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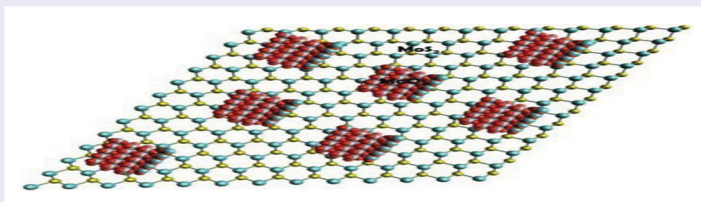
Tiny MoO_3 nanocrystals self-assembled on folded molybdenum disulfide nanosheets via a hydrothermal method for supercapacitor

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ABSTRACT

Coupling of two active semiconductors can easily lead to a deterioration of their intrinsic properties. In this work, tiny MoO_3 nanocrystals were deposited on 3D MoS_2 frameworks via a hydrothermal reaction, with heterostructures forming by oxygen-bonding interactions at their interface. When tested as a supercapacitor electrode, the $\text{MoS}_2/\text{MoO}_3$ heterostructure exhibited a high specific capacitance of 287.7 F g^{-1} at a current density of 1 A g^{-1} , and a remarkable cycling stability after 1000 cycles at 1 A g^{-1} in an aqueous solution compared to pristine MoS_2 . The results thus reveal the superior properties of the $\text{MoS}_2/\text{MoO}_3$ heterostructure for supercapacitor electrode.



IMPACT STATEMENT

We successfully synthesized tiny MoO_3 nanocrystals deposited on 3D MoS_2 frameworks via a self-assembly. The $\text{MoS}_2/\text{MoO}_3$ heterostructure exhibited a high specific capacitance and cycling stability compared to pristine MoS_2 .

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KEYWORDS

Heterojunction; layered materials; supercapacitor; MoS_2

1. Introduction

Supercapacitors that can realize the conversion of chemical energy are currently predominantly used in power supplies with an extensive range of applications. Studies on the design and development of supercapacitor electrode materials have shown their great promise in providing significant improvements in practical applications. To meet the requirements of energy storage applications based on the electrochemical performance of electrodes, a vigorous pursuit of active materials with long-term cyclic stability is necessary [1–3]. Because exposed edge sites show excellent electrochemical performance, the use of two-dimensional (2D) layered MoS_2 as an electrode material has recently gained significant attention. Numerous studies have demonstrated that

MoS_2 materials on various structures exhibit superior electrochemical performance for supercapacitor applications [4,5]. The structure of MoS_2 is analogous to graphite in which one layer of Mo atoms is sandwiched by two layers of S atoms forming a three-atom layer. These layers are stacked together by weak van der Waal forces of attractions. The interlayer spacings of these stacked layers play an important role in determining the thermal and electrical conductivities of the MoS_2 . The improved spacings in between the MoS_2 sheets significantly reduce the energy barrier required for the intercalation and transportation of ions (enhanced redox reactions) and thus improve the supercapacitor performance. Hence, many researchers across the globe are working on improving the interlayer spacings of the MoS_2 layers

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by intercalating the metal ions or introducing the metal oxide species. In addition, enhancing the active edge sites and conductivity of MoS₂ simultaneously with a single component remains a challenging task. In this respect, the development of heterostructures by coupling MoS₂ with other semiconductor materials, including graphene [6], graphitic carbon nitride [7], CoS₂ [8], MoO₃ [9], VS₂ [10], and MoO₂ [11], has been undertaken to ameliorate the poor conductivity of MoS₂ and improve the specific capacitance and long-term stability. Hunag et al. [6] developed a layered MoS₂/graphene nanocomposite via a modified L-cysteine-assisted solution phase method. The as-synthesized MoS₂/graphene nanocomposite electrode material demonstrated a maximum specific capacitance of 243 F g⁻¹ at a discharge current density of 1 A g⁻¹. Ansari et al. [7] reported the use of a mechanochemically synthesized MoS₂-g-C₃N₄ heterostructure as an electrode material for supercapacitors, which delivered a higher specific capacitance of 240.85 F g⁻¹ than that of pristine g-C₃N₄ (48.77 F g⁻¹) at a current density of 1 A g⁻¹. Wang et al. [8] reported the hydrothermally synthesized MoS₂/CoS₂ nanotube electrode that exhibited an excellent areal capacitance of 142.5 mF cm⁻² at 1 mA cm⁻² with a good cyclic stability. Zhou et al. [9] demonstrated the oxygen-incorporated MoS₂ nanosheets with rich defects that exhibited a superior specific capacitance of 145 F g⁻¹ at a current density of 0.5 A g⁻¹. Nonetheless, there is still room for enhancement of the electrochemical activity of MoS₂ by coupling with other materials.

Molybdenum trioxide (MoO₃) is a class of widely used energy storage materials because of their remarkable specific theoretical capacitance, good electrochemical properties, simple, low cost and controllable preparation [12]. But, their low conductivity inhibits to use in many fields [13]. For instance, MoO₃ is regarded to be a promising candidate for energy storage and has been extensively studied in recent years [12–14]. However, MoO₃ electrode has few disadvantages including (i) sluggish faradic redox kinetics, (ii) fast degradation of cycling performance, and (iii) low volumetric capacitance, due to its poor intrinsic conductivity (10⁻⁵ S cm⁻¹) [14]. Several methods have been applied to increase the overall performance of MoO₃ including, coupling of MoO₃ with other materials or ion-intercalation or oxygen and nitrogen doping, etc. [11,15,16].

