



Cite this: *J. Mater. Chem. A*, 2016, 4, 6411

# Symmetric pseudocapacitors based on molybdenum disulfide (MoS<sub>2</sub>)-modified carbon nanospheres: correlating physicochemistry and synergistic interaction on energy storage†

Tobile N. Y. Khawula,<sup>a</sup> Kumar Raju,<sup>b</sup> Paul J. Franklyn,<sup>c</sup> Iakovos Sigalas<sup>a</sup> and Kenneth I. Ozoemena<sup>\*bc</sup>

Molybdenum disulfide-modified carbon nanospheres (MoS<sub>2</sub>/CNS) with two different morphologies (spherical and flower-like) have been synthesized using hydrothermal techniques and investigated as symmetric pseudocapacitors in an aqueous electrolyte. The physicochemical properties of these MoS<sub>2</sub>/CNS layered materials have been investigated using surface area analysis (BET), scanning electron microscopy (SEM), transmission electron microscopy (TEM), X-ray diffraction (XRD), Raman, Fourier transform infrared (FTIR) spectroscopy, and advanced electrochemistry, including cyclic voltammetry (CV), galvanostatic cycling with potential limitation (GCPL), long-hour voltage-holding tests, and electrochemical impedance spectroscopy (EIS). The two different MoS<sub>2</sub>/CNS layered materials exhibit unique differences in morphology, surface area, and structural parameters, which have been correlated with their electrochemical capacitive properties. The flower-like morphology (f-MoS<sub>2</sub>/CNS) shows lattice expansion (XRD), large surface area (BET analysis), and small-sized nanostructures (corroborated by the larger FWHM of the Raman and XRD data). In contrast to the f-MoS<sub>2</sub>/CNS, the spherical morphology (s-MoS<sub>2</sub>/CNS) shows lattice contraction and small surface area with relatively large-sized nanostructures. The presence of CNS on the MoS<sub>2</sub> structure leads to slight softening of the characteristic Raman bands (E<sub>2g</sub><sup>1</sup> and A<sub>1g</sub> modes) with larger FWHM. MoS<sub>2</sub> and its CNS-based composites have been tested in symmetric electrochemical capacitors in an aqueous 1 M Na<sub>2</sub>SO<sub>4</sub> solution. CNS improves the conductivity of the MoS<sub>2</sub> and synergistically enhances the electrochemical capacitive properties of the materials, especially the f-MoS<sub>2</sub>/CNS-based symmetric cells (most notably, in terms of capacitance retention). The f-MoS<sub>2</sub>/CNS-based pseudocapacitor shows a maximum capacitance of 231 F g<sup>-1</sup>, with high energy density 26 W h kg<sup>-1</sup> and power density 6443 W kg<sup>-1</sup>. For the s-MoS<sub>2</sub>/CNS-based pseudocapacitor, the equivalent values are 108 F g<sup>-1</sup>, 7.4 W h kg<sup>-1</sup> and 3700 W kg<sup>-1</sup>. The high-performance of the f-MoS<sub>2</sub>/CNS is consistent with its physicochemical properties as determined by the spectroscopy and microscopy data. These findings have opened doors for further exploration of the synergistic effects between MoS<sub>2</sub> graphene-like sheets and CNS for energy storage.

Received 5th January 2016  
Accepted 23rd March 2016

DOI: 10.1039/c6ta00114a

www.rsc.org/MaterialsA

## Introduction

Pseudocapacitors are redox-based electrochemical capacitors (ECs). Unlike their counterparts, the electrical double layer capacitors (EDLC) that only use carbon materials as electrode materials, pseudocapacitors employ redox-active materials such

as conducting polymers, metal oxides and metal sulphides.<sup>1–4</sup> Unlike batteries with high energy densities, ECs are characterized by their high power characteristics, which make them very attractive for several technologies and devices that require high-power applications (*i.e.*, the ability to release energy pulses in a very short time, in a few seconds) such as in regenerative braking energy systems in vehicles and metro-rails, “stop–start” applications in modern cars, uninterrupted power supply (UPS), emergency doors in aircrafts, and escalators in buildings.<sup>5,6</sup>

One of the emerging high-power supercapacitor electrode materials is molybdenum disulfide (MoS<sub>2</sub>), a member of the transition-metal dichalcogenides (TMDs). MoS<sub>2</sub> has found applications in electrochemical devices, hydrogen storage, catalysis, capacitors, solid lubricants, and intercalation hosts.<sup>7,8</sup>

<sup>a</sup>School of Chemical and Metallurgical Engineering, University of the Witwatersrand, PO Wits 2050, Johannesburg, South Africa

<sup>b</sup>Energy Materials, Materials Science and Manufacturing, Council for Scientific and Industrial Research (CSIR), Pretoria 0001, South Africa. E-mail: kozoemena@csir.co.za

<sup>c</sup>Molecular Sciences Institute, School of Chemistry, University of the Witwatersrand, PO Wits 2050, Johannesburg, South Africa

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c6ta00114a

MoS<sub>2</sub> is a layered-structured material with close relationship to graphene, characterized by a sheet-like morphology. The Mo layer is sandwiched between two S layers and the triple layers are stacked and held together by weak van der Waals interactions.<sup>2,9–11</sup> Due to its higher intrinsic fast ionic conductivity (than oxides) and higher theoretical capacity (than graphite), MoS<sub>2</sub> continues to attract a lot of attention, particularly in supercapacitors.<sup>2,7,12</sup> Soon and Loh<sup>13</sup> have pointed out the use of MoS<sub>2</sub> as an electrode material for supercapacitors, and the results suggest that the supercapacitor performance of MoS<sub>2</sub> is comparable to that of carbon nanotube (CNT) array electrodes. In addition to double-layer capacitance, diffusion of the ions into the MoS<sub>2</sub> at slow scan rates obtains faradaic capacitance. Analogous to Ru in RuO<sub>2</sub>, the Mo central atom displays a range of oxidation states from +2 to +6. This plays an important role in enhancing charge storage capabilities.<sup>14</sup> However, the electronic conductivity of MoS<sub>2</sub> is still lower compared to graphite and the specific capacitance of MoS<sub>2</sub> is still very limited when used alone for energy storage applications.<sup>12,13,15</sup> As evident in several reports, there is the need to improve the capacitance of MoS<sub>2</sub> with conductive materials such as CNT,<sup>12</sup> polyaniline (PANI),<sup>2</sup> polypyrrole (PPy),<sup>9</sup> and reduced graphene (RGO).<sup>11</sup> In a review by Márquez *et al.*,<sup>16</sup> carbon nanospheres (CNS) were described as good candidates for catalytic and adsorption applications and their unclosed graphitic flakes provide the necessary ‘dangling bonds’ that could enhance surface reactions. CNS has also been used to enhance the conductivity of the battery cathode material, LiFePO<sub>4</sub>.<sup>17</sup>

To the best of our knowledge, the supercapacitive properties of MoS<sub>2</sub> have only been investigated in half-cells (*i.e.*, 3-electrode systems), which creates a huge knowledge gap on the true behavior of the electrode material when used in full-cells (2-electrode systems). Moreover, there is no literature on the effect of CNS on the supercapacitance of MoS<sub>2</sub>. Pseudocapacitors usually suffer from poor electrical conductivity and irreversible redox-activity, thereby leading to gradual loss of capacitance. To tackle the abovementioned challenges, this study adopted two different synthesis protocols to prepare MoS<sub>2</sub> and MoS<sub>2</sub>/CNS composites with different physicochemistries (*i.e.*, spherical and flower-like morphologies, structure, porous textures and electrochemistry) and then used them to fabricate symmetric pseudocapacitors. We clearly show that the pseudocapacitive properties of the MoS<sub>2</sub>/CNS (especially, in terms of cycling stability and electronic conductivity) are intrinsically linked to the presence of CNS.

## Experimental procedure

### Materials

Sodium molybdate dihydrate, Na<sub>2</sub>MoO<sub>4</sub>·2H<sub>2</sub>O (Analytical Reagent BDH chemicals Ltd, Poole England), thiourea (CH<sub>4</sub>N<sub>2</sub>S, Sigma-Aldrich Inc., USA), polyethylene glycol 1000 (PEG-1000, Fluka Analytical, Germany), L-cysteine (C<sub>3</sub>H<sub>7</sub>NO<sub>2</sub>S, Sigma-Aldrich Inc., USA). Hydrochloric acid (HCl, 32%), acetone (C<sub>3</sub>H<sub>6</sub>O) and absolute ethanol (C<sub>2</sub>H<sub>6</sub>O) were purchased from Associated Chemical Enterprises, in Johannesburg. All chemicals had purity higher than 98.99%. Distilled de-ionised water

(18 MΩ cm) used in this study was obtained from the School of Chemistry at the University of the Witwatersrand.

### Synthesis

**Spherical MoS<sub>2</sub>.** Spherical MoS<sub>2</sub> was synthesized using a well-established method by Huang *et al.*,<sup>18</sup> as follows: 0.31 g Na<sub>2</sub>MoO<sub>4</sub>·2H<sub>2</sub>O were dissolved in 30 mL deionized water. After adjusting the pH value to 6.5 with 12 M HCl, 0.82 g L-cysteine was added and the mixture was diluted with water to 35 mL and then the solution was rapidly stirred for about an hour. Subsequently, the mixture was transferred into a 40 mL Teflon-lined stainless steel autoclave and heated at 180 °C for 48 hours. The black MoS<sub>2</sub> precipitate was cooled naturally to room temperature, collected by centrifugation, washed with distilled water and absolute ethanol in three cycles and then dried in vacuum at 60 °C for 24 hours. For simplicity, the obtained spherical material (as evident from SEM and TEM images) is abbreviated as s-MoS<sub>2</sub>.

**Flower-like MoS<sub>2</sub>.** Flower-like MoS<sub>2</sub> was synthesized as suggested by Wang *et al.*<sup>19</sup> 1.21 g Na<sub>2</sub>MoO<sub>4</sub>·2H<sub>2</sub>O and 1.56 g thiourea powders were mixed together in 30 mL deionised water, and 0.14 g PEG-1000 were added. The resulting mixture was transferred to a Teflon cup of capacity 40 mL and heated in a stainless steel autoclave at 180 °C for 24 h. After cooling naturally to room temperature, the black MoS<sub>2</sub> precipitate was collected by centrifugation, washed with distilled water and absolute ethanol in three cycles, and then dried under vacuum at 60 °C for 24 h.<sup>19</sup> The obtained flower-like material (as evident from SEM and TEM images) is abbreviated herein as f-MoS<sub>2</sub>.

**Carbon nanospheres (CNS).** Carbon nanospheres (CNS) were obtained using the established method by Dlamini *et al.*<sup>20</sup> In brief, sucrose solution (0.3 M) was transferred into a 100 mL Teflon-lined stainless steel autoclave and heated at 150 °C for 5 hours. The reaction was then left to cool at room temperature. At this stage, the black precipitate that formed was purified by Soxhlet extraction, washed with ethanol and water and then dried at 80 °C in an oven.

The CNS-modified spherical MoS<sub>2</sub> (abbreviated herein as s-MoS<sub>2</sub>/CNS) composite was prepared as follows. First, 0.028 g CNS were ultrasonically dispersed in 20 mL deionized water. Then, 0.30 g Na<sub>2</sub>MoO<sub>4</sub>·2H<sub>2</sub>O were added and ultrasonically dispersed for 30 min. After adjusting the pH value to 6.5 with 12 M HCl, 0.80 g L-cysteine was added. The resultant mixture was diluted with water to 30 mL and rapidly stirred for about 1 h. The mixture was then transferred into a 40 mL Teflon cup and heated in a stainless steel autoclave at 180 °C for 36 h. Upon completion, the product was cooled naturally to room temperature, the s-MoS<sub>2</sub>/CNS composite was collected by filtration, washed with distilled water and acetone several times, and finally dried in the oven at 80 °C for 24 h.

The CNS-modified flower-like MoS<sub>2</sub> composite (abbreviated herein as f-MoS<sub>2</sub>/CNS) was prepared as follows. 1.21 g Na<sub>2</sub>MoO<sub>4</sub>·2H<sub>2</sub>O were added to the sonicated CNS in 20 mL deionised water and further sonicated for 30 min. Then, 1.56 g thiourea and 0.28 g PEG-1000 were added to the solution and the mixture diluted to 30 mL before heating to 180 °C using



a Teflon-lined stainless steel autoclave for 36 h. Upon completion, the product was cooled naturally to room temperature, the f-MoS<sub>2</sub>/CNS composite was collected by filtration, washed with distilled water and acetone several times, and finally dried in oven at 80 °C for 24 h. To homogenize the as-synthesized materials and further promote crystallization, the as-synthesized materials were annealed in a horizontal furnace with a quartz tube at 900 °C under a flow of nitrogen at a rate of 100 mL min<sup>-1</sup> for 4 h.

