite films of  $\text{CoSe}_2$ /carbon ( $\text{CoSe}_2/\text{C}$ ) deposited on FTO substrates having three different morphologies, developed using electro-deposition, followed by an annealing process at  $500^\circ\text{C}$  for 30 minutes in vacuum. In the first stage, three types of  $\text{CoSe}_2$ /carbon films containing nanowalls were deposited with an electro-deposition process employing different pH baths, while in the second stage, the morphology of the films was transformed after the annealing. The N719 dye-adsorbed  $\text{TiO}_2$  film was used as a photoanode for DSSCs.  $\text{CoSe}_2/\text{C}$  films had three different morphologies, including nanograin (NG), nanorock (NR), and nanoclimbing-wall (NCW), which were used as CEs for DSSCs. The electrocatalytic activity of these three CEs was analyzed by CV, RDE, Tafel polarization curves, and EIS, which showed a relative order of  $\text{CoSe}_2/\text{C-NCW} > \text{CoSe}_2/\text{C-NG} > \text{Pt} > \text{CoSe}_2/\text{C-NR}$  as CEs in the DSSCs, a similar order as was

observed for the  $R_{CT}$  values obtained by EIS and Tafel measurements. The  $\text{CoSe}_2/\text{C-NCW}$  showed higher electrical conductivity and a large effective surface area and, therefore, the best electrocatalytic ability for triiodide ( $\text{I}_3^-$ ) reduction. The DSSCs with  $\text{CoSe}_2/\text{C-NG}$ ,  $\text{CoSe}_2/\text{C-NCR}$ ,  $\text{CoSe}_2/\text{C-NCW}$ , and Pt CEs exhibited IPCE values between 80–95% in the 400 to 600 nm wavelength region, where the highest IPCE value of 95% was observed for the  $\text{CoSe}_2/\text{C-NCW}$  CE. The DSSC having a  $\text{CoSe}_2/\text{C-NCW}$  CE showed the highest PCE value of 8.92%, even higher than compared with the Pt CE (8.25%). The  $\text{CoSe}_2/\text{C-NCW}$  CEs were electro-deposited onto low-cost, flexible, and highly porous substrates, such as carbon cloth (CC, sheet resistance =  $0.63 \Omega \text{ sq}^{-1}$ ) and nickel foam (NF, porosity = 95%, sheet resistance =  $0.45 \Omega \text{ sq}^{-1}$ ). Fig. 26 shows photographs of the flexible nickel foam (NF) and carbon cloth (CC), SEM images of  $\text{CoSe}_2/\text{C-NCW}$  film on the flexible NF and CC substrates, and  $J$ – $V$  curves of the DSSCs, with  $\text{CoSe}_2/\text{C-NCW}$  on NF and CC CEs measured at different light intensities (20–100  $\text{mW cm}^{-2}$ ). The  $\text{CoSe}_2/\text{carbon-NCW}$  CEs shell covered all the minute parts of the carbon cloth and nickel foam core shell structures. The DSSC containing the CE with  $\text{CoSe}_2/\text{C-NCW}$  deposited on nickel foam exhibited the highest PCE of 10.46% at  $100 \text{ mW cm}^{-2}$  (1 Sun) and 7.90% at  $20 \text{ mW cm}^{-2}$  (0.2 Sun). The DSSC with the CE of  $\text{CoSe}_2/\text{C-NCW}$  deposited on low-weight carbon cloth showed a PCE of 9.87% at 1 Sun and 7.83% at 0.2 Sun. The low cost and flexible  $\text{CoSe}_2/\text{C-NCW}$  CEs seem to be promising materials to



**Table 4** Photovoltaic parameters of MoSe<sub>2</sub>, WSe<sub>2</sub>, TaSe<sub>2</sub>, NbSe<sub>2</sub>, FeSe<sub>2</sub>, CoSe<sub>2</sub> and Bi<sub>2</sub>Se<sub>3</sub> based CE for DSSCs. FTO glass is the common substrate used in assembling the DSSCs with different CE materials. The measurements were conducted at a simulated solar light intensity of 100 mW cm<sup>-2</sup> (AM 1.5G) unless specified. The photovoltaic parameters short-circuit photocurrent density ( $J_{sc}$ ), open-circuit voltage ( $V_{oc}$ ), fill factor (FF), and power conversion efficiency ( $\eta$ ), series resistance ( $R_s$ ), charge-transfer resistance ( $R_{CT}$ ), electrolyte and dye used for DSSCs are summarized and compared with a standard Pt CE<sup>a</sup>