Zhang et al. [11] demonstrated hydrothermally synthesized Molybdenum oxide–MoS₂ electrodes that exhibited a high specific capacitance of 433.3 F g⁻¹ at a scan rate of 5 mV s⁻¹. More recently, Li et al. [15] synthesized an α -MoO₃@MoS₂ heterojunction via a two-step hydrothermal method for photocatalytic applications. The MoO₃@MoS₂ heterojunction contributed to

the effective separation of photoinduced carriers. Impressively, a MoS₂–MoO₃ hybrid nanostructure was developed by Yin et al. [16] and used for light-emitting diode applications. Although a lot of studies have attributed their superior supercapacitor properties of MoO₃ based hybrids to the good interfacial interaction, complete analysis of the interface is still rare until now. Therefore, we attempted to apply a MoS₂/MoO₃ heterostructure as an electrode material for a supercapacitor.

In this study, we synthesized self-assembled MoO₃ nanocrystals on three-dimensional (3D) MoS₂ nanosheets, defined as a MoS₂/MoO₃ heterostructure, which were obtained from the introduction of MoO₃ precursor oxygen bonding on MoS₂ nanosheets via a hydrothermal reaction. This kind of architecture facilitates a strategy for simultaneously enhancing the density of active edge sites and the electron transfer pathway. Moreover, the MoO₃ nanoparticles on the surface of MoS₂ layers prohibit the stacking of MoS₂ nanosheets which contribute to improved supercapacitor performance. The experimental results demonstrate that the MoS₂/MoO₃ heterostructure has a superior specific capacitance compared to that of pristine MoS₂ in an alkaline solution. Furthermore, an examination of the long-term stability shows that this heterostructure design is very stable, even after 1000 cycles. More importantly, this study illustrates a facile approach to synthesizing low-cost and highly efficient electrode materials for energy storage devices.

2. Experimental details

2.1. Synthesis of MoS₂/MoO₃

A modified procedure for synthesizing molybdenum disulfide (MoS₂) was followed as reported in our previous studies [17]. Typically, 0.14 mmol of (NH₄)₆Mo₇O₂₄·4H₂O was added to 25 mL ethanol in a glass beaker. After stirring for 10 min, C₄H₄S (15 mL) was added drop by drop and immediately added HCl (2 mL) to above solution and maintained at 90°C with continuous stirring for 15 min. Then, the resultant solution was transferred into a Teflon-lined autoclave, placed inside a furnace, and maintained at 190°C for 8 h. After the nature cooling of autoclave, the products were collected using a centrifuge at 5000 rpm and washed three times with ethanol. Finally, the precipitates were heated in a vacuum oven at 110°C for 3 h.

A MoS₂/MoO₃ heterostructure was synthesized via a simple hydrothermal reaction. In a typical procedure, 20 mL of an MoS₂ (6 mg mL⁻¹) solution in ethanol containing certain amount of sodium molybdate dihydrate was isolated evenly with a magnetic stirrer for 30 min

to obtain a suspension. The resulting solution was transferred into a Teflon-lined autoclave and maintained at 190°C for 15 h. Once the autoclave naturally cooled to room temperature, the precipitates were collected via centrifugation at 7000 rpm and washed with deionized water and ethanol four times, and the as-prepared material was heated at 120°C for 16 h.

3. Results and discussion

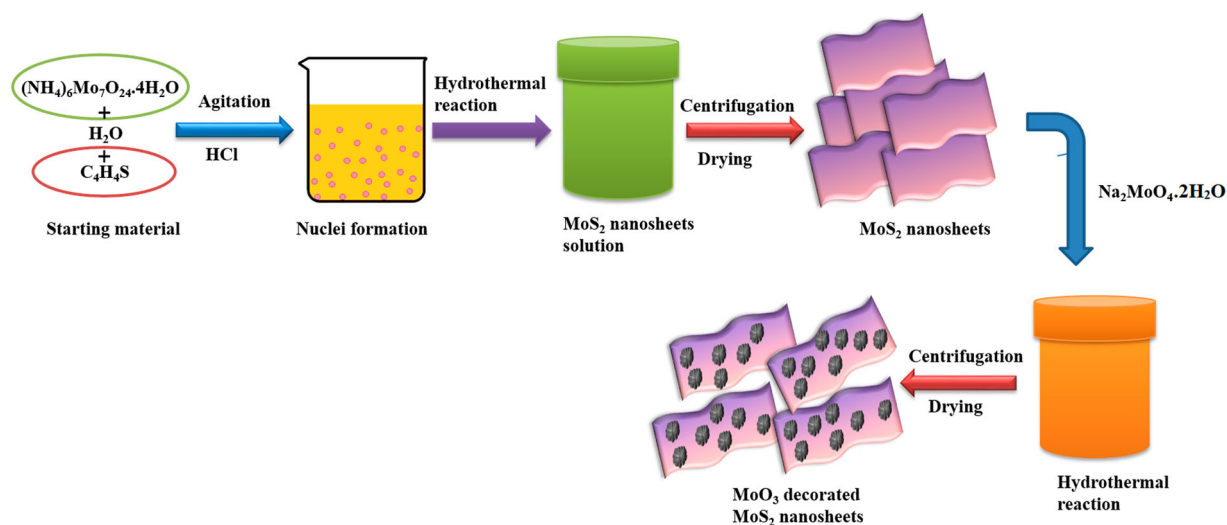
Scheme 1 displays a schematic illustration of the formation of the MoS₂/MoO₃ heterostructure. Firstly, Na₂MoO₄·2H₂O produces Na⁺ and MoO₄²⁻ ions, the MoO₄²⁻ ions react with ethanol and allows in situ nucleation and formation of MoO₃ on MoS₂.