### Characterization techniques

The XRD patterns of the as-prepared MoS<sub>2</sub> and MoS<sub>2</sub>/CNS nanopowders were obtained from a DMax/2500PC diffractometer using Co K $\alpha$  radiation ( $K = 1.5418$  Å) at 40 kV, 100 mA and a  $2\theta$  range of 10–90°. The FTIR spectra were obtained using a Bruker Tensor 27 FTIR spectrometer equipped with ZnSe crystal that absorbs strongly below 500 cm<sup>-1</sup>. FTIR spectra were obtained in the range of 550–4000 cm<sup>-1</sup>; a single beam measurement as the background spectrum was acquired prior to running the actual sample. Raman measurements were carried out in air using a Horiba Jobin Yvon spectrometer equipped with an Olympus BX40 microscope attachment to focus the laser beam on a small selected area of the sample, a 30 mW green argon laser ( $\lambda = 514$  nm) as the excitation source, and a 1800 lines per mm grating monochromator with liquid nitrogen-cooled CCD. The BET (Brunauer, Emmett and Teller) measurements were performed to determine the specific surface area and pore size of the nano-sheets using a Micromeritics TriStar II instrument. The SEM images were obtained using a JEOL-JSM 7500F scanning electron microscope operated at 2.0 kV and a FEI Nova Nanolab 600 SEM. TEM images were obtained from a FEI Tecnai T12 microscope operated at an acceleration voltage of 120 kV. Elemental composition was obtained using the Oxford INCA EDS software on the SEM.

### Fabrication of the symmetric pseudocapacitor and electrochemical measurements

Symmetric pseudocapacitive properties of the materials were investigated using Swagelok cells (MTI, Inc., USA). Nickel foam (Celmet: thickness = 1.6 mm, surface area 7500 m<sup>2</sup>, cell size = 0.5 mm, 48–52 cells per inch) was used as substrate and current collector in the fabrication of the symmetric pseudocapacitors. Before use, the nickel foam was thoroughly cleaned by sonicating in 1 M HCl solution for 30 min, washing with copious amount of distilled water, and finally drying under vacuum. A 1 M Na<sub>2</sub>SO<sub>4</sub> solution was used as the electrolyte, whereas a porous filter paper (Whatman®) served as the separator. The electrode materials were prepared by first thoroughly mixing the active materials, either MoS<sub>2</sub>/CNS or MoS<sub>2</sub>, carbon black as the conducting agent, and polyvinylidene fluoride (PVDF) as the binder (80 : 15 : 5 weight ratio) with a few drops of anhydrous *N*-methyl-2-pyrrolidone (NMP) using pestle and mortar, to produce a homogeneous paste. The resulting slurry was coated onto the nickel foam substrate with a spatula. The electrode was then dried at 60 °C overnight in a vacuum oven. The mass of the active material on the nickel foam was between 5 and 20 mg. For

complete impregnation, the assembled cells were left for 12 hours prior to testing. The measurements were carried out in 1 M Na<sub>2</sub>SO<sub>4</sub> aqueous electrolyte. All electrochemical measurements, cyclic voltammetry (CV), galvanostatic cycling with potential limitation (GCPL), and electrochemical impedance spectroscopy (EIS) were performed at room temperature using a computer-controlled multi-channel Potentiostat/Galvanostat Bio-Logic VMP3 work station driven by EC-Lab® v10.40 software with Z-fit tool for EIS data analysis. EIS measurements were carried out in the frequency ranging from 10 kHz to 10 mHz at the open circuit voltage, with AC voltage amplitude of 1.5 mV.

The specific capacitance ( $C_{sp}$ ), maximum specific power density ( $P_{max}$ ) and specific energy density ( $E_{sp}$ ) were evaluated using the conventional eqn (1)–(5):<sup>21,22</sup>

$$C(F) = \frac{i\Delta t}{\Delta V} \quad (1)$$

$$C_{sp}(F\text{ g}^{-1}) = \frac{4C}{m} \quad (2)$$

$$P_{max}(10^3\text{ W kg}^{-1}) = \frac{V^2}{4mR_{ir}}, \quad (3)$$

where

$$R_{ir}(\Omega) = \frac{\Delta V_{ir}}{2I} \quad (4)$$

$$E\left(\frac{1}{3.6}\text{ W h kg}^{-2}\right) = \frac{CV^2}{2m}, \quad (5)$$

where  $i$  (A) is the applied current,  $\Delta V(V)/\Delta t$  (s) is the slope of the discharge curve,  $m$  (g) is the total mass of the two electrodes,  $C$  (F) is the calculated capacitance,  $V$  (V) is the maximum voltage obtained during charge, and  $R_{ir}$  is the internal resistance, which is determined from the voltage drop at the beginning of each discharge, whereas  $\Delta V_{ir}$  represents the voltage drop.

## Results and discussion

### Material characterization

A one-pot hydrothermal route was used for the synthesis of MoS<sub>2</sub>, CNS and MoS<sub>2</sub>/CNS. Fig. 1 shows the SEM and TEM images of the CNS (Fig. 1c and d), confirming the spherical nature of the CNS in agreement with literature. The micrographs show the interconnected uniform amorphous CNS in the particle size diameter range of 100–200 nm. Fig. 1 compares the SEM and TEM images of the s-MoS<sub>2</sub> and s-MoS<sub>2</sub>/CNS. The SEM and TEM micrographs of the s-MoS<sub>2</sub> (Fig. 1a and b) show the formation of a sphere-like morphology consisting of several agglomerated clusters of s-MoS<sub>2</sub> sheets.

A closer examination of the TEM images of the CNS (Fig. 1d) and s-MoS<sub>2</sub>/CNS (Fig. 1f–h) clearly suggests a uniform dispersion and excellent integration of the MoS<sub>2</sub> with the CNS. The value of the  $d$ -spacing of the s-MoS<sub>2</sub> shown in the TEM image (Fig. 1i) is 0.62 nm, which is in agreement with literature.<sup>23</sup> In this synthesis method, it seems that the CNS particles acted as substrates for nucleation, wherein MoO<sub>4</sub><sup>-</sup> ions reacted with sulphur ions from L-cysteine to form the MoS<sub>2</sub> sheets on the





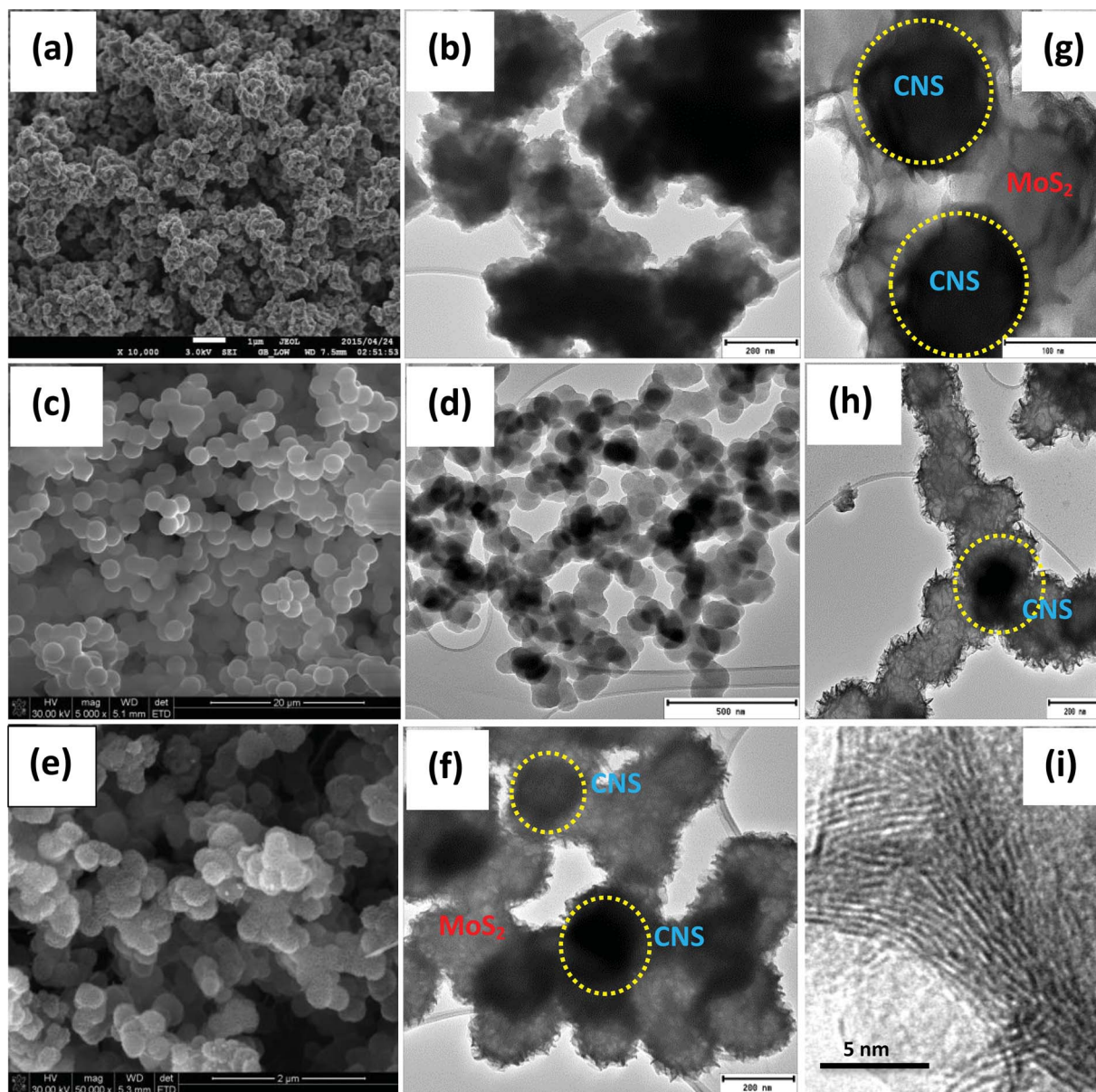


Fig. 1 SEM (a, c and e) and TEM (b, d, f, h and i) micrographs of s-MoS<sub>2</sub> (a and b), CNS (c and d), s-MoS<sub>2</sub>/CNS (e and f); magnified views of s-MoS<sub>2</sub>/CNS (g and h), and *d*-spacing of s-MoS<sub>2</sub> (i).

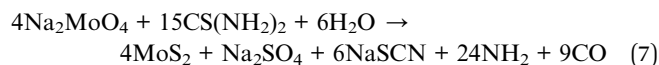
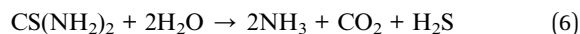
CNS. The presence of CNS prevented MoS<sub>2</sub> stacking and thus the formation of a porous 3-D sphere-like architecture with highly dispersed wrinkled and fluffy MoS<sub>2</sub> sheets on CNS particles. This unique structure is also apparent in the TEM images (Fig. 1f and h). In the s-MoS<sub>2</sub>/CNS composite, the MoS<sub>2</sub> nano-sheet edges are readily exposed and not entangled as in MoS<sub>2</sub>. This loose structure is desirable for superior charge storage. However, the MoS<sub>2</sub> sheets in the composite are not visible as layered; instead, they grew in various orientations and were intertwined around the spheres. An important consequence is the small accessible surface area coupled with the small micropores. This could potentially cause an obstruction for ion transportation and thus limit the capacitance. The elemental composition of as-synthesized s-MoS<sub>2</sub>, obtained from

the EDS (see ESI, Fig. S1†) obtained Na (3.35), S (66.11) and Mo (30.55) by weight percentage, clearly confirming the stoichiometry of the MoS<sub>2</sub>. The impurity 'Na' is attributed to the starting precursor Na<sub>2</sub>MoO<sub>4</sub>·2H<sub>2</sub>O.