| Counter electrodes   | Redox couple                                | Dye  | $J_{sc}$ (mA cm <sup>-2</sup> ) | $V_{oc}$ (V) | FF (%) | PCE ( $\eta$ , %) | $R_s$ ( $\Omega$ cm <sup>2</sup> ) | $R_{CT}$ ( $\Omega$ cm <sup>2</sup> ) | Ref. |
|--|---|------|---------------------------------|--------------|--------|-------------------|------------------------------------|---------------------------------------|------|
| MoSe <sub>2</sub> /Mo ( <i>in situ</i> sulfurization)            | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.71                           | 0.746        | 72.2   | 9.00              | 1.74                               | 1.39                                  | 260  |
| MoSe <sub>2</sub> /Mo ( <i>in situ</i> sulfurization)            | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.95                           | 0.726        | 70.6   | 8.69              | 1.21                               | 5.25                                  | 260  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 17.19                           | 0.740        | 68.3   | 8.68              | 12.52                              | 0.22                                  | 260  |
| MoSe <sub>2</sub> /Mo ( <i>in situ</i> selenization)             | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.07                           | 0.805        | 67     | 8.13              | 2.64                               | 0.30                                  | 261  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.11                           | 0.794        | 63     | 8.06              | 15.98                              | 8.95                                  | 261  |
| NiSe <sub>2</sub>  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.3                            | 0.75         | 68     | 7.3               | 20.9                               | 45.0                                  | 262  |
| NiS <sub>2</sub>   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.7                            | 0.72         | 52     | 5.5               | 28.4                               | 50.4                                  | 262  |
| CoSe <sub>2</sub>  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.5                            | 0.72         | 68     | 6.6               | 14.8                               | 102.7                                 | 262  |
| MoSe <sub>2</sub>  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.0                            | 0.67         | 68     | 5.9               | 16.5                               | 229.8                                 | 262  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.0                            | 0.75         | 69     | 7.2               | 18.5                               | 34.2                                  | 262  |
| MoSe <sub>2</sub> (hollow spheres)                               | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N749 | 16.06                           | 0.704        | 38.67  | 4.46              | —                                  | 10.24                                 | 264  |
| MoSe <sub>2</sub> /graphene (12.5% N <sub>2</sub> -doped)        | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N749 | 19.73                           | 0.724        | 70.07  | 10.01             | 7.18                               | 3.04                                  | 264  |
| MoSe <sub>2</sub> /graphene                                      | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N749 | 17.12                           | 0.710        | 60.41  | 7.34              | —                                  | 8.49                                  | 264  |
| Graphene   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N749 | 16.67                           | 0.535        | 54.12  | 4.83              | —                                  | 16.27                                 | 264  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N749 | 19.93                           | 0.723        | 73.22  | 10.55             | 7.14                               | 2.81                                  | 264  |
| MoSe <sub>2</sub> /PEDOT:PSS                                     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.97                           | 0.70         | 67     | 7.58              | 18.08                              | 5.43                                  | 265  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.38                           | 0.74         | 65     | 7.81              | 20.19                              | 4.60                                  | 265  |
| MoSe <sub>2</sub> /PEDOT:PSS@Ti                                  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.41                           | 0.75         | 69     | 8.51              | —                                  | —                                     | 265  |
| Pt@Ti reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.31                           | 0.74         | 68     | 8.21              | —                                  | —                                     | 265  |
| Bare MoSe <sub>2</sub>   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.65                           | 0.66         | 28     | 2.29              | 20.50                              | 39.74                                 | 265  |
| Bare PEDOT:PSS   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 9.32                            | 0.67         | 46     | 2.90              | 17.36                              | 190.91                                | 265  |
| Co <sub>0.85</sub> Se  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.41                           | 0.763        | 62.7   | 6.42              | —                                  | —                                     | 266  |
| 3Co <sub>0.85</sub> Se/0.5MoSe <sub>2</sub> /0.5MoO <sub>3</sub> | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.43                           | 0.765        | 65.7   | 6.75              | —                                  | —                                     | 266  |
| 2Co <sub>0.85</sub> Se/MoSe <sub>2</sub> /MoO <sub>3</sub>       | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.80                           | 0.768        | 67.1   | 7.10              | —                                  | —                                     | 266  |
| Co <sub>0.85</sub> Se/1.5MoSe <sub>2</sub> /1.5MoO <sub>3</sub>  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.06                           | 0.760        | 64.4   | 6.39              | —                                  | —                                     | 266  |
| MoSe <sub>2</sub> /MoO <sub>3</sub>                              | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.95                           | 0.754        | 62.7   | 6.12              | —                                  | —                                     | 266  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.05                           | 0.759        | 60.9   | 6.03              | —                                  | —                                     | 266  |
| Co <sub>0.85</sub> Se  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.44                           | 0.66         | 68     | 6.03              | 55.83                              | 9.28                                  | 267  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.37                           | 0.67         | 67     | 6.45              | 30.64                              | 13.89                                 | 267  |
| Co <sub>0.85</sub> Se (front irradiation)                        | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.74                           | 0.742        | 66.8   | 8.30              | —                                  | 2.84                                  | 268  |
| Co <sub>0.85</sub> Se (rear irradiation)                         | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 9.92                            | 0.721        | 64.7   | 4.63              | —                                  | —                                     | 268  |
| Ni <sub>0.85</sub> Se (front irradiation)                        | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.67                           | 0.740        | 63.6   | 7.85              | —                                  | 2.96                                  | 268  |
| Ni <sub>0.85</sub> Se (rear irradiation)                         | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 9.26                            | 0.731        | 64.6   | 4.37              | —                                  | —                                     | 268  |
| Cu <sub>0.50</sub> Se (front irradiation)                        | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.55                           | 0.713        | 62.0   | 6.43              | —                                  | 5.44                                  | 268  |
| Cu <sub>0.50</sub> Se (rear irradiation)                         | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 10.01                           | 0.666        | 63.6   | 4.24              | —                                  | —                                     | 268  |
| FeSe (front irradiation)   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 17.10                           | 0.733        | 61.0   | 7.64              | —                                  | 4.90                                  | 268  |
| FeSe (rear irradiation)  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 10.49                           | 0.732        | 65.8   | 5.05              | —                                  | —                                     | 268  |
| Ru <sub>0.33</sub> Se (front irradiation)                        | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 18.93                           | 0.715        | 68.1   | 9.22              | —                                  | 2.77                                  | 268  |
| Ru <sub>0.33</sub> Se (rear irradiation)                         | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 11.89                           | 0.714        | 69.5   | 5.90              | —                                  | —                                     | 268  |
| Pt (front irradiation)   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.09                           | 0.712        | 66.3   | 6.18              | —                                  | 7.23                                  | 268  |
| Pt (rear irradiation)  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 9.48                            | 0.652        | 57.6   | 3.56              | —                                  | —                                     | 268  |
| NiCo <sub>2</sub> S <sub>4</sub> (hydrothermal method)           | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.38                           | 0.76         | 63.2   | 6.9               | —                                  | —                                     | 269  |
| NiCo <sub>2</sub> O <sub>4</sub> (hydrothermal method)           | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 8.2                             | 0.67         | 26.7   | 1.5               | —                                  | —                                     | 269  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.20                           | 0.8          | 63.4   | 7.7               | —                                  | —                                     | 269  |
| NbSe <sub>2</sub> (nanosheets)                                   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.04                           | 0.77         | 63     | 7.34              | 27.72                              | 2.59                                  | 279  |
| NbSe <sub>2</sub> (nanorods)                                     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.94                           | 0.76         | 64     | 6.78              | 19.38                              | 6.21                                  | 279  |
| NbSe <sub>2</sub> /C   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.58                           | 0.77         | 65     | 7.80              | 24.07                              | 3.52                                  | 279  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.88                           | 0.72         | 69     | 7.90              | 8.15                               | 2.35                                  | 279  |
| NbSe <sub>2</sub> (nanosheets)                                   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.85                           | 0.74         | 62     | 7.73              | —                                  | —                                     | 280  |
| NbSe <sub>2</sub> (nanorods)                                     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.85                           | 0.74         | 46     | 5.05              | —                                  | —                                     | 280  |
| NbSe <sub>2</sub> (microparticles)                               | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.93                           | 0.75         | 55     | 6.27              | —                                  | —                                     | 280  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.59                           | 0.72         | 62     | 7.01              | —                                  | —                                     | 280  |
| MoSe <sub>2</sub> (solvothermal reaction)                        | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.11                           | 0.73         | 65     | 6.70              | 10.32                              | 2.43                                  | 281  |
| WSe <sub>2</sub> (solvothermal reaction)                         | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.50                           | 0.73         | 66     | 7.48              | 10.70                              | 0.78                                  | 281  |
| TaSe <sub>2</sub> (solvothermal reaction)                        | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.81                           | 0.73         | 64     | 7.32              | 10.00                              | 1.89                                  | 281  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.84                           | 0.70         | 67     | 7.91              | 6.32                               | 1.32                                  | 281  |
| NiSe <sub>2</sub> (hydrothermal reaction)                        | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.94                           | 0.734        | 74.3   | 8.69              | 2.57                               | 0.81                                  | 282  |
| Pt reference   | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.26                           | 0.731        | 72.1   | 8.04              | 2.50                               | 0.97                                  | 282  |
| NiCo <sub>2</sub> S <sub>4</sub> /NiS (spin casting)             | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 17.7                            | 0.744        | 67     | 8.8               | —                                  | —                                     | 286  |





Table 4 (Contd.)