Figure 1(a) displays the XRD patterns of the pristine MoS₂ and MoS₂/MoO₃ heterostructure. It is found that there are five diffraction peaks at $2\theta = 14.12^\circ$, 32.91° , 39.5° , 49.41° , and 58.7° , which can be ascribed respectively to the (002), (100), (103), (105), and (110) planes of the hexagonal phase MoS₂ (JCPDS card no. 75-1539). The MoS₂/MoO₃ heterostructure possesses coexisting phases of MoO₃ and MoS₂ and additional peaks (apart from those of pristine MoS₂) at $2\theta = 12.75^\circ$, 23.31° , 25.67° , 27.26° , 33.72° , 35.45° , 45.75° , 46.31° , 49.17° , and 55.11° , which can be attributed respectively to the (020), (110), (040), (021), (111), (041), (200), (061), (002), and (112) planes of the orthorhombic phase α -MoO₃ (JCPDS carb no. 05-0508). Interestingly, it is observed that the peak position at 13.6° related to the (002) plane shifts to the left for the MoS₂/MoO₃ sample, as compared to the peak position of the pristine MoS₂ (14.12°), indicating that the distance between the (002) planes increased, which is confirmed from the TEM image (Figure 3(e)).

Apart from the (002) peak, other peaks have no apparent shifts because their corresponding interplanar spacings are too small.

Figure 1(b) shows the Raman spectrum of the MoS₂/MoO₃ heterostructure. It is observed that the Raman spectrum from 350 to 420 cm⁻¹ reveals two vibration peaks at 381 and 406 cm⁻¹, corresponding respectively to the E_{2g}¹ and A_{1g} vibration modes of hexagonal MoS₂ [18]. Additional band peaks located at 284, 641, 820, and 987 cm⁻¹ correspond to the α -MoO₃ crystal phase [19]. Among these, the intense broad peak at 987 cm⁻¹ is ascribed to the terminal oxygen (Mo⁶⁺=O) stretching mode along the 'a' and 'b' directions, resulting from unshared oxygen and also responsible for the nanocrystalline structure of α -MoO₃ [18,19]. The intense Raman peak at 820 cm⁻¹ is assigned to the doubly coordinated oxygen (Mo₂-O) stretching mode, which results from corner-shared oxygen in common with two octahedral (i.e. alternating bond lengths of MoO₆) [19]. The Raman peaks at 284 cm⁻¹ can be attributed to O-Mo-O scissoring modes of the α -MoO₃ crystal phase. Therefore, the results obtained from Raman spectroscopy analysis are in good agreement with the conclusions drawn from XRD analysis.

Figure 1(c) shows the FTIR spectra of pristine MoS₂ and the MoS₂/MoO₃ heterostructure in the range of 400–4000 cm⁻¹. The measured FTIR reflectance spectrum of pristine MoS₂ shows several significant absorption peaks positioned at 3667, 2977, 1402, 1068, 891, and 551 cm⁻¹. In the case of the MoS₂/MoO₃ heterostructure, additional peaks located at 1631, 1386, 843, 749, and 537 cm⁻¹ are ascribed to the stretching and bending modes of MoO₃, which is formed by MoO₆ octahedra [19]. In addition, strong vibration peaks at 1068



Scheme 1. Schematic illustration of the formation of the MoS₂/MoO₃ heterostructure.