Similarly, the flower-like nanostructures (f-MoS<sub>2</sub>) were obtained using a one-pot hydrothermal method. This method relies on sodium molybdate and thiourea to provide MoO<sub>4</sub><sup>2-</sup> ions and sulphur atoms, respectively. Interestingly, the addition of small amounts of PEG in our synthesis protocol assisted in the efficient dispersion of the MoS<sub>2</sub> to generate the flower-like morphology. The starting precursor materials in the MoS<sub>2</sub> formation play a vital role, especially in the achieved morphology; a slight change, even in the reducing agent, can bring about enormous value. In this hydrothermal process, the



reaction involves three steps: (a) the hydrolysis of sulfur precursor to form  $\text{H}_2\text{S}$ , followed by (b) the reduction of Mo and (c) finally the formation of  $\text{MoS}_2$ .<sup>19</sup>



The SEM and TEM images of as-synthesized  $\text{MoS}_2$  in Fig. 2 clearly show flower-like hierarchical 3-D structures. The f- $\text{MoS}_2$  sheets self-assemble into a highly porous structure (Fig. 2a–c and e). The composite structure (Fig. 2d) also exhibits a clear flower-like morphology. The occurrence of this morphology may be associated with the presence of a surfactant (PEG-1000). Remarkably, after coating CNS with  $\text{MoS}_2$  sheets, the surface appears rough and wrinkled by the  $\text{MoS}_2$  sheets (Fig. 2d, f and g). The value of the  $d$ -spacing of the f- $\text{MoS}_2$  (Fig. 2h) is 0.61 nm, which is in agreement with literature.<sup>23</sup> The EDS data (see ESI, Fig. S2†) depict strong Mo and S overlapping signals, the  $\text{MoS}_2$  contains Na 1.3 atomic%, S 62.09 atomic% and Mo 36.61 atomic%, confirming the stoichiometry of the  $\text{MoS}_2$ .

$\text{MoS}_2$  has a hexagonal crystal system and layer-structured  $D_{6h}^4$  crystal system and  $P6_3$  space group. Fig. 3 compares the XRD patterns of the CNS and its  $\text{MoS}_2$  spherical and flower-like composites. There is no significant difference between the  $\text{MoS}_2$

and  $\text{MoS}_2/\text{CNS}$  patterns, confirming good integration of the CNS with the  $\text{MoS}_2$  structure. The diffraction peaks at  $2\theta = 15.8^\circ$ ,  $37.9^\circ$  and  $41.5^\circ$  are indexed to the hexagonal phase of  $\text{MoS}_2$  (002), (100) and (201), respectively. For the spherical morphology (s- $\text{MoS}_2/\text{CNS}$  composite), the diffraction peaks are similar to the individual s- $\text{MoS}_2$ , meaning that CNS fully interacts with the  $\text{MoS}_2$  and its presence does not interfere with the structure of the  $\text{MoS}_2$ . For the spherical material, s- $\text{MoS}_2/\text{CNS}$ , the incorporation of CNS into the  $\text{MoS}_2$  nanosheets decreases the intensity of the peaks, in particular the (002). The result indicates the formation of few layers of the  $\text{MoS}_2$  in the composite; thus, CNS impedes the growth of the  $\text{MoS}_2$  layer in a hexagonal array. Importantly, upon incorporation of the CNS, there is a slight shift in the diffraction lines of the  $\text{MoS}_2$  to higher  $2\theta$  (see Fig. 3a–c), which is an indication of a lattice contraction. However, for the flower-like morphology (f- $\text{MoS}_2/\text{CNS}$ ), the incorporation of the CNS results in a slight shift to the lower  $2\theta$  (see Fig. 3d–f), which is an indication of lattice expansion in the S–Mo–S interlayer spacing and formation of a few layers of  $\text{MoS}_2$ . In addition, unlike the spherical composite (Fig. 3a–f), the presence of the CNS did not negatively impact the peak intensity of (002). In fact, the (002) peak became more intense and sharper, indicating a higher degree of crystallinity, comparable to that of the bulk  $\text{MoS}_2$ . This finding may be due to strong integration between the  $\text{MoS}_2$  and CNS arising from the synthesis protocol adopted in this study, which allowed for the

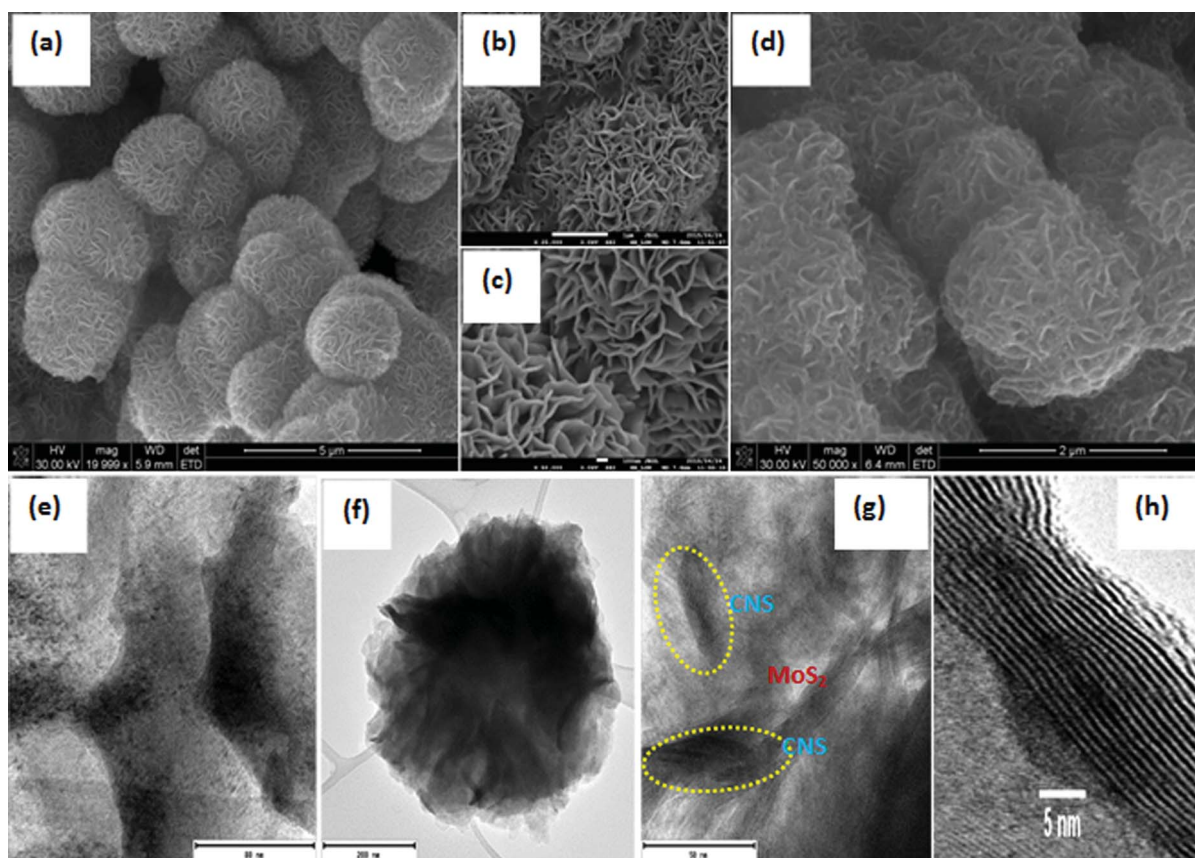


Fig. 2 SEM (a–d) and TEM (e–h) micrographs of f- $\text{MoS}_2$  (a–c), f- $\text{MoS}_2/\text{CNS}$  (d), f- $\text{MoS}_2$  (e); magnified views of f- $\text{MoS}_2/\text{CNS}$  (f and g) and  $d$ -spacing of f- $\text{MoS}_2$  (h).





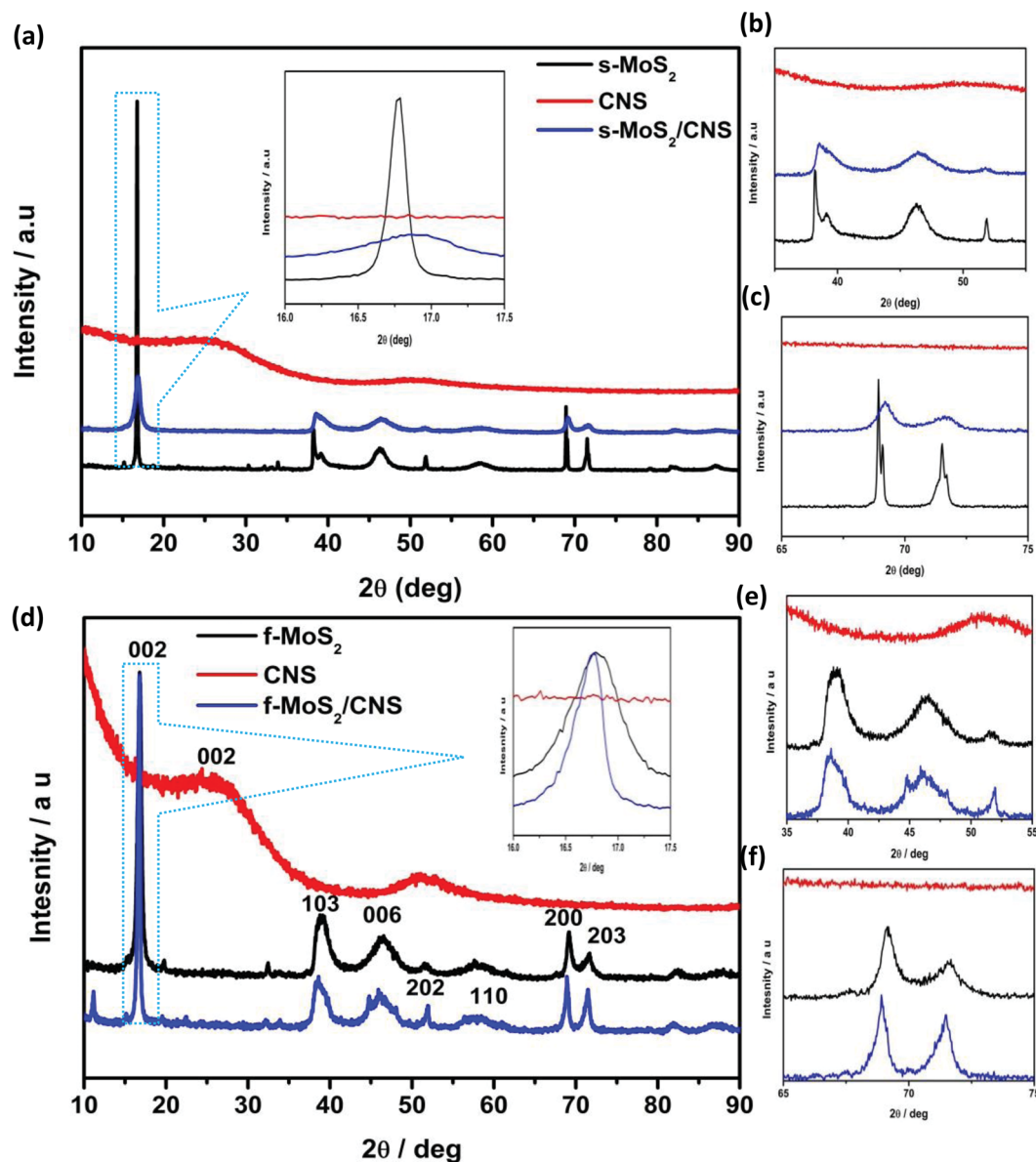


Fig. 3 XRD patterns of MoS<sub>2</sub>, CNS and MoS<sub>2</sub>/CNS composites for spherical (a–c) and flower-like (d–f) products and their magnified views.

two materials to undergo chemical reaction rather than just physical mixing. Furthermore, the peak (103) is more apparent, with a new broad peak (006) of hexagonal MoS<sub>2</sub> at 46° (Fig. 3d and e).