| Counter electrodes                                    | Redox couple                                | Dye  | $J_{sc}$ (mA cm <sup>-2</sup> ) | $V_{oc}$ (V) | FF (%) | PCE ( $\eta$ , %) | $R_s$ ( $\Omega$ cm <sup>2</sup> ) | $R_{CT}$ ( $\Omega$ cm <sup>2</sup> ) | Ref. |
|---|---|------|---------------------------------|--------------|--------|-------------------|------------------------------------|---------------------------------------|------|
| NiCo <sub>2</sub> S <sub>4</sub> (spin casting)       | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 17.4                            | 0.743        | 66     | 8.5               | —                                  | —                                     | 286  |
| Co <sub>9</sub> S <sub>8</sub> (spin casting)         | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.2                            | 0.741        | 64     | 7.7               | —                                  | —                                     | 286  |
| NiS (spin casting)                                    | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.9                            | 0.735        | 63     | 6.9               | —                                  | —                                     | 286  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.5                            | 0.736        | 67     | 8.1               | —                                  | —                                     | 286  |
| Ni <sub>0.33</sub> Co <sub>0.67</sub> Se              | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 17.29                           | 0.789        | 67     | 9.01              | 30.40                              | 1.11                                  | 287  |
| Ni <sub>0.5</sub> Co <sub>0.5</sub> Se                | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.42                           | 0.783        | 69     | 8.80              | 30.38                              | 1.50                                  | 287  |
| Ni <sub>0.67</sub> Co <sub>0.33</sub> Se              | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.89                           | 0.784        | 69     | 8.59              | 30.04                              | 1.96                                  | 287  |
| Co <sub>3</sub> Se <sub>4</sub>                       | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.96                           | 0.793        | 67     | 7.95              | 29.94                              | 7.66                                  | 287  |
| NiSe  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.54                           | 0.783        | 64     | 7.23              | 29.87                              | 13.88                                 | 287  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.33                           | 0.791        | 69     | 8.30              | 30.30                              | 2.88                                  | 287  |
| FeSe <sub>2</sub> (nanosheets, under N <sub>2</sub> ) | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 17.49                           | 0.718        | 60     | 7.53              | 8.07                               | 0.53                                  | 302  |
| FeSe <sub>2</sub> (nanosheets, air exposed)           | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.51                           | 0.708        | 56     | 6.15              | 10.13                              | 6.26                                  | 302  |
| FeSe <sub>2</sub> (microparticles)                    | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.32                           | 0.715        | 59     | 6.88              | 8.51                               | 4.10                                  | 302  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 17.77                           | 0.725        | 58     | 7.47              | 7.94                               | 1.68                                  | 302  |
| FeSe <sub>2</sub> microparticles (MPs)                | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.63                           | 0.745        | 66     | 7.68              | 9.03                               | 2.32                                  | 303  |
| FeSe <sub>2</sub> nanosheets (NSs)                    | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.14                           | 0.744        | 70     | 8.39              | 8.78                               | 0.49                                  | 303  |
| FeSe <sub>2</sub> nanorods (NRs)                      | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.79                           | 0.748        | 68     | 8.03              | 8.71                               | 1.62                                  | 303  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.87                           | 0.750        | 69     | 8.20              | 8.62                               | 1.15                                  | 303  |
| FeSe <sub>2</sub> (3D flower-like)                    | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.93                           | 0.744        | 72.1   | 8.00              | 16.82                              | 0.53                                  | 304  |
| FeSe <sub>2</sub> (sphere-shaped)                     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 14.60                           | 0.724        | 69.8   | 7.38              | 27.05                              | 0.96                                  | 304  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.13                           | 0.741        | 70.2   | 7.87              | 17.01                              | 0.78                                  | 304  |
| CoSe <sub>2</sub> (hydrothermal, 140 °C)              | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.65                           | 0.750        | 64.4   | 8.04              | 8.783                              | 0.132                                 | 309  |
| CoSe <sub>2</sub> (hydrothermal, 160 °C)              | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 17.04                           | 0.743        | 66.2   | 8.38              | 8.034                              | 0.097                                 | 309  |
| CoSe <sub>2</sub> (hydrothermal, 180 °C)              | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.44                           | 0.750        | 63.9   | 7.40              | 15.17                              | 0.932                                 | 309  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.88                           | 0.743        | 62.4   | 7.83              | 12.86                              | 1.923                                 | 309  |
| CoSe <sub>2</sub> /C-NG                               | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 17.51                           | 0.73         | 67     | 8.41              | 20.6                               | 0.85                                  | 310  |
| CoSe <sub>2</sub> /C-NR                               | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.98                           | 0.73         | 67     | 7.83              | 20.6                               | 1.16                                  | 310  |
| CoSe <sub>2</sub> /C-NCW                              | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 18.03                           | 0.73         | 67     | 8.92              | 20.6                               | 0.52                                  | 310  |
| CoSe <sub>2</sub> /C-NCW on nickel foam               | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 18.86                           | 0.78         | 71     | 10.46             | —                                  | —                                     | 310  |
| CoSe <sub>2</sub> /C-NCW on carbon cloth              | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 18.16                           | 0.76         | 71     | 9.87              | —                                  | —                                     | 310  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.43                           | 0.74         | 67     | 8.25              | 20.6                               | 1.04                                  | 310  |
| CoSe <sub>2</sub>                                     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.95                           | 0.773        | 65     | 6.47              | —                                  | 0.50                                  | 311  |
| CoSe <sub>2</sub> @RGO                                | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.24                           | 0.792        | 72     | 7.01              | —                                  | 0.20                                  | 311  |
| Reduced graphene oxide (RGO)                          | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 12.11                           | 0.761        | 40     | 3.66              | —                                  | 64.75                                 | 311  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 13.12                           | 0.765        | 67     | 6.77              | —                                  | 0.61                                  | 311  |
| Ni <sub>0.85</sub> Se                                 | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.63                           | 0.739        | 72     | 8.32              | 1.8                                | 1.8                                   | 312  |
| Co <sub>0.85</sub> Se                                 | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.98                           | 0.738        | 75     | 9.40              | 2.1                                | 0.6                                   | 312  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.03                           | 0.738        | 73     | 8.64              | 2.6                                | 1.1                                   | 312  |
| Bi <sub>2</sub> Se <sub>3</sub> nanoparticles         | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 7.02                            | 0.55         | 46     | 1.86              | —                                  | —                                     | 325  |
| Bi <sub>2</sub> Se <sub>3</sub> /graphene (40 mg)     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.42                           | 0.78         | 50     | 6.35              | —                                  | —                                     | 325  |
| Bi <sub>2</sub> Se <sub>3</sub> /graphene (60 mg)     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.36                           | 0.75         | 57     | 7.09              | —                                  | —                                     | 325  |
| Bi <sub>2</sub> Se <sub>3</sub> /graphene (80 mg)     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 16.01                           | 0.76         | 53     | 6.66              | —                                  | —                                     | 325  |
| Pt reference  | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 15.65                           | 0.68         | 59     | 6.47              | —                                  | —                                     | 325  |
| ZnO (photoanode)                                      | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 8.189                           | 0.656        | 55.2   | 2.96              | 16.6                               | 7.23                                  | 335  |
| Bi <sub>2</sub> Te <sub>3</sub> /ZnO (photoanode)     | I <sup>-</sup> /I <sub>3</sub> <sup>-</sup> | N719 | 11.767                          | 0.637        | 57.0   | 4.27              | 15.8                               | 3.75                                  | 335  |

<sup>a</sup> Nanograin (NG), nanorock (NR), nanoclimbing-wall (NCW), nickel foam (NF), carbon cloth (CC), rGO = reduced graphene oxide. In the case of  $R_s$  and  $R_{CT}$ : some of the authors used  $\Omega$  instead of  $\Omega$  cm<sup>2</sup> for the resistances without mentioning the size of the electrode.

replace expensive Pt CEs for DSSCs for indoor, outdoor or wearable applications.

CoSe<sub>2</sub> and RGO composites were also explored as CEs in DSSCs, which showed a PCE of 7.01% *versus* a Pt CE ( $\eta$  = 6.77%).<sup>311</sup> Co<sub>0.85</sub>Se and Ni<sub>0.85</sub>Se was deposited on FTO glass substrate by a low-temperature hydrothermal process and were used as CEs for DSSCs by Gong *et al.*<sup>312</sup> Co<sub>0.85</sub>Se has a graphene-like nanostructure and possesses a large surface area, while Ni<sub>0.85</sub>Se is composed of aggregated particles. The graphene-like Co<sub>0.85</sub>Se CE showed higher electrocatalytic activity than that of

the Pt CE for the reduction of triiodide (I<sub>3</sub><sup>-</sup>). DSSCs with Co<sub>0.85</sub>Se CEs showed a PCE of 9.40%, significantly higher than that of a Pt CE (8.64%), under simulated solar light of 100 mW cm<sup>-2</sup> (AM 1.5G). In the case of the Ni<sub>0.85</sub>Se CE, the PCE of 8.32% was slightly lower than a Pt CE. Both  $J_{sc}$  and PCE values showed a relative order of Ni<sub>0.85</sub>Se < Pt < Co<sub>0.85</sub>Se. The  $R_{CT}$  value was found to increase in the relative order Co<sub>0.85</sub>Se (0.6  $\Omega$  cm<sup>2</sup>) < Pt (1.1  $\Omega$  cm<sup>2</sup>) < Ni<sub>0.85</sub>Se (1.8  $\Omega$  cm<sup>2</sup>), suggesting an inverse order of electrocatalytic activity of these CEs in the DSSCs. Table 4 summarizes the photovoltaic parameters of MoSe<sub>2</sub>, WSe<sub>2</sub>,



TaSe<sub>2</sub>, NbSe<sub>2</sub>, FeSe<sub>2</sub>, CoSe<sub>2</sub> and Bi<sub>2</sub>Se<sub>3</sub> based CEs for DSSCs, and their comparison with a standard Pt CE.