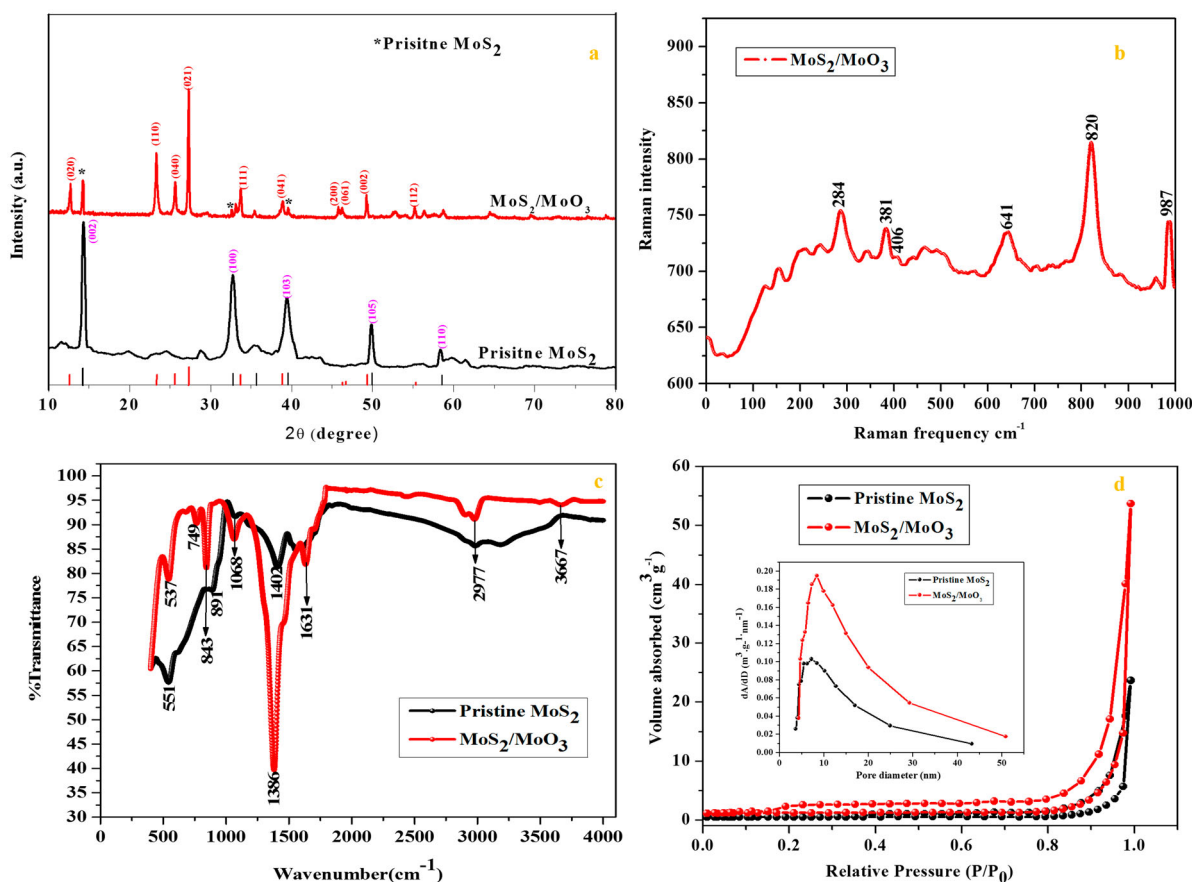


Figure 1. (a) XRD patterns of pristine MoS₂ and the MoS₂/MoO₃ heterostructure. (b) Raman spectra of the MoS₂/MoO₃ heterostructure. (c) FTIR spectra of pristine MoS₂ and the MoS₂/MoO₃ heterostructure. (d) N₂ adsorption-desorption isotherms (inset: Barrett-Joyner-Halenda (BJH) pore size distribution) data of pristine MoS₂ and the MoS₂/MoO₃ heterostructure.

and 843 cm^{-1} are assigned to the symmetric stretching mode of oxygen in the Mo–O–Mo and Mo=O stretching modes, respectively. A broad band positioned at 537 cm^{-1} corresponds to the typical vibration of the Mo_2O_2 , which is formed by edge-shared MoO_6 polyhedra constructing an orthorhombic MoO_3 structure.

It is found from the BET results (Figure 1(d)) that the specific surface area of the obtained MoS₂/MoO₃ heterostructure is 56.2 m²g⁻¹, which is higher than that of pristine MoS₂ (45.1 m²g⁻¹). The pore size and pore volume of the MoS₂/MoO₃ heterostructure is 16.4 nm and 0.019 cm³ g⁻¹. While, the pore size and pore volume of the pristine MoS₂ is 21.3 nm and 0.012 cm³ g⁻¹. These results indicate that the obtained MoS₂/MoO₃ heterostructure comprises mesopores, which are favorable for oxidation and reduction reactions.

High-resolution XPS was carried out to determine the chemical composition and other bonding information of the MoS₂/MoO₃ heterostructure; the results are shown in Figure 2. The surveyed XPS spectra (Figure 2(a)) of pristine MoS₂ and MoS₂/MoO₃ heterostructure evidently reveals the presence of Mo and S elements and Mo, S, and

O elements, respectively. Figure 2(b) shows two broad peaks positioned at 228.73 and 231.86 eV, which correspond respectively to spin orbits of Mo 3d_{5/2} and Mo 3d_{3/2} of the Mo⁴⁺ chemical state, and a minor peak at 225.93 eV, which is ascribed to S 2s of MoS₂. In addition, small peak at 236.1 eV corresponding to Mo⁶⁺ state was observed, representing the formation of oxygen bonding within the MoS₂/MoO₃ heterostructure, which is in consistent with reported literatures [20]. The formation of oxygen bonding is explained by the fact that, during hydrothermal reaction, energetic oxygen atoms of the MoO₃ contact the MoS₂ surface and the S atoms can move out of the lattice site, forming lattice vacancies. The S of MoS₂ bonding with the O of MoO₃ was also observed in the S 2p spectra. Figure 2(c) displays the XPS spectrum of S 2p. A broad peak at the binding energies of 161.78 is ascribed to S 2p_{3/2} and a small peak positioned at 162.85 eV is assigned to S 2p_{1/2} of the S²⁻ chemical state. In addition to these two peaks, a small peak at higher energy (164.5 eV) corresponds to the oxidized sulfur further prove the formation of chemical bonding in between the MoS₂ and MoO₃. Figure 2(d) displays the