BET (five-point analysis) was used to measure the specific surface area and porosity of the as-synthesized materials. As

shown in Table 1, the s-MoS<sub>2</sub> has a specific surface area of 17.8 m<sup>2</sup> g<sup>−1</sup>; on the other hand, the specific surface area of the s-MoS<sub>2</sub>/CNS decreased to 9.17 m<sup>2</sup> g<sup>−1</sup>. This dramatic reduction is explained by the hindrance to the growth of the MoS<sub>2</sub>, due to the presence of the CNS (also confirmed by the XRD patterns). In fact, the CNS makes the surface area of MoS<sub>2</sub> inaccessible. Moreover, the pore sizes of MoS<sub>2</sub> and MoS<sub>2</sub>/CNS were revealed to be 22.9 and 18.61 nm, respectively. The f-MoS<sub>2</sub>/CNS composite had a higher surface area with value of 61 m<sup>2</sup> g<sup>−1</sup> compared to 25 m<sup>2</sup> g<sup>−1</sup> recorded for the flower-like MoS<sub>2</sub>. This means that incorporation of CNS prevented the agglomeration of MoS<sub>2</sub> sheets (also suggested from the XRD data). Surprisingly, the BET data follow the XRD data, especially the (002) peak height. Considering that capacitance is a function of the surface area, one would expect the materials with higher surface area (such as the f-MoS<sub>2</sub>/CNS) to provide the best capacitance

Table 1 Porous texture of the as-synthesized materials

| Sample                  | S <sub>A</sub> <sup>BET</sup><br>(m <sup>2</sup> g <sup>−1</sup> ) | Pore volume<br>(cm <sup>3</sup> g <sup>−1</sup> ) | Pore size<br>(nm) |
|-------------------------|--|---|-------------------|
| s-MoS <sub>2</sub>      | 17.80  | 0.100   | 22.93             |
| s-MoS <sub>2</sub> /CNS | 9.17   | 0.040   | 18.61             |
| f-MoS <sub>2</sub>      | 25.00  | 0.018   | 36.13             |
| f-MoS <sub>2</sub> /CNS | 61.00  | 0.020   | 14.68             |



Table 2 Comparison of Raman spectral data

|  | Raman shift/cm <sup>-1</sup> |                 |                              |                 |                              |                 |                              |                 |
|--|------------------------------|-----------------|------------------------------|-----------------|------------------------------|-----------------|------------------------------|-----------------|
|  | s-MoS <sub>2</sub>           |                 | s-MoS <sub>2</sub> /CNS      |                 | f-MoS <sub>2</sub>           |                 | f-MoS <sub>2</sub> /CNS      |                 |
|  | E <sub>2g</sub> <sup>1</sup> | A <sub>1g</sub> | E <sub>2g</sub> <sup>1</sup> | A <sub>1g</sub> | E <sub>2g</sub> <sup>1</sup> | A <sub>1g</sub> | E <sub>2g</sub> <sup>1</sup> | A <sub>1g</sub> |
| Peak position                                  | 375.69                       | 402.49          | 375.07                       | 400.84          | 374.91                       | 401.78          | 375.23                       | 400.95          |
| E <sub>2g</sub> <sup>1</sup> - A <sub>1g</sub> | 26.8                         |                 | 25.77                        |                 | 26.87                        |                 | 25.72                        |                 |
| FWHM   | 8.47                         | 8.23            | 8.19                         | 8.71            | 9.29                         | 8.72            | 13.55                        | 10.88           |

value. Moreover, despite the fact that the pores do not directly contribute to the surface area, they provide accessible pathways for easy diffusion of ions and reversible charge storage.

Raman spectroscopy was used to provide more insight into the structure and topology of the as-synthesized MoS<sub>2</sub>-based nanocomposites. Fig. 4 shows the Raman spectra of as-synthesized MoS<sub>2</sub> nanosheets, CNS and MoS<sub>2</sub>/CNS nanocomposites. The CNS exhibited the signature D and G peaks of carbon-based materials at 1347 and 1590 cm<sup>-1</sup>, respectively. As we expected, the MoS<sub>2</sub>/CNS composites also showed the D and G peaks close to the regions wherein they were observed for the CNS alone, confirming the successful integration of the CNS into the two MoS<sub>2</sub>-based composites. There was no detectable difference in

the intensity ratios of the D to G band ( $I_D : I_G$ ) of the CNS (0.95), s-MoS<sub>2</sub>/CNS (0.94) and f-MoS<sub>2</sub>/CNS (0.94), which implies that the CNS essentially retained its pristine structure even after integration with the MoS<sub>2</sub>. The characteristic Raman bands for bulk s-MoS<sub>2</sub> were observed at 375.69 and 402.49 cm<sup>-1</sup> due to E<sub>2g</sub><sup>1</sup> and A<sub>1g</sub> modes with full-widths at half maximum (FWHM) of 8.47 and 8.23 cm<sup>-1</sup>, respectively. The E<sub>2g</sub><sup>1</sup> mode describes the in-layer displacement of the Mo and S atoms, whereas the A<sub>1g</sub> mode relates to the out-of-layer symmetric displacements of S atoms along the *c* axis.<sup>24,25</sup> Interestingly, the incorporation of the CNS into the MoS<sub>2</sub> resulted in the slight softening of these two Raman bands compared to those of the bulk MoS<sub>2</sub>; the spherical MoS<sub>2</sub>/CNS appeared at 375.07 cm<sup>-1</sup> (E<sub>2g</sub><sup>1</sup>) and 400.84 cm<sup>-1</sup>

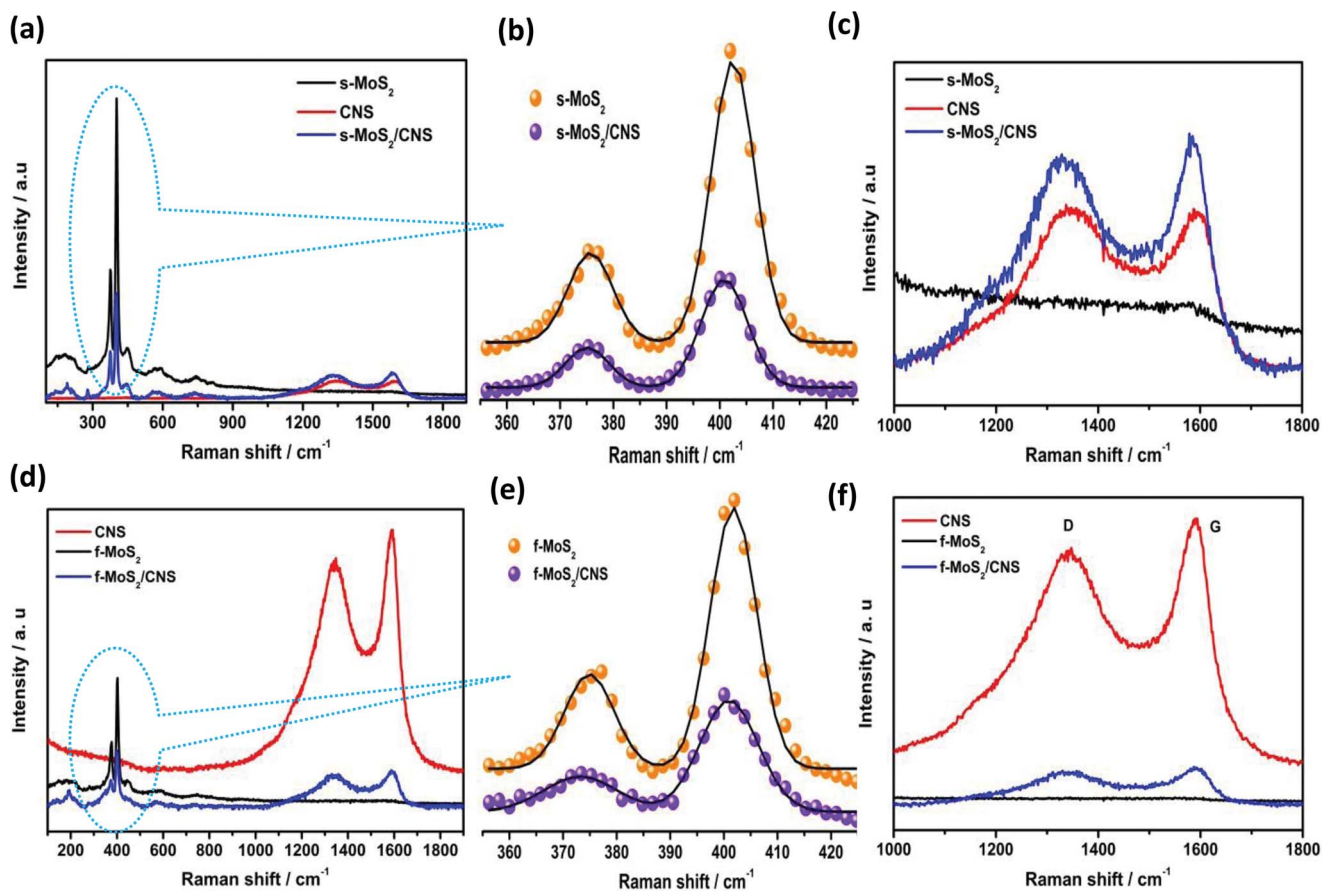


Fig. 4 Raman spectra of spherical (a–c) and flower-like (d–f) MoS<sub>2</sub>, CNS and MoS<sub>2</sub>/CNS nanocomposites and their magnified views.



( $A_{1g}$ ), while the flower-like morphology appeared at  $374.91\text{ cm}^{-1}$  ( $E_{2g}^1$ ) and  $401.78\text{ cm}^{-1}$  ( $A_{1g}$ ). Moreover, the increase in the FWHM values were more pronounced for the flower-like morphology than for the spherical morphology.

In the flower-like morphology, FWHM values are larger in the f-MoS<sub>2</sub>/CNS than in the bulk f-MoS<sub>2</sub> (cf.  $E_{2g}^1 = 13.55$  vs.  $9.29\text{ cm}^{-1}$  of the bulk f-MoS<sub>2</sub> or  $A_{1g} = 10.88$  vs.  $8.72\text{ cm}^{-1}$  of the bulk f-MoS<sub>2</sub>). The broadening of the Raman bands is related to phonon confinement and also indicates that the lateral dimensions of these MoS<sub>2</sub> layers are in the nano-dimension.<sup>25</sup> The larger FWHM for the f-MoS<sub>2</sub>/CNS compared to its s-MoS<sub>2</sub>/CNS counterpart is indicative of the smaller particle sizes and larger surface area, which corroborates the BET analysis. In a recent study by Lee *et al.*,<sup>26</sup> the authors showed that the frequency difference between  $E_{2g}^1$  and  $A_{1g}$  modes could serve as a convenient and robust diagnosis of the layer thickness of MoS<sub>2</sub> samples. From our results in Table 2, the frequency difference (*i.e.*,  $|E_{2g}^1 - A_{1g}|$ ) decreases as follows: bulk MoS<sub>2</sub> (*ca.*  $27\text{ cm}^{-1}$ ) > f-MoS<sub>2</sub>/CNS (*ca.*  $26\text{ cm}^{-1}$ ) = s-MoS<sub>2</sub>/CNS (*ca.*  $26\text{ cm}^{-1}$ ). Thus, our results indicate that there is no significant difference in the layer thicknesses of the two MoS<sub>2</sub>/CNS composites and the two synthesis methods we adopted in this study further confirm the change in the physicochemical properties of the MoS<sub>2</sub> complexes.

Fig. 5 shows FT-IR spectra of the MoS<sub>2</sub>, CNS and MoS<sub>2</sub>/CNS nanocomposites. In MoS<sub>2</sub>, the peaks at  $1583$  and  $1518\text{ cm}^{-1}$  are consistent with NH<sub>2</sub> in-group deformation (arising from the thiourea or L-cysteine used in the synthesis), and the peak at  $1466\text{ cm}^{-1}$  is assigned to the N-C-N asymmetric stretching mode. The band at  $1231\text{ cm}^{-1}$  is assigned to stretching vibrations of O-H bonds. The C-O-H stretching mode occurred at  $1092\text{ cm}^{-1}$ . The C-S stretching vibrations are observed at  $729\text{ cm}^{-1}$ . The weak peak around  $600\text{ cm}^{-1}$  is assigned to Mo-S vibration. Similar peaks are observed for the MoS<sub>2</sub>/CNS nanocomposite with the additional peaks at  $2892\text{ cm}^{-1}$  and  $2971\text{ cm}^{-1}$  due to C=C symmetric and asymmetric stretching vibrations as explained elsewhere.<sup>27</sup> Indeed, the presence of the functional groups on the CNS could have contributed to the efficient integration of the CNS with the MoS<sub>2</sub> (as observed in the TEM images).

Fig. 6 compares the XPS data of s-MoS<sub>2</sub>/CNS (Fig. 6a and b) and f-MoS<sub>2</sub>/CNS (Fig. 6c and d). XPS analysis reveals the predominant Mo 3d and S 2p characteristic peaks for both s-MoS<sub>2</sub>/CNS and f-MoS<sub>2</sub>/CNS. The two materials clearly show that the only elements present are Mo, S, adventitious C and O, and Na 'impurity' (Table 3).