#### 4.7 Bi<sub>2</sub>Se<sub>3</sub> counter electrodes

Bismuth selenide (Bi<sub>2</sub>Se<sub>3</sub>) and bismuth telluride (Bi<sub>2</sub>Te<sub>3</sub>) have been previously studied as topological insulators.<sup>313,314</sup> Bi<sub>2</sub>Se<sub>3</sub>, a semiconducting and thermoelectric material, can be processed into single layers, nanosheets, nanotubes, nanoribbons, and nanowires<sup>315–318</sup> and has applications in field-effect transistors,<sup>319</sup> sensors,<sup>320</sup> non-volatile memory devices,<sup>321</sup> photovoltaic devices,<sup>322</sup> and drug delivery and anti-cancer therapy.<sup>323,324</sup> Bi<sub>2</sub>Se<sub>3</sub>/RGO nanocomposites were prepared by a microwave-assisted hydrothermal method as a CE for a DSSC by Zhu *et al.*<sup>325</sup> Fig. 27 shows the TEM images of the graphene nanosheets, Bi<sub>2</sub>Se<sub>3</sub> nanospheres and Bi<sub>2</sub>Se<sub>3</sub>/graphene nanocomposites containing 60 mg graphene contents. The TEM images showed that 10–15 nm Bi<sub>2</sub>Se<sub>3</sub> nanoparticles were attached onto graphene nanosheets. SEM images showed that the graphene had a flake-like structure while the Bi<sub>2</sub>Se<sub>3</sub> nanoparticles were large size spheres. Furthermore, the surface of the graphene oxide was found to be very smooth in comparison with graphene nanosheets doped with Bi<sub>2</sub>Se<sub>3</sub> nanoparticles. The inclusion of Bi<sub>2</sub>Se<sub>3</sub> nanoparticles onto graphene nanosheets was controlled to achieve high electrocatalytic activity of the CE for the reduction of triiodide (I<sub>3</sub><sup>−</sup>). The DSSC with a Bi<sub>2</sub>Se<sub>3</sub>/graphene (60 mg) CE yielded a high PCE of 7.09%,

which is comparable to a Pt CE ( $\eta = 6.23\%$ ). The Bi<sub>2</sub>Se<sub>3</sub>/graphene nanocomposite CEs with 40 mg and 80 mg graphene content showed PCE values of 6.35% and 6.66% for the DSSCs, respectively, which was much higher than that of pure Bi<sub>2</sub>Se<sub>3</sub> CE ( $\eta = 1.86\%$ ), but still comparable to a Pt CE.

## 5. Bi<sub>2</sub>Te<sub>3</sub> based photoanodes

Bismuth telluride (Bi<sub>2</sub>Te<sub>3</sub>) has been studied for thermoelectric applications and can be processed into nanowires arrays,<sup>326–329</sup> nanotubes,<sup>330</sup> nanoplates,<sup>331</sup> nanosheets,<sup>332,333</sup> and thin films.<sup>334</sup> Dou *et al.*<sup>335</sup> developed hybrid photoanodes by dispersing Bi<sub>2</sub>Te<sub>3</sub> nanotubes into ZnO nanoparticles. The 0.5, 1.0, 1.5, 2.0, and 2.5 wt% of highly crystalline Bi<sub>2</sub>Te<sub>3</sub> nanotubes were mixed with ZnO nanoparticles to fabricate photoanodes for DSSCs. Pt films deposited on FTO glass was used as a CE. The electrolyte consisted of 0.05 M I<sub>2</sub>, 0.5 M LiI, and 0.1 M 4-*tert*-butylpyridine in acetonitrile-propylene carbonate (1 : 1) solution. In the Bi<sub>2</sub>Te<sub>3</sub>/ZnO hybrid, Bi<sub>2</sub>Te<sub>3</sub> nanotubes provided a conduction pathway which facilitated electron transfer. The  $J_{sc}$  value increased gradually with increasing Bi<sub>2</sub>Te<sub>3</sub> nanotubes content up to 1.5 wt% (11.767 mA cm<sup>−2</sup>) and then started decreasing as the Bi<sub>2</sub>Te<sub>3</sub> nanotubes content exceeded 2.0 wt% (9.957 mA cm<sup>−2</sup>), due to the low dye loading on the surface of ZnO nanoparticles. A similar trend was observed for the PCE values. The DSSCs with

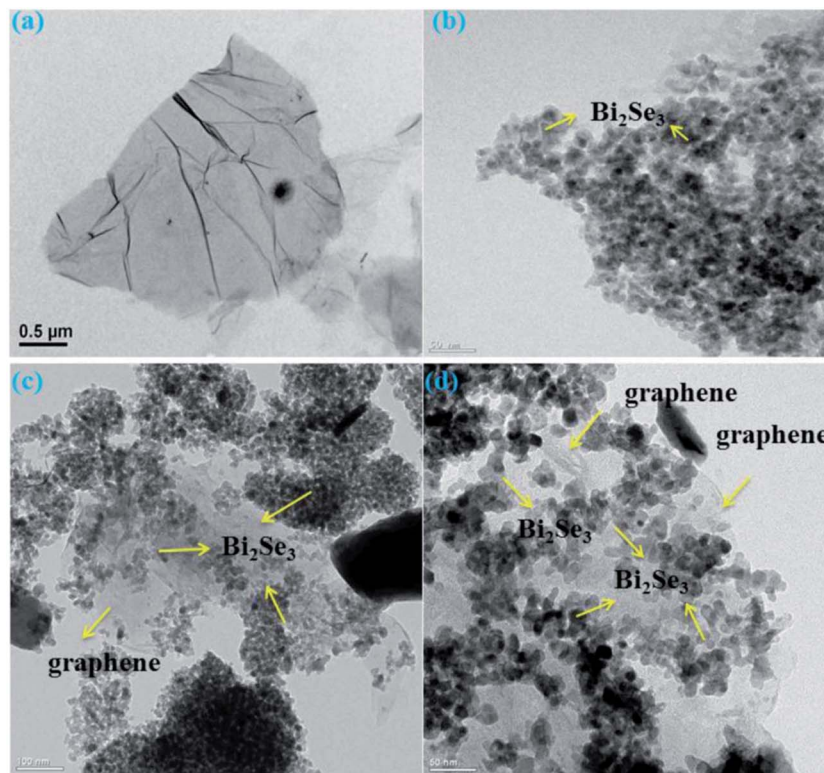


Fig. 27 TEM images of (a) graphene nanosheet, (b) Bi<sub>2</sub>Se<sub>3</sub> nanospheres (c) and (d) Bi<sub>2</sub>Se<sub>3</sub>/graphene nanocomposite (60 mg graphene). Reprinted with permission from ref. 325, L. Zhu, K. Y. Cho and W. C. Oh, microwave-assisted synthesis of Bi<sub>2</sub>Se<sub>3</sub>/reduced graphene oxide nanocomposite as efficient catalytic counter electrode for dye-sensitized solar cell, *Fullerenes, Nanotubes, Carbon Nanostruct.*, 2016, **24**, 622–629. Copyright© Taylor & Francis Group.



a  $\text{Bi}_2\text{Te}_3/\text{ZnO}$  composite photoanode containing 1.5 wt%  $\text{Bi}_2\text{Te}_3$  nanotubes in the ZnO photoanode showed a PCE of 4.27%, which is 44.3% higher compared with a pure ZnO photoanode. The PCE values were 2.96% for the bare ZnO photoanode, and 3.74, 3.96, 4.27, 3.41 and 3.01% for the 0.5, 1.0, 1.5, 2.0 and 2.5 wt%  $\text{Bi}_2\text{Te}_3$  nanotubes content photoanodes, respectively. This study indicated that loading of thermoelectric  $\text{Bi}_2\text{Te}_3$  in a ZnO photoanode improves the photovoltaic performance of DSSCs. Wan *et al.*<sup>336</sup> prepared hexagonal  $\text{Bi}_2\text{Te}_3$  nanosheets of 300–400 nm length by a hydrothermal method. The nanocomposites of the  $\text{Bi}_2\text{Te}_3$  nanosheets and ZnO nanoparticles were used as photoanodes for DSSCs, where the  $\text{Bi}_2\text{Te}_3$  nanosheet concentration was varied from 0 to 0.25 wt%. The DSSCs with 0.15 wt% of  $\text{Bi}_2\text{Te}_3$  nanosheets in the  $\text{Bi}_2\text{Te}_3$  nanosheet/ZnO nanoparticle composite photoanode showed a PCE of 4.10%, which was improved by 46.95% compared with the bare ZnO photoanode. The thermoelectric  $\text{Bi}_2\text{Te}_3$  nanosheets in the composite photoanode helped in enhancing the electron density and reducing the temperature of the DSSCs. The  $\text{Bi}_2\text{Te}_3$  nanosheet/ZnO nanoparticles composite photoanode significantly improved the DSSC performance. A thermoelectric  $\text{Bi}_2\text{Te}_3/\text{TiO}_2$  composite based photoanode was also used for DSSCs, where  $\text{Bi}_2\text{Te}_3$  nanoplates help in converting heat into electricity and enhanced the rate of charge transfer.<sup>337</sup> This resulted in a 28% increase of the PCE of the DSSC. The  $\text{Bi}_2\text{Te}_3$  nanoplates have also been used for doping  $\text{TiO}_2$  photoanodes.<sup>338</sup> The effect of  $\text{Bi}_2\text{Te}_3$  nanoplates size was evaluated for DSSCs, where a decrease in the size of the  $\text{Bi}_2\text{Te}_3$  nanoplates led to and higher PCE. The performance of DSSCs with a  $\text{Bi}_2\text{Te}_3/\text{TiO}_2$  photoanode increased by 15.3% compared to the undoped  $\text{TiO}_2$  photoanode.