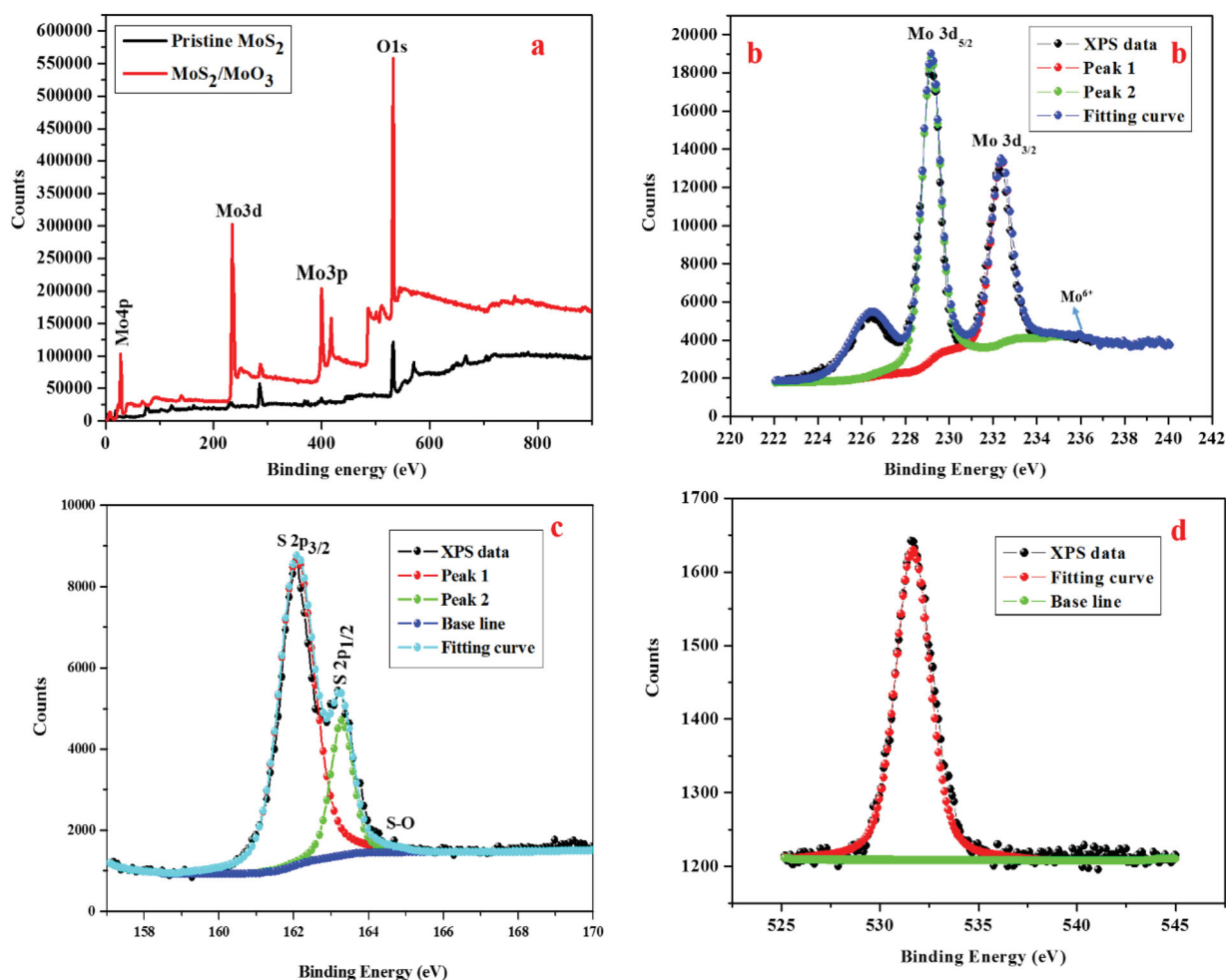


Figure 2. (a) XPS survey spectrum. XPS spectra of (b) Mo, (c) S, and (d) O of the MoS₂/MoO₃ heterostructure.

O1s peak observed at 531.52 eV, which is from the MoO₃ in the MoS₂/MoO₃ heterostructure.

Figure 3 shows representative HRTEM images of the resulting pristine MoS₂ and MoS₂/MoO₃ heterostructure samples. The 3D nanosheets possess a morphology with abundant folded edges, as can be clearly seen in Figure 3(a). From Figure 3(b), the (002) and (100) planes of the pristine MoS₂ can be clearly seen with lattice spacings of 0.63 nm and 0.27 nm. For the MoS₂/MoO₃ heterostructure (Figure 3(c,d)), it can be seen that the MoO₃ nanocrystals were uniformly decorated with 3D MoS₂ nanosheets with abundant folded edges and numerous active sites, which is favorable for enhanced supercapacitor performance. From Figure 3(e), the periodic fringe spacing of 0.37 nm agrees well with the interplanar spacing of (040) for α -MoO₃ (orthorhombic, $a = 0.396$ nm, $b = 1.385$ nm, $c = 0.369$ nm). In addition, lattice fringe spacing is increased (0.67 nm) for MoS₂/MoO₃ heterostructure as compared to pristine MoS₂ (0.63 nm), which is in good agreement with (002) peak shift towards smaller 2θ in XRD and

suggests forming the solid solution reaction of MoO₃ in MoS₂/MoO₃. Figure 3(f) shows the selected area electron diffraction (SAED) ring pattern with a coexisting phase of the MoS₂/MoO₃ heterostructure.

Figure 4 shows the electrochemical performance of the pristine MoS₂ and the MoS₂/MoO₃ heterostructure when used as electrode materials in supercapacitors. Figure 4(a) shows the cyclic voltammetry (CV) curves for pristine MoS₂ and the MoS₂/MoO₃ heterostructure at a scan rate of 50 mVs⁻¹. The nature of CV of MoS₂ reveals that the material exhibits broad peaks which closely resemble the non-faradic reactions. While on the addition of MoO₃ to MoS₂ apart from non-faradic process the CV curves shows peaks that corresponds to faradic reaction which corresponds to pseudo capacitance behavior. In other words, the introduction of MoO₃ nanocrystals onto the MoS₂ nanosheets produces a pair of redox peaks, proving the occurrence of pseudocapacitance and reversible faradic reactions. Figure 4(b) displays the CV curves at different scan rates, ranging from 1 to 150 mVs⁻¹. As the scan rate