Both materials show the typical spectral signature of MoS<sub>2</sub>, with the co-existence of metallic (1T) and semiconducting (2H) phases.<sup>28–30</sup> There is a clear difference between the two complexes, notably the S 2p splits into two peaks in the s-MoS<sub>2</sub>/CNS ( $162.42$  and  $163.67\text{ eV}$  for S 2p<sub>3/2</sub> and S 2p<sub>1/2</sub>, respectively), whereas the f-MoS<sub>2</sub>/CNS splits into four peaks (located at  $162.31$ ,  $163.34$ ,  $164.63$  and  $169.23$ , which are assigned to S 2p<sub>3/2</sub>, S 2p<sub>1/2</sub>, S<sub>2</sub><sup>2−</sup> or S<sup>2−</sup> and S<sup>4+</sup>, respectively), suggesting that the S atoms exist in two different chemical states. This finding is indicative of f-MoS<sub>2</sub>/CNS undergoing partial oxidation into MoS<sub>x</sub>O<sub>y</sub> at the edges and defect sites, which effectively leads to

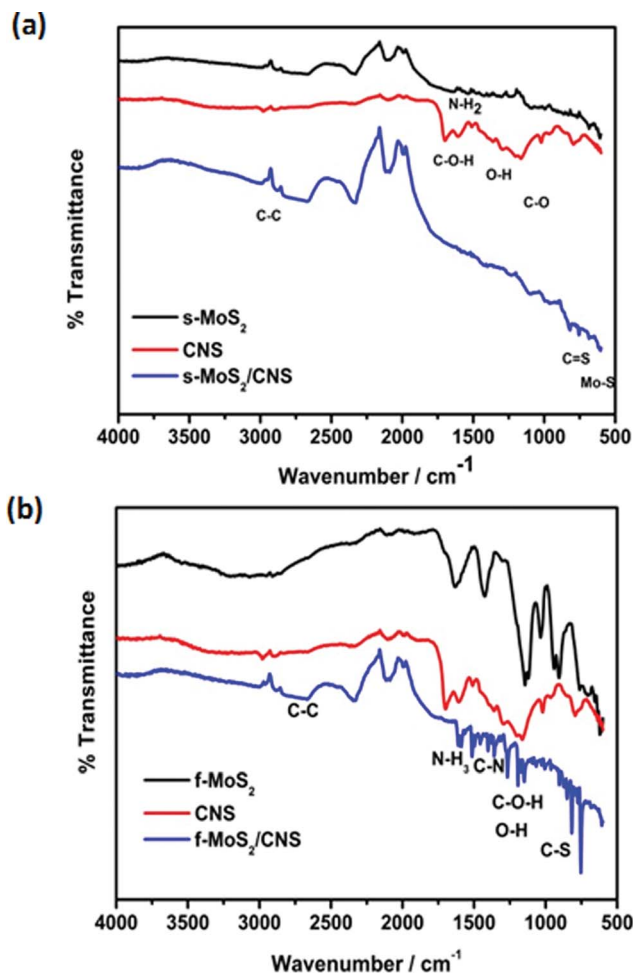


Fig. 5 FT-IR spectra of spherical (a) and flower-like (b) MoS<sub>2</sub>, CNS and MoS<sub>2</sub>/CNS nanocomposites.

enhanced redox processes. The molybdenum spectra (Fig. 6a and c) show the expected Mo 3d<sub>5/2</sub> and Mo 3d<sub>3/2</sub>, including the Mo<sup>6+</sup> species (*ca.*  $236\text{ eV}$ ) usually observed in partially oxidized MoS<sub>2</sub> complexes. In addition to the significant changes in the S 2p of the f-MoS<sub>2</sub>/CNS, its surface atoms, with the exception of O and Na, are lower than observed for the s-MoS<sub>2</sub>/CNS. Considering that surface Na species are involved in the storage mechanism, one may conclude that Na will be more accessible to the f-MoS<sub>2</sub>/CNS in an aqueous solution for enhanced energy storage than the s-MoS<sub>2</sub>/CNS.

### Electrochemical properties

Fig. 7a shows the cyclic voltammetric (CV) evolutions of the individual CNS, s-MoS<sub>2</sub> and f-MoS<sub>2</sub> obtained from the 3-electrode configuration in  $1\text{ M Na}_2\text{SO}_4$  at  $5\text{ mV s}^{-1}$ . These results show that s-MoS<sub>2</sub> is more capacitive than the f-MoS<sub>2</sub> but, as it will be shown later, the capacitance retention of the s-MoS<sub>2</sub> is worse than that of the f-MoS<sub>2</sub>. From Fig. 7a, it is evident that CNS do not show any significant current response. Fig. 7b compares the CVs of the composite materials, showing that the f-MoS<sub>2</sub>/CNS has better performance (high current response and





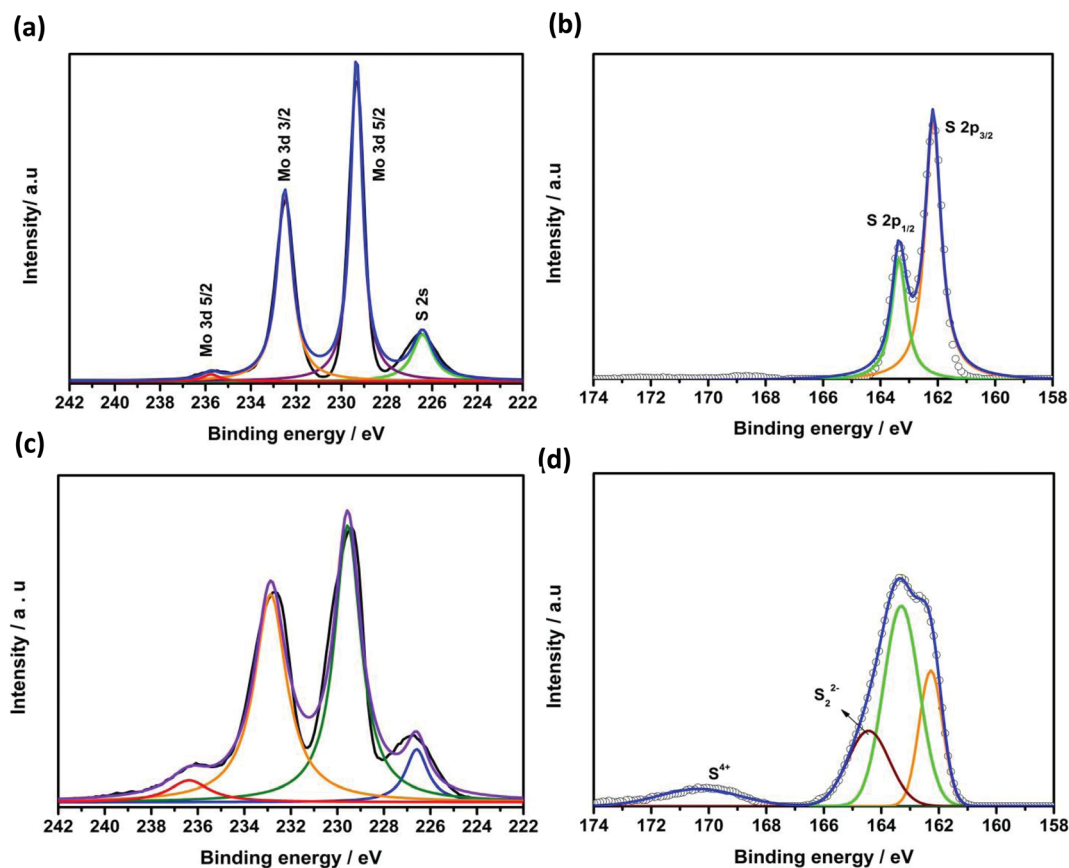


Fig. 6 High resolution XPS analysis of s-MoS<sub>2</sub>/CNS (a and b) and f-MoS<sub>2</sub>/CNS (c and d). Mo 3d (a and c) and S 2p (b and d).

Table 3 XPS data for the s-MoS<sub>2</sub>/CNS and f-MoS<sub>2</sub>/CNS samples

| Sample                  | Binding energy/eV    |                      |                      | Atomic/%, det. limit of 0.1 at% |      |      |      |     |
|-------------------------|----------------------|----------------------|----------------------|---------------------------------|------|------|------|-----|
|                         | Mo 3d <sub>5/2</sub> | Mo 3d <sub>3/2</sub> | Mo 3d <sub>5/2</sub> | Mo 3d                           | S 2p | C 1s | O 1s | Na  |
| s-MoS <sub>2</sub> /CNS | 229.33               | 232.70               | 235.75               | 25.5                            | 31.6 | 29.8 | 12.1 | 1.0 |
| f-MoS <sub>2</sub> /CNS | 229.00               | 232.80               | 236.50               | 22.8                            | 28.4 | 15.8 | 23.1 | 9.9 |

slightly wider voltage window) compared to the s-MoS<sub>2</sub>/CNS. Fig. 7c and d exemplify typical GCPL curves of the various symmetric cells obtained in 1 M Na<sub>2</sub>SO<sub>4</sub> at 0.5 A g<sup>-1</sup>. The performance of the s-MoS<sub>2</sub> is better than its composite, whereas the f-MoS<sub>2</sub>/CNS is better than its precursor f-MoS<sub>2</sub>. As will be shown later, the nanocomposite materials (both spherical and flower-like) show better capacitance retention and cycling stability than their MoS<sub>2</sub> materials. As observed in Fig. 7, the CV and GCPL curves of the composite materials, notably the flower-like materials, show quasi-rectangular shapes, which is a strong deviation from the ideal rectangular shape that was expected from the EDLC. Furthermore, the GCPL of the flower-like composite (Fig. 7d) shows a broad peak at around 0.3 V. These results clearly confirm the pseudocapacitive behavior of these MoS<sub>2</sub>-based composite materials.

Fig. 8 shows the plots of specific capacitance *versus* current densities. With the exception of the s-MoS<sub>2</sub>/CNS-based cell, the

capacitance values of all the cells decrease with increasing gravimetric currents. The capacitance of the s-MoS<sub>2</sub>/CNS-based cell remains essentially the same (*cf.* 108 F g<sup>-1</sup> at 0.1 A g<sup>-1</sup> *versus* 94 F g<sup>-1</sup> at 1 A g<sup>-1</sup>, which is about 13% capacitance loss). This ability of the s-MoS<sub>2</sub>/CNS to maintain high capacitance even at high current density is indicative of high-power performance.

Table 4 compares the values of capacitance, maximum energy and power density of the symmetric cells; unfortunately, there is no related literature with which to compare our results, except for 3-electrode systems. The maximum specific capacitance for the flower-like composite f-MoS<sub>2</sub>/CNS electrodes is 231 F g<sup>-1</sup>, with maximum energy density 26 W h kg<sup>-1</sup> and power density 6443 W kg<sup>-1</sup>. For the sphere-like morphologies, the equivalent values obtained were 108 F g<sup>-1</sup>, 7.4 W h kg<sup>-1</sup> and 3700 W kg<sup>-1</sup>. The inferior performance of the s-MoS<sub>2</sub>/CNS electrodes can be explained by the inaccessible surface area for charge storage in the MoS<sub>2</sub>/CNS composite due to the presence