## 6. Long-term stability of TMDs based DSSCs

The long-term stability of DSSCs is one of the most important parameters for commercial applications. The stability of DSSC devices depends upon a number of factors and the components used in their fabrication. The decrease in power conversion

efficiency of a DSSC can be associated with the stability of different electrolyte components, photosensitizing dyes, aging of the  $\text{TiO}_2$  photoanode, degradation of the CE (cathode), corrosion of components by electrolytes, sealant, leakage, exposure to solar irradiation, high humidity, and elevated temperature.<sup>339–349</sup>

A few research reports have been published on the long-term stability of TMDs based DSSCs which are briefly discussed here. Infant *et al.*<sup>131</sup> studied the stability of CVD-deposited vertically oriented  $\text{MoS}_2$  thin films on an FTO surface used as a CE in a DSSC. The electrochemical stability of a  $\text{MoS}_2$  CE based DSSC was analyzed by CV measurements, where electrodes were repeatedly subjected to 20 cycles at a  $10 \text{ mV s}^{-1}$  scan rate for the  $\text{I}^-/\text{I}_3^-$  redox couple in the electrolyte. The  $\text{MoS}_2$  based CE showed no significant change up to 20th consecutive cycle, whereas the Pt CE exhibited some changes between the cycles (Fig. 28). This confirms that CVD deposited  $\text{MoS}_2$  strongly adhered onto the surface of the FTO substrate. The stability of  $\text{MoS}_2$  CEs was measured under ambient conditions by storing them for 15 days, where the PCE remained at 94% of its initial efficiency value, which was much higher than that of the Pt CE.

For preparing Pt-free dye-sensitized solar cells, Liu *et al.*<sup>350</sup> fabricated DSSCs using  $\text{MoS}_2$  and RGO composite as a CE for the reduction of triiodide ( $\text{I}_3^-$ ) to iodide ( $\text{I}^-$ ). AFM, XPS, and XRD confirmed the deposition of  $\text{MoS}_2$  nanoparticles onto the RGO surface. The CV measurement showed a higher current density for the  $\text{MoS}_2/\text{RGO}$  nanocomposite based CE compared to RGO,  $\text{MoS}_2$ , and Pt-sputtered CEs due to an increased surface area. The  $\text{MoS}_2/\text{RGO}$  CE also exhibited a low  $R_{\text{CT}}$  of  $0.57 \Omega \text{ cm}^2$  for the reduction of triiodide ( $\text{I}_3^-$ ) to iodide ( $\text{I}^-$ ). The  $\text{MoS}_2/\text{RGO}$  nanocomposite CE based DSSC showed a PCE of 6.04%, comparable to a PCE of 6.38% for the conventional Pt CE.  $\text{MoS}_2/\text{RGO}$  nanocomposites based CEs also have better electrochemical stability, as no degradation in current densities was observed up to 100 repeated CV tests. The stability test conducted on a DSSC having  $\text{MoS}_2/\text{RGO}$  nanocomposites as CEs showed over 10% degradation in PCE over a period of 20 days, as depicted in (Fig. 29a). Therefore,  $\text{MoS}_2/\text{RGO}$  nanocomposites based CEs were found to be stable both for environmental and consecutive electrochemical tests. Li *et al.*<sup>200</sup> prepared a composite film of  $\text{TiS}_2/\text{PEDOT:PSS}$  on an ITO substrate as a CE

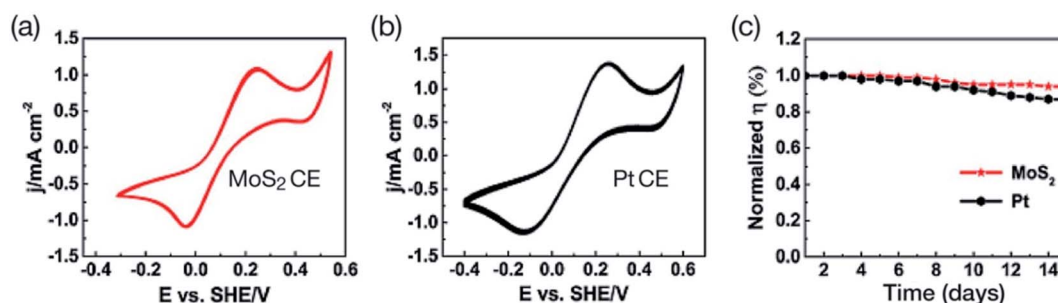


Fig. 28 Electrochemical properties of thin films of  $\text{MoS}_2$  prepared at  $600^\circ\text{C}$  for 15 minutes. 20 consecutive cyclic voltammogram (CV) curve of  $\text{MoS}_2$  (a) and Pt (b) counter electrodes recorded at the scan rate of  $10 \text{ mV s}^{-1}$  and (c) PCE of  $\text{MoS}_2$  and Pt CEs based DSSCs measured for 15 days under ambient conditions. Reprinted with permission from ref. 131, R. S. Infant, X. Xu, W. Yang, F. Yang, L. Hou and Y. Li, highly active and reflective  $\text{MoS}_2$  counter electrode for enhancement of photovoltaic efficiency of dye sensitized solar cells. *Electrochim. Acta*, 2016, **212**, 614–620. Copyright© Elsevier.





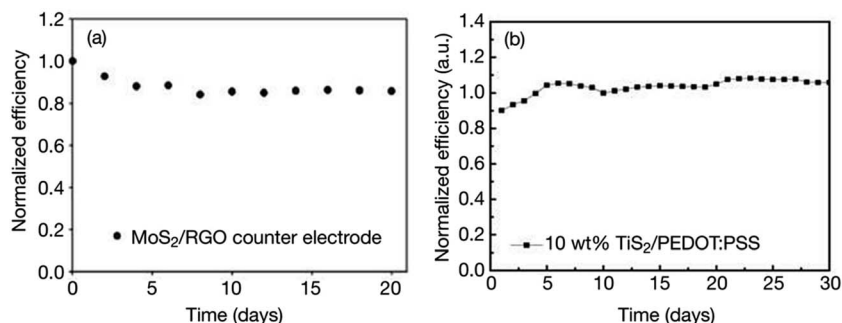


Fig. 29 (a) Stability of a DSSC with MoS<sub>2</sub>/RGO based counter electrode recorded for 20 days. Reprinted with permission from ref. 350, C. J. Liu, S. Y. Tai, S. W. Chou, Y. C. Yu, K. D. Chang, S. Wang, F. S. S. Chien, J. Y. Lin and T. W. Lin, facile synthesis of MoS<sub>2</sub>/graphene nanocomposite with high catalytic activity toward triiodide reduction in dye-sensitized solar cells. *J. Mater. Chem.*, 2015, **22**, 21057–21064. Copyright© Royal Society of Chemistry. (b) The long-term stability of the DSSCs with 10 wt% TiS<sub>2</sub>/PEDOT:PSS composite CE. Reprinted with permission from ref. 200, C. T. Li, C. P. Lee, Y. Y. Li, M. H. Yeh and K. C. Ho, a composite film of TiS<sub>2</sub>/PEDOT:PSS as the electrocatalyst for the counter electrode in dye-sensitized solar cells. *J. Mater. Chem. A*, 2013, **1**, 14888–14896. Copyright© Royal Society of Chemistry.

of DSSCs for the I<sup>−</sup>/I<sub>3</sub><sup>−</sup> redox system, which exhibited a PCE as high as 7.04% and is comparable to a Pt CE. Fig. 29b shows dark current density–voltage curves of DSSCs with Pt, bare TiS<sub>2</sub>, bare PEDOT:PSS, and 10 wt% TiS<sub>2</sub>/PEDOT:PSS composite CEs, and also the long-term stability of a 10 wt% TiS<sub>2</sub>/PEDOT:PSS composite CE based DSSC. This another example of long-term stability of DSSCs based on TiS<sub>2</sub>/PEDOT:PSS CEs.