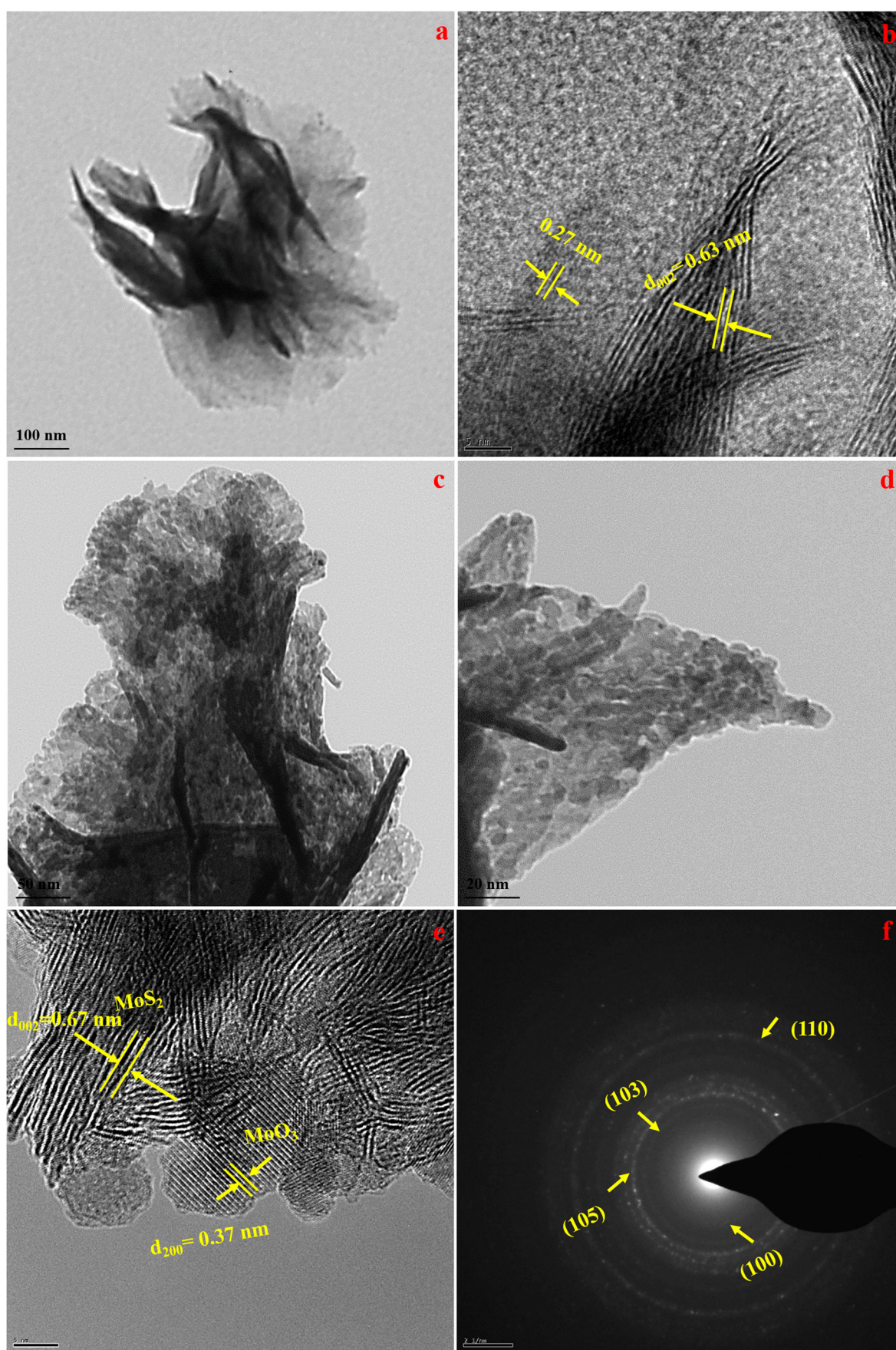


Figure 3. HRTEM images of (a,b) pristine MoS₂, (c)–(e) MoS₂/MoO₃ heterostructure, and (f) the SAED pattern of the MoS₂/MoO₃ heterostructure.