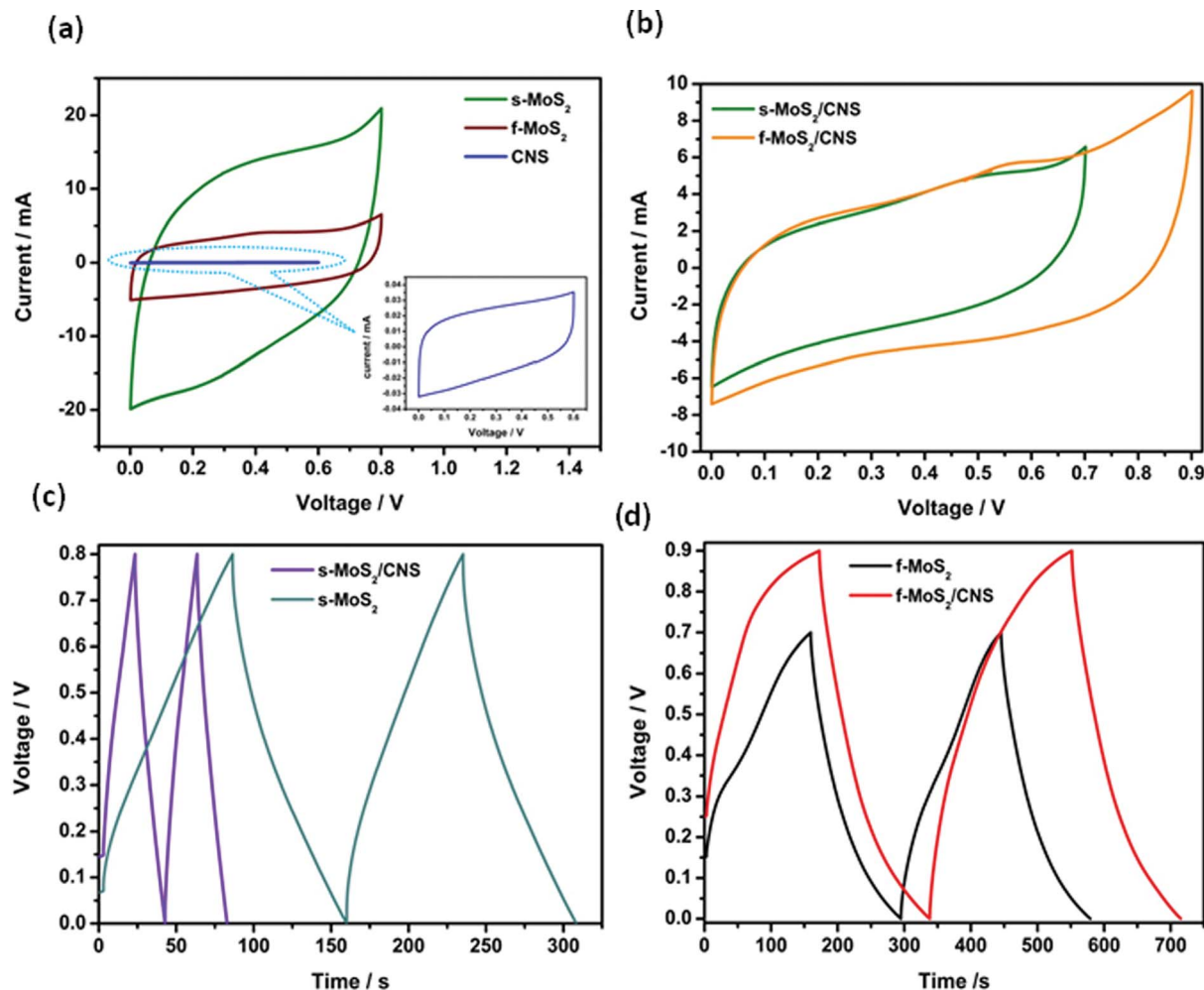


Fig. 7 CV comparison of (a) s-MoS<sub>2</sub>, f-MoS<sub>2</sub> and CNS; (b) s-MoS<sub>2</sub>/CNS and f-MoS<sub>2</sub>/CNS. GCD comparison of (c) s-MoS<sub>2</sub>/CNS and s-MoS<sub>2</sub>, and (d) f-MoS<sub>2</sub>/CNS and f-MoS<sub>2</sub>. Conditions: CVs obtained at 5 mV s<sup>-1</sup>, while the GCD was obtained at 0.5 A g<sup>-1</sup>; all data were acquired in 1 M Na<sub>2</sub>SO<sub>4</sub>.

of CNS, as shown by the Raman spectroscopic data. The maximum energy density achievable with f-MoS<sub>2</sub>/CNS (26 W h kg<sup>-1</sup>) is more than twice that of MoS<sub>2</sub> (10 W h kg<sup>-1</sup>) alone. The high energy density is owed to the favorable porous nanostructure of the composite, in which MoS<sub>2</sub> sheets serve as active sites for redox reactions, coupled with CNS interaction with electrolyte and the synergistic effects of MoS<sub>2</sub>/CNS composites.

In theory, the specific capacitance of the MoS<sub>2</sub> may be estimated from the amount of power needed to carry out the electrolysis of 1 mol of active material (*i.e.*, 1 F = 96 485 C) and the molar mass of the material (MoS<sub>2</sub> = 160.07 g mol<sup>-1</sup>) using the eqn (8):<sup>31</sup>

$$F = \frac{Q}{U} \quad (8)$$

where  $U$  is the voltage window and  $Q$  is electrical energy per 1 gram. Because our  $U$  ranges between 0.8 and 1 V, the theoretical pseudocapacitance is between 603 and 754 F g<sup>-1</sup>. If we consider that the supercapacitance of a 3-electrode cell is about a quarter that of a 2-electrode system, our value for the f-MoS<sub>2</sub>/CNS based

symmetric pseudocapacitor (231 F g<sup>-1</sup>) is in good agreement with theory.

Voltage-holding cycling experiments, complemented with EIS experiments, were performed to provide insight into the cycling stability of the four symmetric cells. The zeroth hour cycling capacitance (brown data points in Fig. 9 and 10) for each of the four symmetric cells was found to be lower than that at the 10<sup>th</sup> hour cycling, which suggests that MoS<sub>2</sub>-based cells require a significant amount of time to equilibrate prior to recording data from voltage-holding tests. Thus, the best voltage-holding test data were obtained from the 10<sup>th</sup> hour. Fig. 9 exemplifies the typical voltage-holding test performed at 0.7 A g<sup>-1</sup> for the spherical morphology. At the 10<sup>th</sup> hour, the s-MoS<sub>2</sub> started with about 140 F g<sup>-1</sup> and obtained 20 F g<sup>-1</sup> at the end of the 50<sup>th</sup> hour (Fig. 9a), which is about 86% loss of capacitance. The composite s-MoS<sub>2</sub>/CNS started with about 90 F g<sup>-1</sup>, but maintained 55 F g<sup>-1</sup> at the end of the 50<sup>th</sup> hour (Fig. 9c), which is about 39% loss of capacitance. The fitted EIS data for both the s-MoS<sub>2</sub> (Fig. 9b) and its composite form (s-MoS<sub>2</sub>/CNS, Fig. 9d) obtained before and after the 50 hour long-cycling



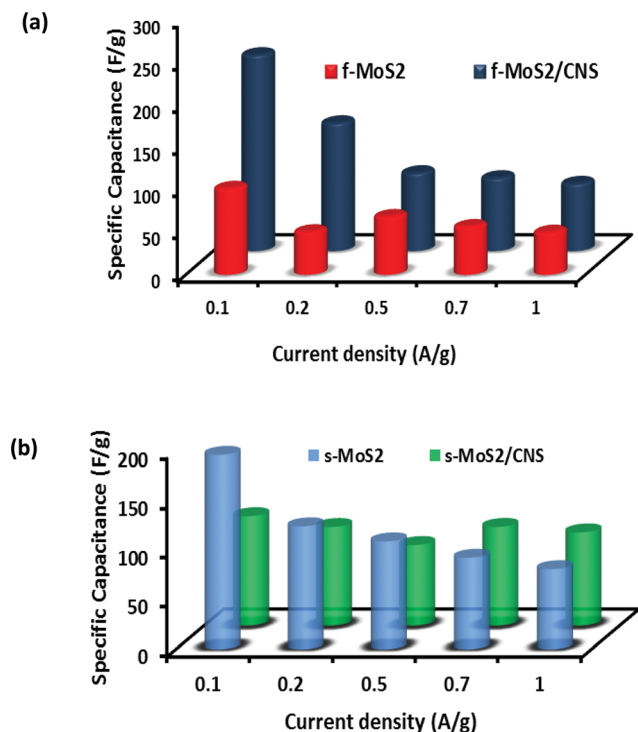


Fig. 8 GCPL results for specific capacitance at various current densities of spherical and flower-like MoS<sub>2</sub> and MoS<sub>2</sub>/CNS.

experiments are summarized in Table 5. For the flower-like materials (Fig. 10), the capacitance of the f-MoS<sub>2</sub> at the 10<sup>th</sup> hour was about 24 F g<sup>-1</sup> and obtained 14 F g<sup>-1</sup> at the end of the 50<sup>th</sup> hour (Fig. 10a), which is about 42% loss of capacitance. The composite f-MoS<sub>2</sub>/CNS started with about 90 F g<sup>-1</sup>, but maintained 84 F g<sup>-1</sup> at the end of the 50<sup>th</sup> hour (Fig. 10c), which is a mere 6% loss of capacity. The fitted EIS data for both the f-MoS<sub>2</sub> (Fig. 10b) and its composite form (f-MoS<sub>2</sub>/CNS, Fig. 10d), obtained before and after the 50 hour long-cycling experiments are summarized in Table 6.

From the results of the cycling performances of the spherical (Fig. 9) and flower-like (Fig. 10) materials, the following important findings should be emphasized. First, the zeroth hour cycling capacitance for each of the cells was found to be lower than that at the 10<sup>th</sup> hour cycling, which suggests that MoS<sub>2</sub>-based cells or related layered materials require a significant amount of time to equilibrate prior to recording data from voltage-holding tests. Second, the cycling stability for MoS<sub>2</sub> is very poor, but can be greatly improved by integrating it with conductive carbon materials such as the CNS. Third, the cycling stability of the cells from the MoS<sub>2</sub> or its carbon composite is strictly dependent on its morphology; the flower-like morphology shows enhanced electrochemistry compared to the spherical morphology.

Finally, to obtain some insight into the capacitive properties of the cells, we were able to satisfactorily fit the raw EIS data with the electrical equivalent circuit (EEC). The EEC consists of Voigt RC elements (Fig. 9e), involving series resistance ( $R_s$ ), charge-transfer resistance ( $R_{ct}$ ) and constant-phase elements (CPE or  $Q$ ). For the cell with the spherical morphology (Table 5), the  $R_s$  values of the s-MoS<sub>2</sub> before and after the 50<sup>th</sup> hour were 0.23 and 0.49  $\Omega$ , respectively. For the s-MoS<sub>2</sub>/CNS, the  $R_s$  values before and after the 50<sup>th</sup> hour were 0.33 and 1.14  $\Omega$ , respectively. The combined  $R_{ct}$  values before and after the 50<sup>th</sup> hour were 16.26 and 17.28  $\Omega$ , respectively. For the s-MoS<sub>2</sub>/CNS it was 2.45  $\Omega$  before and 4.62  $\Omega$  after the 50<sup>th</sup> hour cycling. The result clearly proves that the presence of the CNS enhanced the conductivity of the s-MoS<sub>2</sub>-based cells. However, the data for the cells fabricated from the flower-like morphology (Table 6), the  $R_s$  values of the f-MoS<sub>2</sub> before and after the 50<sup>th</sup> hour, were 0.21 and 0.40  $\Omega$ , respectively. For the f-MoS<sub>2</sub>/CNS, the  $R_s$  values before and after the 50<sup>th</sup> hour were 0.26 and 0.31  $\Omega$ , respectively. The combined  $R_{ct}$  values for the f-MoS<sub>2</sub> before and after the 50<sup>th</sup> hour were 3.43 and 4.14  $\Omega$ , respectively. For the f-MoS<sub>2</sub>/CNS, it was 3.37 before and 5.09  $\Omega$  after the 50<sup>th</sup> hour cycling. Like the s-MoS<sub>2</sub>-based cells, the results for the f-MoS<sub>2</sub>-based cells suggest that the CNS component serves to decrease the internal resistance of the f-MoS<sub>2</sub>, thereby improving the conductivity and

Table 4 Comparison of the capacitive performance of various MoS<sub>2</sub>-based supercapacitors<sup>a</sup>

| Aqueous electrolyte                 | Electrode material                   | Device configuration | Voltage (V) | $C_{sp}/F\ g^{-1}$ | $E_{sp}/W\ h\ kg^{-1}$ | $P_{max}/W\ kg^{-1}$ | Ref.      |
|-------------------------------------|--------------------------------------|----------------------|-------------|--------------------|------------------------|----------------------|-----------|
| 1 M Na <sub>2</sub> SO <sub>4</sub> | f-MoS <sub>2</sub> /CNS              | Symmetric            | 0.9         | 231                | 26                     | 6443                 | This work |
| 1 M Na <sub>2</sub> SO <sub>4</sub> | s-MoS <sub>2</sub> /CNS              | Symmetric            | 0.7         | 108                | 7.4                    | 3700                 | This work |
| 1 M Na <sub>2</sub> SO <sub>4</sub> | s-MoS <sub>2</sub>                   | Symmetric            | 1.0         | 195                | 27                     | 8750                 | This work |
| 1 M Na <sub>2</sub> SO <sub>4</sub> | f-MoS <sub>2</sub>                   | Symmetric            | 0.8         | 96                 | 8.59                   | 4000                 | This work |
| 1 M Na <sub>2</sub> SO <sub>4</sub> | MoS <sub>2</sub>                     | 3-Electrode          | 0.7         | 92.85              | 7.25                   | 186.5                | 14        |
| 1 M H <sub>2</sub> SO <sub>4</sub>  | PANI/MoS <sub>2</sub>                | 3-Electrode          | 1.0         | 575                | 265                    | 18 000               | 2         |
| 1 M KCl                             | PPy/MoS <sub>2</sub>                 | 3-Electrode          | 0.8         | 553.7              | 49                     | 400                  | 8         |
| 1 M Na <sub>2</sub> SO <sub>4</sub> | MoS <sub>2</sub> -graphene composite | 3-Electrode          | 1.0         | 243                | 85                     | 7600                 | 6         |
| 1 M Na <sub>2</sub> SO <sub>4</sub> | MoS <sub>2</sub> /RGO                | 3-Electrode          | 0.6         | 253                | 12.65                  | 300                  | 10        |
| 1 M Na <sub>2</sub> SO <sub>4</sub> | MoS <sub>2</sub> /MWCNT              | 3-Electrode          | 1.0         | 452.7              | —                      | —                    | 12        |
| 3 M KOH                             | Porous tubular C/MoS <sub>2</sub>    | 3-Electrode          | 0.5         | 210                | —                      | —                    | 14        |

<sup>a</sup> Key: PANI = polyamine; PPy = polypyrrole; RGO = reduced graphene oxide; MWCNT = multi-walled carbon nanotubes.