The stability of DSSCs with a TiS<sub>2</sub>/graphene hybrid CE was studied by Meng *et al.*<sup>199</sup> (Fig. 30). The TiS<sub>2</sub>–graphene hybrid CE maintained 96% of its initial PCE value after 500 hours in air, also exhibiting higher electrochemical stability. The *R*<sub>s</sub> and *Z*<sub>N</sub> values for the TiS<sub>2</sub>–graphene hybrid CE based DSSC did not change after 10 cyclic measurements. The *R*<sub>CT</sub> value of a DSSC with Pt CE significantly increased with increasing cycling number, while there was no change in the *R*<sub>CT</sub> value of the TiS<sub>2</sub>–graphene hybrid after 10 cycles. This indicates better electrochemical stability of the TiS<sub>2</sub>–graphene hybrid CE than the Pt CE. The stability of photovoltaic parameters of DSSCs having

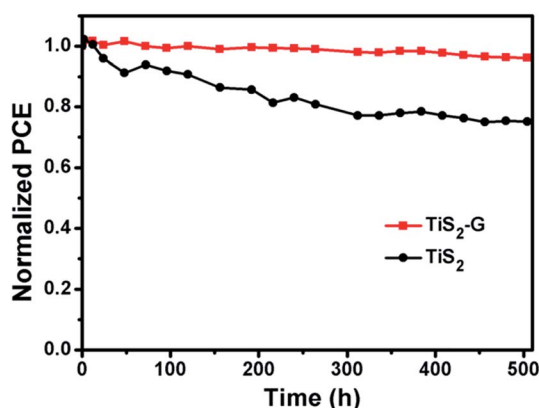


Fig. 30 Stability of DSSCs with TiS<sub>2</sub>–graphene hybrid and Pt CEs. Reprinted with permission from ref. 199, X. Meng, C. Yu, B. Lu, J. Yang and J. Qiu, dual integration system endowing two-dimensional titanium disulfide with enhanced triiodide reduction performance in dye-sensitized solar cells. *Nano Energy*, 2016, **22**, 59–69. Copyright© Elsevier.

mesoporous CoS<sub>2</sub> nanotube arrays as CEs was recorded for 10 days by Tsai *et al.*<sup>233</sup> a slight drop in the *V*<sub>oc</sub> and FF values were observed, which resulted in a 2.2% decrease in the PCE of the CoS<sub>2</sub> nanotube array CEs. The photovoltaic parameters of the DSSC were quite stable up to 10 days, indicating good stability of DSSCs with mesoporous CoS<sub>2</sub> nanotube array CEs (Fig. 31).

The electrochemical stability of DSSCs with FeSe<sub>2</sub> nanosheets and Pt CEs in an iodine-based electrolyte was studied by Huang *et al.*<sup>302</sup> Both CEs were subjected to consecutively CV scanning. The FeSe<sub>2</sub> nanosheets-based CE showed no change in the current densities and *E*<sub>pp</sub> values up to 1000 cycles, whereas the *E*<sub>pp</sub> value for the Pt-based CE was observed to increase after 1000 consecutive cycles (Fig. 32). This study confirmed a better corrosion resistance of FeSe<sub>2</sub> nanosheets CE to the iodine-based electrolyte than a Pt CE. Both CEs were also subjected to sequential EIS scanning, where negligible changes in *R*<sub>CT</sub> were noticed after 10 cycles, again indicating an excellent electrochemical stability of both CEs. Furthermore, *R*<sub>s</sub> and *Z*<sub>N</sub> values also showed no change upon repeated scanning cycles.

The stability of a FeS<sub>2</sub> nanorod based CE was also measured in an iodide (I<sup>−</sup>) electrolyte up to 10 days, and CV plots showed slight change at different times of aging.<sup>222</sup> The hydrothermally synthesized CoSe<sub>2</sub> nanorods were used as an electrocatalyst for a DSSC for the reduction of I<sub>3</sub><sup>−</sup> using N719 dye by Sun *et al.*<sup>351</sup> The single crystalline CoSe<sub>2</sub> nanorods based CE showed a PCE of 10.20%, compared with a PCE of 8.17% for a Pt CE, under 1 Sun illumination. The DSSCs having CoSe<sub>2</sub> CEs were stored in daylight and their photovoltaic properties were measured every day, and showed long-term stability. These studies show an excellent electrochemical stability of TMDs-based CEs for DSSCs in iodine-based electrolyte, with no corrosion. The TMDs CEs are also quite stable when stored under ambient conditions of up to 2–3 weeks, as no significant changes were observed in the PCEs of the DSSC devices. Furthermore, TMDs based CEs should be further investigated to exhibit better electrochemical stability and environmental stability than that of standard Pt CEs, and endurance tests should be carried out to study the their stability. The DSSS devices should have a service life of at least 20 years under ambient conditions as pointed out by



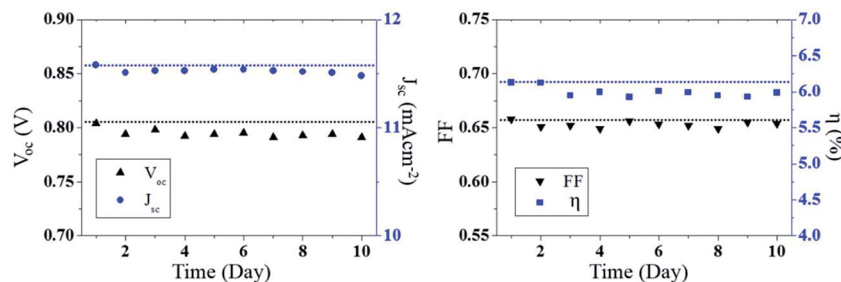


Fig. 31 Stability of photovoltaic parameters; open-circuit voltage ( $V_{oc}$ ), short-circuit photocurrent density ( $J_{sc}$ ), fill factor (FF), and power conversion efficiency ( $\eta$ ) of DSSCs with mesoporous  $\text{CoS}_2$  nanotube array CE as a function of time. Reprinted with permission from ref. 233, J. C. Tsai, M. H. Hon and I. C. Leu, fabrication of mesoporous  $\text{CoS}_2$  nanotube arrays as the counter electrodes of dye-sensitized solar cells. *Chem. – Asian J.*, 2015, **10**, 1932–1939. Copyright© Wiley-VCH.