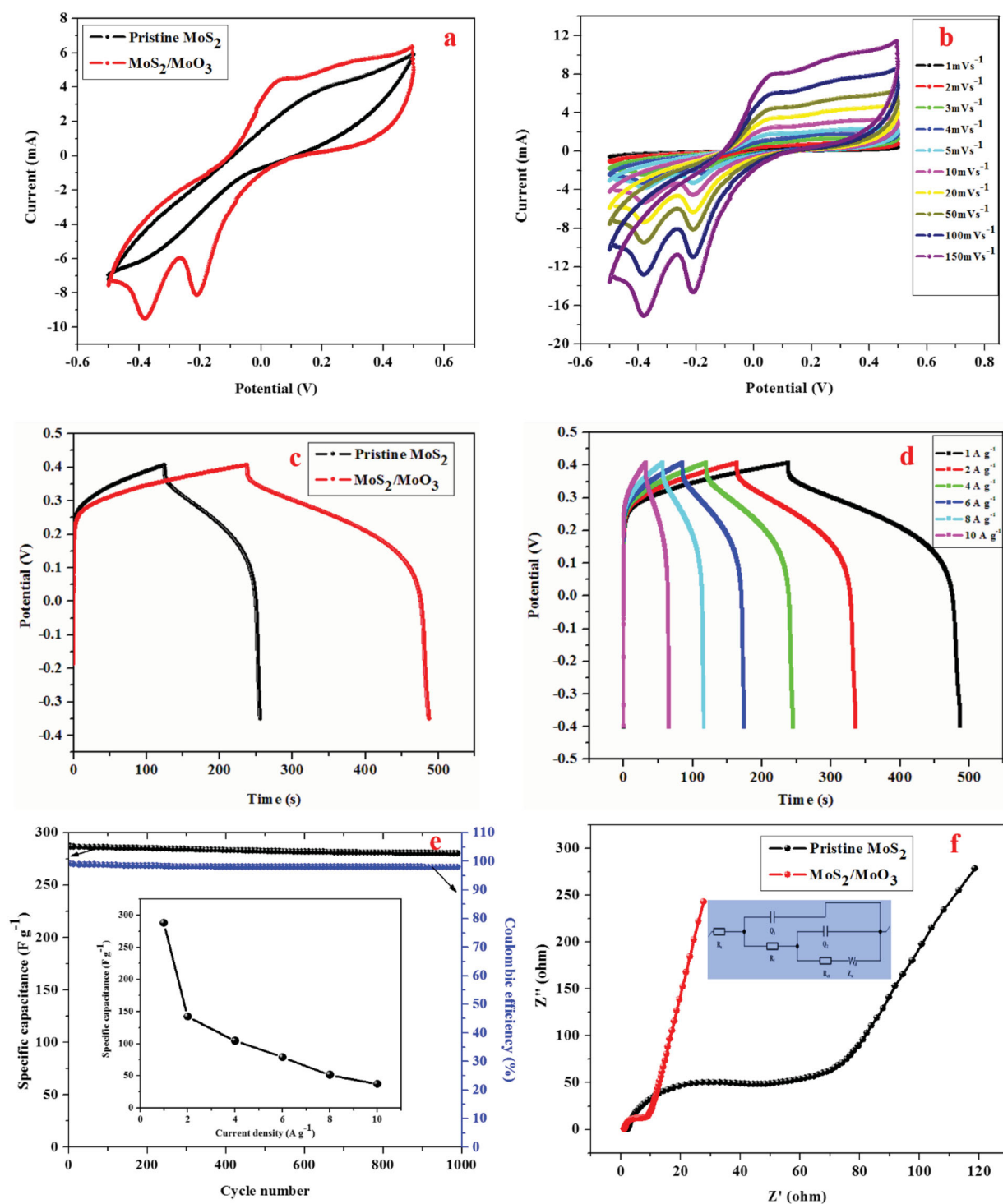


Figure 4. (a) CV curves of the pristine MoS₂ and MoS₂/MoO₃ heterostructure electrodes at a scan rate of 50 mV s⁻¹. (b) CV curves of the MoS₂/MoO₃ heterostructure at different scan rates. (c) Galvanostatic charge–discharge curves of the pristine MoS₂ and MoS₂/MoO₃ heterostructure electrodes at a constant current density of 1 A g⁻¹ in 0.5-M NaOH. (d) Galvanostatic charge–discharge curves of the MoS₂/MoO₃ heterostructure at different current densities. (e) Cyclic stability and Coulombic efficiency of the MoS₂/MoO₃ heterostructure electrode for 1000 cycles at a constant current density of 1 A g⁻¹. (f) Impedance spectra in the range 100 mHz to 1 MHz of the pristine MoS₂ and MoS₂/MoO₃ heterostructure electrodes at a 0.0-V applied potential.

increases, the current response gradually increases as a result and the peak position changes. However, the shapes of the CV curves remain the same, which reflects the

good electrochemical stability and scan rate performance of the MoS₂/MoO₃ heterostructure. Figure 4(c) shows the galvanostatic charge–discharge curves of the pristine

Table 1. Comparison of performance metrics for the MoS₂/MoO₃ heterostructure electrode materials with several reported electrode materials in existing literatures.

Electrode materials	Electrolyte	Current density/Scan rate (A g ⁻¹)	Capacitance (F g ⁻¹)	Number of cycles	Retention (%)	Ref.
MoS ₂ (bulk)	1M Na ₂ SO ₄	0.5	92	1000	~ 93.8	[25]
1T phase MoS ₂	6 M KOH	0.5	366.9	1000	~ 92.2	[26]
MoS ₂ /Fe ₃ O ₄	1M H ₂ SO ₄	1	624	2200	~ 96	[27]
MoS ₂ /Mn ₃ O ₄	1M Na ₂ SO ₄	1	119.3	2000	~ 69.3	[28]
Ni ₃ S ₂ @MoS ₂	6 M KOH	0.5	1418.5	1250	~ 75.8	[29]
MoS ₂ /C	1M Na ₂ SO ₄	1	411	1000	~ 93.2	[30]
MoS ₂ /NiCo ₂ O ₄	3 M KOH	1.5	51.7	8000	~ 98.2	[31]
MoS ₂ /3DG	1M H ₂ SO ₄	1	410	10000	~ 80.3	[32]
NiS ₂ /MoS ₂	3 M KOH	0.5	108	10000	~ 100	[33]
Co ₃ O ₄ /C-MoS ₂	2 M KOH	1	1076	5000	~ 64.5	[34]
NiFe ₂ O ₄ /MoS ₂	1MKOH	1	506	3000	~ 90.7	[35]
CoS ₂ @MoS ₂	2M KOH	1	1038	10000	~ 84.76	[36]
MoS ₂ /rGO	1M Na ₂ SO ₄	1	318	5000	~ 82	[37]
MoS ₂ /BiVO ₄	2 NaOH	10	166.6	200	~ 80	[38]
MoS ₂ /MoO ₃	0.5M NaOH	1	287.7	1000	~ 97.4	This work