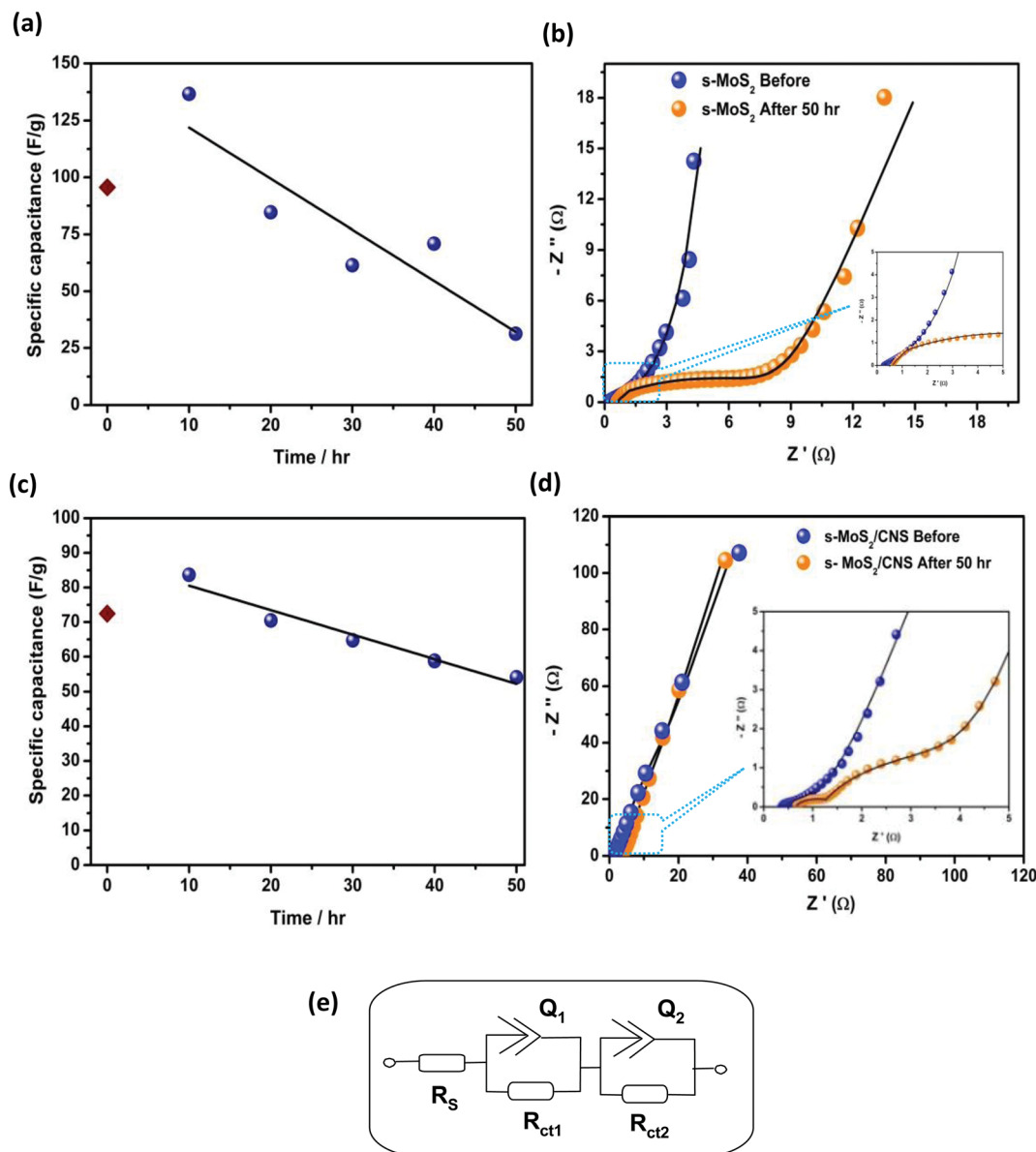


Fig. 9 Typical GCPL plots at  $0.7 \text{ A g}^{-1}$  (a and c) and Nyquist plots (b and d) obtained before and after 50 hour voltage experiments for the spherical (a and b)  $\text{MoS}_2$  and  $\text{MoS}_2/\text{CNS}$ -based (c and d) symmetric pseudocapacitors. The electrical equivalent circuit used in fitting the Nyquist plots is shown in (e).

capacitance of the  $\text{f-MoS}_2/\text{CNS}$ -based symmetric pseudocapacitor. The impedance of the CPE ( $Z_{\text{CPE}}$ ) is related to the frequency-independent constant ( $Q$ ) and radial frequency ( $\omega$ ) according to the eqn (9):<sup>32</sup>

$$Z_{\text{CPE}} = \frac{1}{[Q(j\omega)^n]} \quad (9)$$

where  $n$  (with values in the  $-1 \leq n \leq 1$  range) is obtained from the slope of  $\log Z$  versus  $\log f$ . When  $n = 0, 1, -1$  or  $0.5$ , the CPE describes a pure resistor, a pure capacitor, an inductor, or Warburg impedance ( $Z_w$ ), respectively, due to the diffusion of the ions. For all the cells, the  $n$  values observed for these electrodes are generally greater than  $0.5$ , which confirms the pseudocapacitive properties of the  $\text{MoS}_2$ -based symmetric cells, corroborating the CV data in Fig. 7a and b.

The data for the Bode plots (see ESI, Fig. S3†) summarised in Tables 5 and 6 show that the phase angle for each of the systems before and after 50 hour cycling was greater than  $-75^\circ$ , but lower than the  $-90^\circ$  expected of an ideal EDLC system. The phase angle result is a further confirmation of the pseudocapacitive behaviour of these  $\text{MoS}_2$ -based systems. In addition, the knee frequency ( $f_o$ ,  $\phi = 45^\circ$ ), which is the maximum frequency at which the dominant behaviour of the supercapacitor (power density), can be observed. The knee frequency relates to the rate or power capability of the supercapacitor; the higher the  $f_o$  value is, the more rapidly such a supercapacitor can be charged and discharged. The  $f_o$  values for the  $\text{s-MoS}_2/\text{CNS}$  are  $50 \text{ Hz}$  (time constant =  $0.02 \text{ s}$ ) before cycling and  $5 \text{ Hz}$  (time constant =  $0.2 \text{ s}$ ) after the 50<sup>th</sup> hour voltage-holding testing. However, for the  $\text{f-MoS}_2/\text{CNS}$  system, the  $f_o$  value



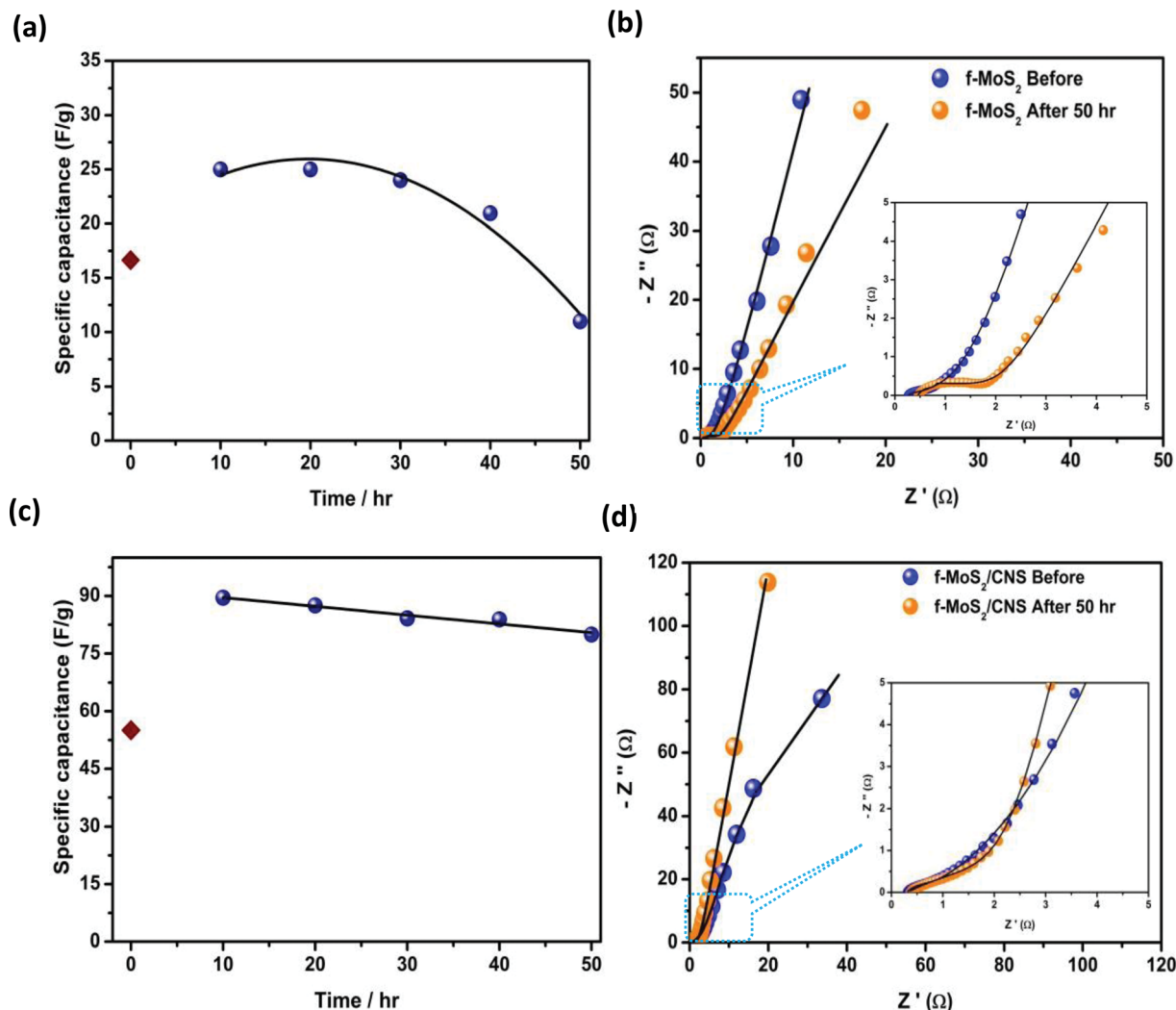


Fig. 10 Typical GCPL plots at  $1 \text{ A g}^{-1}$  for f-MoS<sub>2</sub> (a) and  $1.5 \text{ A g}^{-1}$  for f-MoS<sub>2</sub>/CNS (c); Nyquist plots for f-MoS<sub>2</sub> (b) and f-MoS<sub>2</sub>/CNS (d) obtained before and after 50 hour voltage experiments. The electrical equivalent circuit used in fitting the Nyquist plots is shown in Fig. 9e.

Table 5 Cycling performance of the spherical MoS<sub>2</sub> and MoS<sub>2</sub>/CNS based symmetric pseudocapacitors in  $1 \text{ M Na}_2\text{SO}_4$ . EIS data before and after 50 h voltage-holding experiments were fitted with the Voigt equivalent circuit

| Parameter                     | s-MoS <sub>2</sub> /s-MoS <sub>2</sub> |                             | s-MoS <sub>2</sub> /CNS/s-MoS <sub>2</sub> /CNS |                             |
|-------------------------------|--|-----------------------------|---|-----------------------------|
|                               | 0 <sup>th</sup> hour cycle             | 50 <sup>th</sup> hour cycle | 0 <sup>th</sup> hour cycle                      | 50 <sup>th</sup> hour cycle |
| $R_s/\Omega$                  | $0.23 \pm 0.05$                        | $0.49 \pm 0.06$             | $0.33 \pm 0.19$                                 | $1.14 \pm 0.87$             |
| $Q_1/\text{mF s}(\alpha - 1)$ | $0.33 \pm 0.08$                        | $0.47 \pm 0.03$             | $0.2 \pm 0.03$                                  | $2.21 \pm 0.11$             |
| $n_1$                         | $0.40 \pm 0.09$                        | $0.77 \pm 0.15$             | $0.82 \pm 0.17$                                 | $0.64 \pm 0.18$             |
| $R_{ct1}/\Omega$              | $3.75 \pm 0.42$                        | $10.08 \pm 2.7$             | $0.72 \pm 0.21$                                 | $1.39 \pm 0.13$             |
| $Q_2/\text{mF s}(\alpha - 1)$ | $8.10 \pm 0.34$                        | $8.70 \pm 0.02$             | $13.32 \pm 1.32$                                | $9.38 \pm 0.02$             |
| $n_2$                         | $0.80 \pm 0.25$                        | $0.80 \pm 0.22$             | $0.47 \pm 0.29$                                 | $0.83 \pm 0.17$             |
| $R_{ct2}/\Omega$              | $12.51 \pm 0.07$                       | $7.20 \pm 1.95$             | $1.73 \pm 0.55$                                 | $3.23 \pm 0.29$             |
| Phase angle                   | $-73^\circ$                            | $-53^\circ$                 | $-80^\circ$                                     | $-80^\circ$                 |
| Knee frequency                | 1 Hz                                   | 1 Hz                        | 50 Hz   | 5 Hz                        |

remained at 50 Hz before and after the voltage-holding test, which is a further confirmation of the high electrochemical cycling stability of the f-MoS<sub>2</sub>/CNS system.