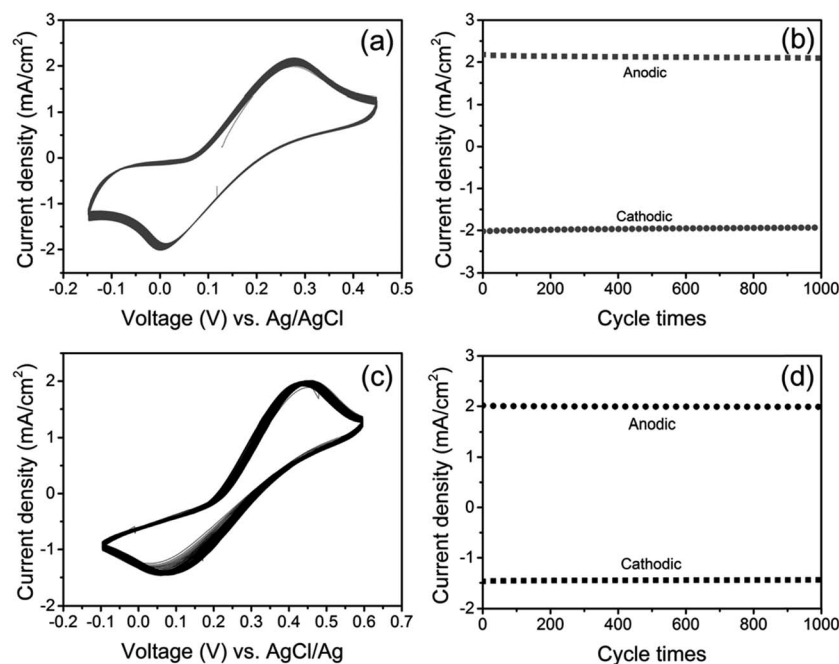


Fig. 32 1000 consecutive cycles of CVs of  $\text{FeSe}_2$  nanosheets-based CE (a) and Pt-based CE (c) at a scan rate of  $50 \text{ mV s}^{-1}$  and the anodic as well as cathodic peak current densities up to 1000 cycles for  $\text{FeSe}_2$ - (b) and Pt-based CEs (d), respectively. Reprinted with permission from ref. 302, S. Huang, Q. He, W. Chen, Q. Qiao, J. Zai and X. Qian, ultrathin  $\text{FeSe}_2$  nanosheets: controlled synthesis and application as a heterogeneous catalyst in dye-sensitized solar cells. *Chem. – Eur. J.*, 2015, **21**, 4085–4091. Copyright© Wiley-VCH.

Grätzel.<sup>342</sup> The long-term stability of DSSCs is feasible by carefully selecting components and solar cell structure. The TMDs based CEs may overcome the concerns associated with scarcity, high production cost, and corrosion of Pt CEs in electrolyte solutions. Researchers in this field should address the stability for of TMDs based CEs to evaluate the performance of Pt-free DSSCs.

Some achievements and strategies to overcome the long-term stability of Pt-free DSSCs are summarized in the following section. Kato *et al.*<sup>352</sup> used Raman spectroscopy and EIS to evaluate the durability of DSSCs for 2.5 years in outdoor conditions. Both N719 dye-adsorbed  $\text{TiO}_2$  CEs and carbon CEs were found to be stable. The  $V_{oc}$  and FF values were slightly decreased because of increased  $Z_N$  of triiodide ( $\text{I}_3^-$ ), arising

from the change in electrolyte components. Matsui *et al.*<sup>353</sup> achieved stability over 1000 hours for DSSCs at  $85^\circ\text{C}$  and under 85% relative humidity, and recorded no degradation of the photovoltaic performance between  $-40$  and  $90^\circ\text{C}$  for 200 cycles. Xue *et al.*<sup>354</sup> measured thermal stability of DSSCs between  $-20$  to  $25^\circ\text{C}$  temperature range for 1080 hours. DSSCs with N719 dye absorbed on the  $\text{TiO}_2$  photoanode retained 80% of their initial PCE values after aging for 1080 hours. The deterioration of the N719 dye was found to be the main cause for a decrease the PCE and degradation of DSSC devices. Harikisun and Desilvestro<sup>355</sup> evaluated photovoltaic performance of Z907-based DSSCs after continuous light-soaking at  $55$ – $60^\circ\text{C}$  for 25 600 hours, where a slight degradation was observed. The accelerated aging tests predicted a life time of 40 years for Middle European conditions



while 25 years for Southern European conditions. The 10% and 20% decrease of photovoltaic performance was measured for ionic liquid and solvent based electrolytes over 1000 hours at 180 °C, respectively.

Strategies to improve the long-term stability of DSSCs include developing new photosensitizing dyes, new non-volatile electrolytes, encapsulation, and of course new photoanodes and CEs. Like the heterojunction solar cells,<sup>27</sup> several strategies for improving electrochemical and thermal stability of DSSC devices have been proposed. The role of photosensitizing dyes containing  $\pi$ -conjugated organic systems have been studied for the stability of DSSCs. Wu *et al.*<sup>356</sup> suggested a novel concept of molecular engineering of donor-acceptor- $\pi$ -acceptor (D-A- $\pi$ -A) based photosensitizers, not only to improve the stability of DSSCs but also to enhance the photovoltaic performance. Katoh *et al.*<sup>357</sup> compared the stability of five sensitizing dyes in DSSCs with and without  $\pi$ -conjugated oligothiophene moiety, which indicated that dyes with  $\pi$ -conjugated oligothiophene exhibit higher stability than those of without oligothiophene moiety. Joly *et al.*<sup>358</sup> fabricated DSSCs with a new organic sensitizer (RK1) which showed a  $J_{sc}$  of 18.26 mA cm<sup>-2</sup>,  $V_{oc}$  of 0.76 V, and FF of 0.74, resulting in a PCE value of 10.2% under 1 Sun illumination for the triiodide/iodide ( $I_3^-/I^-$ ) redox couple. A similar PCE of 10.19% was achieved for the ruthenium N719 dye. When RK1 dye was used with a viscous ionic liquid electrolyte, the DSSC yielded a  $J_{sc}$  of 15.40 mA cm<sup>-2</sup>,  $V_{oc}$  of 0.665 V, FF of 0.69, and a PCE of 7.36%, with outstanding stability. The DSSC exhibited no degradation of photovoltaic performance after visible-light soaking at 65 °C for 2200 hours, but, thereafter, DSSC started degrading and retained 75% of its initial PCE at 65 °C after 5000 hours.

A new coumarin dye, namely 2-cyano-3-[5'-[1-cyano-2-(1,1,6,6-tetramethyl-10-oxo-2,3,5,6-tetrahydro-1*H*,4*H*,10*H*-11-oxa-3*a*-aza-benzo[*de*]anthracen-9-yl)-vinyl]-[2,2']bithiophenyl-5-yl]-acrylic acid (NKX-2883) was developed by Wang *et al.*<sup>359</sup> to examine the stability of DSSCs in a nonvolatile electrolyte made of 0.1 M  $I_2$ , 0.6 M 1,2-dimethyl-3-*n*-propylimidazolium iodide (DMPII), and 0.1 M *N*-methylbenzimidazole (NMBI) in 3-methoxypropionitrile. The NKX-2883 dye-based DSSC showed a  $J_{sc}$  value of 18.8 mA cm<sup>-2</sup> and a PCE of 6.5% with 6 micron thick  $TiO_2$  film. The DSSCs maintained a PCE of 6% under continuous light soaking of 100 mW cm<sup>-2</sup> (1 Sun illumination) at 50–55 °C for 1000 hours. Organic photosensitizing dyes having long alkyl chains were also proposed to improve long-term stability for both liquid and quasi-solid-state DSSCs.<sup>360</sup> In another study, quinoxaline based metal-free organic sensitizing dyes were utilized to introduce long-term stability in DSSCs.<sup>361</sup> The length of the alkyl chains on the donor unit was found to affect the performance of DSSC devices. The quasi-solid-state DSSCs with a quinoxaline-based organic dye showed a PCE of 7.14%, and maintained 100% of its initial PCE value after continuous sunlight irradiation for 1000 hours, indicating that molecular engineering of dye molecules can lead to both high PCE and long-term stability of DSSC devices.

The electrochemical stability of CEs in corrosive triiodide/iodide ( $I_3^-/I^-$ ) electrolyte is of significant concern because it restricts commercial applications of DSSCs. To overcome this