MoS₂ and MoS₂/MoO₃ heterostructure samples ranging at 1 A g⁻¹. In addition, Figure 4(d) displays the galvanostatic charge–discharge curves of the MoS₂/MoO₃ heterostructure sample, ranging from 1, 2, 4, 6, 8, and 10 A g⁻¹. The inset in Figure 4(e) shows the specific capacitances at the corresponding current densities and the specific capacitance is estimated like so [21,22]:

$$C = I \times \Delta t / (m \times \Delta V),$$

where I/m (A g⁻¹) is the specific current density, Δt (t) is the discharge time, and ΔV (V) is the potential window for the charge–discharge process. The MoS₂/MoO₃ heterostructure electrode exhibits specific capacitances of 287.7, 142.2, 104.2, 78.3, 51.6, and 37.4 F g⁻¹, corresponding to current densities of 1, 2, 4, 6, 8, and 10 A g⁻¹, respectively. The specific capacitance achieves a maximum of 287.7 F g⁻¹ at a low current density of 1 A g⁻¹, which is higher than that of pristine MoS₂. This enhanced performance may be ascribed to the hierarchically porous structure of the heterostructure, which may deliver shorter pathways for fast and efficient ion transport. The high capacitance may be ascribed to the pseudocapacitance caused by the central Mo atoms with valences ranging from +2 to +6 in the charge/discharge processes [23,24]. Figure 4(e) shows the cyclic stability of the MoS₂/MoO₃ heterostructure at 1 A g⁻¹, which is another critical factor for practical applications, especially at a relatively remarkable current density. From Figure 4(e), the capacitance only decreases by about 2.6% of the initial capacitance after 1000 cycles, representing a remarkable cycling life of the MoS₂/MoO₃ heterostructure. The capacitance retention upon electrochemical cycling and higher specific capacitance of the MoS₂/MoO₃ heterostructure is ascribed to (i) formation of an open structure to enhance the connection between

Table 2. Calculated EIS parameters of pristine MoS₂ and MoS₂/MoO₃.

Sample	R_s (Ω)	R_f (Ω)	Q_1 (F)	R_{ct} (Ω)	Q_2 (F)	W (S.sec ⁵ /cm ²)
MoS ₂	1.12	3.52	2.7×10^{-3}	2.1	1.45×10^{-6}	1.03×10^{-3}
MoS ₂ /MoO ₃	0.89	1.78	1.59×10^{-2}	1.16	7.86×10^{-6}	6.2×10^{-2}

Note: R_s (Ω) denotes the electrolyte resistance attributed to the intercept of the semicircle at high-frequency range; R_f (Ω) and Q_1 (F) are the SEI layer resistance and the constant phase element (CPE), respectively, equivalent to the semicircle at high-frequency range; R_{ct} (Ω) and Q_2 (F) are the charge transfer resistance and related double layer capacitor, respectively, matching to the semicircle in high-middle frequency region; and W (S.sec⁵/cm²) is Warburg impedance assigned to the straight line in low-frequency range related to the sodium-diffusion process.

active material and electrolyte, (ii) make full use of electrochemical active MoS₂ during the charge and discharge processes, and (iii) the improved electrical conductivity of the overall electrode [6]. The specific capacitance is 287.7 F g⁻¹ in the initial cycle and can still maintain 280.3 F g⁻¹ after 1000 cycles, giving a high capacitance retention of ~ 97.4%. This remarkable cyclability may be maintained because the MoO₃ is tightly attached to the MoS₂ layers, which enhances the stability of the heterostructure. Comparison of performance metrics for the MoS₂/MoO₃ heterostructure electrode materials with several reported electrode materials in existing literatures is presented in Table 1.

To obtain further evidence about the improved performance of the MoS₂/MoO₃ heterostructures than pristine MoS₂ as electrodes for supercapacitor, EIS analysis was conducted in 0.5 M aqueous NaOH at 0.0 V (vs Ag/AgCl), as shown in Figure 4(f). Nyquist plots typically include a semicircle in the mid-to-high frequency region that corresponds to the charge transfer resistance (R_{ct}), and a diagonal line in the low-frequency region that corresponds to ion-diffusion behavior in the electrolyte solution and adsorption onto the electrode surface [22]. The calculated EIS parameters of pristine MoS₂ and

MoS₂/MoO₃ heterostructure is listed in Table 2 (see the supplementary information file). The EIS parameter R_{ct} is estimated to be 2.1 for pristine MoS₂ and 1.16 Ω for the MoS₂/MoO₃ heterostructure. The MoS₂/MoO₃ heterostructure demonstrates a lower R_{ct} value than pristine MoS₂, which indicates that the occurrence of fast charge/discharge processes and greater electrical conductivity at the MoS₂/MoO₃ electrode–electrolyte interface. The EIS results show that the MoS₂/MoO₃ heterostructure displays more facile electrode kinetics, which is particularly useful feature for improving the performance of supercapacitance.

4. Conclusions

A simple coupling of MoS₂ with a Na₂MoO₄·2H₂O precursor via a hydrothermal chemical reaction was successfully converted to a MoS₂/MoO₃ heterostructure via oxygen bonding. This strategy involved *in situ* formation of MoO₃ nanocrystals on the surfaces of MoS₂ nanosheets, which was used as a remarkable electrode material for a supercapacitor. The MoS₂/MoO₃ heterostructure demonstrated high capacitance, excellent rate capacitance, and cyclability compared to pristine MoS₂, which may be ascribed to the unique structure of the MoS₂/MoO₃ heterostructure, comprising tiny MoO₃ nanocrystals embedded randomly in the MoS₂ nanosheets. This work offers a unique and simple approach for the formation of heterostructures that holds promise for lithium-ion batteries and photoelectrochemical cells.

Disclosure statement

No potential conflict of interest was reported by the authors.

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