The energy-storage mechanism of MoS<sub>2</sub> in aqueous supercapacitors is well described in the literature;<sup>29,31</sup> it is the combined phenomena involving the transition from EDLC to



**Table 6** Cycling performance of the flower-like MoS<sub>2</sub> and MoS<sub>2</sub>/CNS based symmetric pseudocapacitors in 1 M Na<sub>2</sub>SO<sub>4</sub>. EIS data before and after 50 h voltage-holding experiments were fitted with the Voigt equivalent circuit

| Parameter                     | f-MoS <sub>2</sub> /f-MoS <sub>2</sub> |                             | f-MoS <sub>2</sub> /CNS/f-MoS <sub>2</sub> /CNS |                             |
|-------------------------------|--|-----------------------------|---|-----------------------------|
|                               | 0 <sup>th</sup> hour cycle             | 50 <sup>th</sup> hour cycle | 0 <sup>th</sup> hour cycle                      | 50 <sup>th</sup> hour cycle |
| $R_s/\Omega$                  | 0.21 ± 0.102                           | 0.4 ± 0.1                   | 0.26 ± 0.08                                     | 0.31 ± 0.17                 |
| $Q_1/\text{mF s}(\alpha - 1)$ | 0.2 ± 0.14                             | 0.16 ± 0.03                 | 0.12 ± 0.07                                     | 0.17 ± 0.02                 |
| $n_1$                         | 0.67 ± 0.19                            | 0.73 ± 0.1                  | 0.84 ± 0.14                                     | 0.90 ± 0.13                 |
| $R_{ct1}/\Omega$              | 1.70 ± 0.62                            | 1.57 ± 0.16                 | 0.32 ± 0.13                                     | 1.28 ± 0.74                 |
| $Q_2/\text{mF s}(\alpha - 1)$ | 21.12 ± 0.07                           | 9.4 ± 0.08                  | 12.24 ± 0.68                                    | 9.64 ± 0.36                 |
| $n_2$                         | 0.85 ± 0.15                            | 0.62 ± 0.13                 | 0.68 ± 0.21                                     | 0.47 ± 0.29                 |
| $R_{ct2}/\Omega$              | 1.73 ± 0.18                            | 2.57 ± 1.24                 | 3.05 ± 0.18                                     | 3.81 ± 0.41                 |
| Phase angle                   | −78°                                   | −70°                        | −75°  | −80°                        |
| Knee frequency                | 10 Hz                                  | 10 Hz                       | 50 Hz   | 50 Hz                       |

the pseudocapacitive process (faradaic/redox process) and increased active surface area due to possible exfoliation. First, there is the accumulation of ions at the double layer interface between the MoS<sub>2</sub> flakes and the electrolyte. This is subsequently accompanied by a redox process: upon charging (reduction), the alkali metal ions in the electrolyte (Na<sup>+</sup>) adsorb onto the surface and intercalate between the MoS<sub>2</sub> layers, followed by deintercalation upon discharging (oxidation), as shown in eqn (10).



The repeating intercalation–deintercalation process of the sodium ions over several cycles leads to partial exfoliation of the MoS<sub>2</sub> layers, resulting in an increased surface area and enhanced specific capacitance. The evidence for the possible partial exfoliation of the MoS<sub>2</sub> during the repeated intercalation–deintercalation process of electrolyte ions can be observed from the zeroth hour cycling capacitance (brown data points in Fig. 9 and 10 described above), which was lower than the 10<sup>th</sup> hour cycling before stabilizing.

## Conclusions

Two variants of carbon nanosphere-modified molybdenum disulphide (MoS<sub>2</sub>/CNS) nanostructures were successfully synthesized by a simple one-pot hydrothermal method. The two different synthetic methods obtained two different morphologies: flower-like (f-MoS<sub>2</sub>/CNS) and spherical (s-MoS<sub>2</sub>/CNS) morphologies. The physical and chemical characterisations reveal that the two materials were properly integrated into the CNS surface. The addition of CNS impedes the growth of the s-MoS<sub>2</sub> crystals in the composite, but enhances the growth of the f-MoS<sub>2</sub>, particularly in the (002) plane of hexagonal MoS<sub>2</sub>. The f-MoS<sub>2</sub>/CNS shows lattice expansion and large surface area, whereas the s-MoS<sub>2</sub>/CNS shows lattice contraction and smaller surface area. The presence of CNS on the MoS<sub>2</sub> structure leads to slight softening of the characteristic Raman bands (E<sub>2g</sub><sup>1</sup> and A<sub>1g</sub> modes) with larger FWHM. The electrochemical capacitive behaviour of the MoS<sub>2</sub>-based materials was evaluated in symmetric cells. The electrochemical performance of the

composites demonstrates that the MoS<sub>2</sub>/CNS composite from flower-like MoS<sub>2</sub> exhibits better capacitance, energy and power densities (231 F g<sup>−1</sup>, 26 W h kg<sup>−1</sup> and 6443 W kg<sup>−1</sup>) compared to the spherical morphology (108 F g<sup>−1</sup>, 7.4 W h kg<sup>−1</sup> and 3700 W kg<sup>−1</sup>). CNS play a vital role in improving the electrochemical properties of the MoS<sub>2</sub>-based electrode materials, especially with respect to improving the capacitance retention (*i.e.*, stable electrochemical cycling). The excellent electrochemical performance of MoS<sub>2</sub>/CNS was accredited to the morphology of the composite and synergistic effects between MoS<sub>2</sub> sheets and CNS. These findings show great promise for future studies of MoS<sub>2</sub> modified with other conducting carbon nanostructures for the development of high-performance electrochemical energy storage systems.

## Acknowledgements

This study was supported by the University of the Witwatersrand (Wits) and CSIR, South Africa. The support of the Wits Materials for Energy Research Group (MERG) towards this research is gratefully acknowledged. Opinions expressed and conclusions arrived at are those of the authors and are not necessarily to be attributed to MERG. TNY Khawula thanks MERG for postgraduate bursary. K. Raju thanks the CSIR for postdoctoral fellowships. CSIR is a partner in the CREATE-Network project being funded by the European Commission under the Marie Skłodowska-Curie Actions Research and Innovation Staff Exchange (RISE).

## References

- 1 B. E. Conway, *Electrochemical Supercapacitors, Scientific Fundamentals and Technological Applications*, Kluwer Academic/Plenum Publishers, New York, 1999.
- 2 K. J. Huang, L. Wang, Y. J. Liu, H. B. Wang, Y. M. Liu and L. L. Wang, *Electrochim. Acta*, 2013, **109**, 587.
- 3 G. Wang, L. Zhang and J. Zhang, *Chem. Soc. Rev.*, 2012, **41**, 797.
- 4 G. A. Snook, P. Kao and A. S. Best, *J. Power Sources*, 2011, **196**, 1.





- 5 J. M. Miller, *Energy storage technology markets and applications: Ultracapacitors in combination with lithium-ion*, IEEE XploreDOI: 10.1109/ICPE.2007.4692343: 7th International Conference on Power Electronics, April 2007.
- 6 Mazda 'i-ELOOP' Capacitor-Based Brake Energy Regeneration System, <http://www.mazda.com/publicity/release/2011/201111/111125a.html>.
- 7 K. J. Huang, L. Wang, Y. J. Liu, H. B. Wang, Y. M. Liu and L. L. Wang, *Int. J. Hydrogen Energy*, 2013, **38**, 14027.
- 8 S. Wang, C. An and J. Yuan, *Materials*, 2010, **3**, 401.
- 9 G. Ma, H. Peng, J. Mu, H. Huang, X. Z. Zhou and Z. Lei, *J. Power Sources*, 2013, **229**, 72.
- 10 M. Mandal, D. Ghosh, S. S. Kalra and C. K. Das, *Recent Res. Sci. Technol.*, 2014, **3**, 65.
- 11 K. Changa and W. Chen, *Chem. Commun.*, 2011, **47**, 4252.
- 12 K. J. Huang, L. Wang, J. Z. Zhang, L. L. Wang and Y. P. Mo, *Energy*, 2014, **67**, 234.
- 13 J. M. Soon and K. P. Loh, *Electrochem. Solid-State Lett.*, 2007, **10**, A250.
- 14 B. Hu, X. Qin, A. M. Asiri, K. A. Alamry, A. O. Al-Youbi and X. Sun, *Electrochim. Acta*, 2013, **100**, 24.
- 15 K. K. Moorthy, G. K. V. Subramani, S. R. Krishnan and S. J. Kim, *Mater. Res. Bull.*, 2014, **50**, 499.
- 16 A. N. Márquez, R. Romero, A. Romero and J. L. Valverde, *J. Mater. Chem.*, 2011, **21**, 1664.
- 17 T. Jiang, W. Pan, J. Wang, X. Bie, F. Du, Y. Wei, C. Wang and G. Chen, *Electrochim. Acta*, 2010, **55**, 3864.
- 18 K. J. Huang, L. Wang, J. Li and Y. M. Liu, *Sens. Actuators, B*, 2013, **178**, 671.
- 19 S. Wang, G. Li, G. Du, X. Jiang, C. Feng, Z. Guo and S. J. Kim, *Chinese J. Chem. Eng.*, 2010, **18**, 910.
- 20 M. W. Dlamini, D. O. Kumi, T. N. Phaahlamohlaka, A. S. Lyadov, D. G. Billing, L. L. Jewell and N. J. Coville, *ChemCatChem*, 2015, **7**, 3000.
- 21 F. Béguin, V. Presser, A. Balducci and E. Frackowiak, *Adv. Mater.*, 2014, **26**, 2219.
- 22 K. Makgopa, P. M. Ejikeme, C. J. Jafta, K. Raju, M. Zeiger, V. Presser and K. I. Ozoemena, *J. Mater. Chem. A*, 2015, **3**, 3480.
- 23 C. Wang, W. Wan, Y. Huang, J. Chen, H. H. Zhou and X. X. Zhang, *Nanoscale*, 2014, **6**, 5351.
- 24 H. Li, Q. Zhang, C. C. Ray Yap, B. K. Tay, T. H. Tong Edwin, A. Olivier and D. Baillargeat, *Adv. Funct. Mater.*, 2012, **22**, 1385.
- 25 G. L. Frey, R. Tenne, M. J. Matthews, M. S. Dresselhaus and G. Dresselhaus, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 1999, **60**, 2883.
- 26 C. Lee, H. Yan, L. E. Brus, T. F. Heinz, J. Hone and S. Ryu, *ACS Nano*, 2010, **4**, 2695.
- 27 A. N. Mohan and B. Manoj, *Int. J. Electrochem. Sci.*, 2012, **7**, 9537.
- 28 M. Acerce, D. Voiry and M. Chhowalla, *Nat. Nanotechnol.*, 2015, **10**, 313.
- 29 M. A. Bissett, I. A. Kinloch and R. A. W. Dryfe, *ACS Appl. Mater. Interfaces*, 2015, **7**, 17388–17398.
- 30 D. Voiry, A. Goswami, R. Kappera, C. C. C. Silva, D. Kaplan, T. Fujita, M. Chen, T. Asefa and M. Chhowalla, *Nat. Chem.*, 2015, **7**, 45–49.
- 31 C. Peng, D. Hu and G. Z. Chen, *Chem. Commun.*, 2011, **47**, 4105.
- 32 J. B. Jorcin, M. E. Orazem, N. Pébère and B. Tribollet, *Electrochim. Acta*, 2006, **51**, 1473.