disadvantage of the  $I^-/I_3^-$  redox couple, research activities have been focused on finding alternative iodine-free non-corrosive redox electrolytes.<sup>19,362–366</sup> Cell-sealing conditions are also important when using liquid electrolytes. The DSSCs can be made suitable for outdoor applications by using encapsulation. The role of electrolytes has been studied in the stability of DSSCs by Sauvage *et al.*<sup>367</sup> suggesting a new electrolyte based on butyronitrile solvent with low volatility, along with thiophene-based sensitizer Na-Ru(4,4'-bis(5-(hexylthio)thiophen-2-yl)-2,2'-bipyridine)(4-carboxylic acid-4'-carboxylate-2,2'-bipyridine)(thiocyanate)2, coded C106, for DSSCs which showed >95% retention of PCE value after 1000 hours at 60 °C for an exposure to 100 mW cm<sup>-2</sup> light illumination. Yoon *et al.*<sup>368</sup> fabricated DSSCs with 1-propyl-3-methyl imidazolium iodide (PMII) ion-gel electrolyte with a poly(styrene-block-ethyleneoxide-block-styrene) (SEOS) triblock copolymer. The DSSC with ion-gel electrolyte retained 92% of its initial PCE up to 1440 hours, compared to 78% for the ionic liquid electrolyte. Lee *et al.*<sup>369</sup> reported long-term stability of DSSCs with organic tetrabutylammonium iodide (TBAI) or 1-methyl 3-propyl imidazolium iodide (PMII) in methoxypropionitrile-based electrolytes. The DSSCs having TBAI retained 96.9% of their initial efficiency after being stored for 1000 hours under 1 Sun light irradiation at 60 °C. Yang *et al.*<sup>370</sup> proposed the use of poly(ethylene oxide)-poly(vinylidene fluoride) (PEO-PVDF) polymer-blend electrolytes with water and ethanol for improving stability of DSSCs. The electrical conductivity was found to increase after adding water and ethanol to the PEO-PVDF polymer-blend electrolytes. The cross-linking capability of hydroxyl-rich additives for modified electrolytes was found to have a positive impact. Chen *et al.*<sup>371</sup> demonstrated the long-time durability of DSSCs by using a succinonitrile, silica nanoparticles and 1-butyl-3-methylimidazolium tetrafluoroborate (BMI·BF<sub>4</sub>) gel system which maintained 93% of its initial PCE after aging at 60 °C for 1000 hours. Dembele *et al.*<sup>372</sup> also demonstrated that adding 1.0 wt% concentration of MWCNTs to  $TiO_2$  photoanodes can improve both PCE and stability of a DSSC, where the PCE value increased to 4.1% compared with 3.7% for pure  $TiO_2$  photoanodes. The performance of the DSSC devices was measured for 10 consecutive days under ambient light exposure. The PCE decreased about 10% for the MWCNTs/ $TiO_2$  photoanodes, compared to 35% decrease in pure  $TiO_2$  photoanodes.

The long-term stability of Pt-free DSSCs is of significant importance for both indoor and outdoor applications and different approaches can be examined to improve environmental stability.<sup>356–361,367–377</sup> These studies show that long-term stability may be introduced in TMDs based DSSCs by similar strategies of using long alkyl chain organic dyes, ion-gel and polymer-based electrolytes, silica nanoparticles, or modifying  $TiO_2$  photoanodes. Similar electrochemical and thermal stability studies should be conducted for TMD CEs for DSSC devices.

## 7. Conclusion and perspective

The electrochemical and photovoltaic properties of DSSC devices employing CEs (CEs) of 2D layered transition metal





dichalcogenides (MoS<sub>2</sub>, MoSe<sub>2</sub>, WS<sub>2</sub>, TiS<sub>2</sub>, NbSe<sub>2</sub>, TaSe<sub>2</sub>, NiSe<sub>2</sub>, FeSe<sub>2</sub>, CoSe<sub>2</sub>, SnS<sub>2</sub>, Bi<sub>2</sub>Se<sub>3</sub> and their based composites) have been summarized and discussed. This data indicates that the PCEs of TMDs-based CE surpasses conventional Pt CE in dye-sensitized solar cell (DSSC) devices. The composites of TMDs with graphene, CNTs, carbon, carbon nanofibers (CNFs), and PEDOT:PSS also show a great potential as CEs for DSSCs. The DSSCs having CEs made of chemical vapor deposition (CVD)-grown vertically inclined MoS<sub>2</sub> films,<sup>131</sup> hydrothermally prepared MoS<sub>2</sub> films,<sup>135,141</sup> MoS<sub>2</sub> and MoSe<sub>2</sub> thin films deposited on Mo foil,<sup>260,261</sup> MoS<sub>2</sub>/graphene, MoS<sub>2</sub>/CNTs,<sup>164</sup> MoS<sub>2</sub>/carbon,<sup>171</sup> and MoSe<sub>2</sub>/PEDOT:PSS composites exhibit higher PCE values than that of Pt CE for the reduction of triiodide (I<sub>3</sub><sup>-</sup>) to iodide (I<sup>-</sup>). Furthermore, the CEs of TiS<sub>2</sub>/graphene hybrids,<sup>199</sup> NiS<sub>2</sub>/reduced graphene oxide (RGO) composites,<sup>210</sup> FeS<sub>2</sub>,<sup>221</sup> NbSe<sub>2</sub>,<sup>280</sup> and FeSe<sub>2</sub> nanosheets<sup>302</sup> also show a better photovoltaic performance than that of Pt CE in DSSCs. The low cost and flexible CoSe<sub>2</sub>/carbon-nanoclimbing-wall CE deposited on nickel foam shows the highest PCE of 10.46% *versus* a Pt CE ( $\eta = 8.25\%$ ) at 1 Sun illumination (100 mW cm<sup>-2</sup> (AM 1.5G)).<sup>310</sup> It has been observed that the morphology of CEs also plays an important role in determining the electrocatalytic activity of DSSC devices, where CEs with large surface area nanostructures tend to show larger PCE values and a higher electrocatalytic activity of the DSSCs.<sup>282</sup> The DSSCs with TiS<sub>2</sub>/graphene hybrids<sup>199</sup> and TiS<sub>2</sub>/PEDOT:PSS composites<sup>200</sup> based CEs showed environmental stability of up to 20 and 30 days, respectively, with no degradation in the photovoltaic performance. Interestingly, thermoelectric Bi<sub>2</sub>Te<sub>3</sub> nanosheet/ZnO nanoparticles composite based photoanodes<sup>335</sup> exhibited a 46.95% increase in PCE value compared with a bare ZnO photoanode based DSSC. Also, the DSSC with the Bi<sub>2</sub>Te<sub>3</sub>/TiO<sub>2</sub> composite based photoanode<sup>336</sup> showed a 28% increase in PCE than that of pure TiO<sub>2</sub> photoanode.

Transition metal dichalcogenides (TMDs) based materials which are analogues of 2D graphene are emerging as a great alternative to fabricating low-cost Pt-free DSSC devices. TMDs-based CEs have demonstrated better electrochemical stability than that of standard Pt CE in iodine-based electrolyte and also under ambient conditions. In addition to long-term stability, TMDs may also cause cytotoxicity to humans, as has been observed for other nanostructured materials,<sup>378–383</sup> therefore, aspects of toxicity should be investigated in studies with DSSC devices.

2D TMDs based CEs are a cheap alternative to Pt CE for DSSCs. In this review, we have summarized recent developments of TMDs used as CE materials for DSSCs which are still in their infancy. The low-cost 2D TMDs are abundantly available in nature, and can easily be processed into thin films and hybridized with other inorganic and organic materials for fabricating DSSC devices. The vast majority of 2D TMDs have yet to be studied, even as 2D graphene-based materials, but at this early stage they offer a low-cost alternative and outperform their Pt counterparts. Tremendous possibilities exist for developing new TMDs based CEs for I<sub>3</sub><sup>-</sup>/I<sup>-</sup>, Co<sup>2+</sup>/Co<sup>3+</sup> and T<sub>2</sub>/T<sup>-</sup> redox couples. The important requirements for commercial applications are ease of processing, low-cost manufacturing, high PCE

value, and long-term electrochemical stability. Like graphene-based materials, more edge active sites can be created in TMDs-based CEs to facilitate more dye adsorption. Research on the use of TMDs CE are in very early stage of developing Pt-free DSSCs. TMDs based CEs offer increased charge transfer capability and fast reaction kinetics for the reduction of triiodide (I<sub>3</sub><sup>-</sup>) to iodide (I<sup>-</sup>) in electrolyte for DSSCs and their potential can be realized in parallel to graphene. The large family of TMDs, such as MoS<sub>2</sub>, MoSe<sub>2</sub>, MoTe<sub>2</sub>, WS<sub>2</sub>, WSe<sub>2</sub>, WTe<sub>2</sub>, FeSe<sub>2</sub>, TaS<sub>2</sub>, NbSe<sub>2</sub>, *etc.*, should also be explored with other inorganic and organic materials, as the family of 2D materials is enormously large and are expected to play an important role in developing low-cost highly efficient DSSCs for commercial applications.

## Disclaimer

The authors cannot accept liability for any kind of scientific data contained in this review article whatsoever for the accuracy of contents or any omissions or any errors or a claim of completeness.

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