MoO2-MoS2@PANI composite material is used as the anode material for lithium-ion batteries

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Abstract

The hetero structured arrangement of metal sulfide/oxide is of paramount importance in dictating the electrochemical characteristics of anode materials for lithium-ion batteries (LIBs). In this investigation, a synthesized composite material, integrating molybdenum disulfide (MoS$_2$) and molybdenum dioxide (MoO$_2$) intercalated within polyaniline (PANI) under hydrothermal conditions, was employed. Within the granulated MoO$_2$-MoS$_2$@PANI composite, PANI acts as an efficacious matrix, effectively mitigating the re-agglomeration and pulverization of MoS$_2$-MoO$_2$ during prolonged cycling processes. Concomitantly, the cooperative effects among the MoS$_2$, MoO$_2$, and PANI constituents manifest in copious active sites and shortened ion transport pathways. As an anode material for LIBs, the MoO$_2$-MoS$_2$@PANI sample exhibits exemplary cycling performance, delivering a remarkable capacity of 860 mAh g$^{-1}$ even after enduring 500 cycles at a rate of 0.1 A g$^{-1}$. Furthermore, when scrutinized in a sodium-ion battery (LIB) at a rate of 2 A g$^{-1}$, it demonstrates exceptional cycling performance, retaining a capacity of 490 mAh g$^{-1}$ even after 1000 cycles.

1. Introduction

In recent years, there has been a considerable focus on high-performance energy storage systems based on lithium-ion batteries (LIBs) [1–4]. In determining the electrochemical performance of LIBs, the capacitance of the electrode materials plays a critical role. However, the conventional use of commercial graphite as an anode material falls short of meeting the demands of high-performance energy storage systems [5–7]. Consequently, there has been extensive research on transition metal oxides and sulfides as potential alternatives to graphite due to their higher specific capacity. In particular, due to their unique structures and high specific capacitance, MoS$_2$ and MoO$_2$ have emerged as promising negative electrode materials [8–13]. For instance, MoS$_2$ exhibits a graphene-like structure consisting of S-Mo-S layers. Unfortunately, MoS$_2$ suffers from pulverization of the nanosheets and a rapid loss of capacity during charge and discharge cycles [14]. To tackle these challenges, the incorporation of carbonaceous materials with MoS$_2$ has shown promise in enhancing the electrochemical performance. An innovative approach, as demonstrated by Che et al., involves anchoring MoS$_2$ nanosheets on both sides of reduced graphene oxide (rGO), thereby improving the conductivity of MoS$_2$ to a certain extent [15].

MoO$_2$, as an alternative anode material to MoS$_2$, exhibits a higher theoretical capacity [16–18]. However, issues such as volume changes and capacity degradation during charge/discharge cycles limit the practical application of pure MoO$_2$. To address these limitations, MoO$_2$ has been successfully incorporated with carbonaceous materials, including MoO$_2$/carbon composites and MoO$_2$/graphene oxide [19, 20]. Tang et al. designed a three-step method of hydrothermal synthesis, low temperature drying and reduction to prepare MoO$_2$/rGO composite, which has strong cyclic properties [21].
Furthermore, the composite material of MoS$_2$/MoO$_2$ has gained considerable attention recently due to its improved electrochemical properties \cite{22, 23}. However, the investigation of the integrated structure and synergistic effects between MoO$_2$-MoS$_2$ and polyaniline remains limited with regards to their electrochemical performance. Hence, we propose a straightforward approach that utilizes polyaniline as a substrate and combines it with MoO$_2$-MoS$_2$ to synthesize electrode materials with outstanding electrochemical performance.

The synthesis of MoS$_2$/MoO$_2$ composite materials involves a complex reaction mechanism influenced by multiple factors, including the initial reagent proportions, the source of Mo and S, and the hydrothermal conditions. Wu et al. synthesized MoS$_2$-MoO$_2$/rGO by combining Na$_2$MoO$_4$·2H$_2$O and CH$_4$N$_2$S for 6 hours at 200°C \cite{24}. In this paper, the polyaniline-coated MoS$_2$-MoO$_2$ composite was synthesized by using Na$_2$MoO$_4$·2H$_2$O and CH$_4$N$_2$S as precursors under hydrothermal conditions. The hydrothermal duration was significantly reduced to 6 hours, thereby allowing for the retention of certain amounts of MoO$_2$ in the final product. The synthesized composite material demonstrates exceptional cycling performance, owing to the synergistic architecture involving MoO$_2$, MoS$_2$, and polyaniline layers. Within this architecture, polyaniline functions as a continuous conductive pathway, thereby augmenting the performance of both MoS$_2$ and MoO$_2$.

2. Results and discussions

MoO$_2$-MoS$_2$@PANI The synthesis process of composite materials is shown in Fig. 1. A solution comprising Na$_2$MoO$_4$·2H$_2$O (0.3 g) and CH$_4$N$_2$S (0.8 g) in 60 mL of deionized water was transferred into a 100 mL high-pressure reactor. After undergoing a 6-hour reaction at 200°C, the resulting composite was isolated via vacuum filtration and subsequently rinsed with deionized water and anhydrous ethanol. Following 12 hours drying period at 60°C, a mixture containing 0.15 g of the composite, 3 mL of polyaniline, and 0.5 g of ammonium persulfate was dissolved in 80 mL of deionized water and stirred for 24 hours. The resulting dark precipitate was obtained through vacuum filtration and further washed with deionized water and anhydrous ethanol. Subsequently, the black precipitate was dried at 60°C for 12 hours under N$_2$ protection and subjected to heating at 350°C for 2 hours and 750°C for 2 hours in a tube furnace to yield the MoO$_2$-MoS$_2$@PANI product. The product obtained from the black precipitate under identical conditions, excluding the tube furnace calcination step, is denoted as MoO$_2$-MoS$_2$@PANI-1. Under the same conditions, the product obtained with the addition of 1.5 mL of polyaniline is referred to as MoO$_2$-MoS$_2$@PANI-2, while the product obtained with 6 mL of polyaniline is designated as MoO2-MoS$_2$@PANI-3.

Figure 2(a) shows the SEM characterization results of the morphology of MoO$_2$-MoS$_2$@PANI composites. MoO$_2$-MoS$_2$@PANI shows the cross-linked structure of an interconnected nanosheet MoS$_2$ and MoO$_2$ uniformly inserted on the surface of aniline in sheets (Fig. 2a). The intercalation structure of MoO$_2$-MoS$_2$@PANI tightly connects MoS$_2$, MoO$_2$, and PANI, greatly increasing the surface area and forming a
The conductive structure. The intercalation structure of MoO2-MoS2@PANI facilitates Li\textsuperscript{+} transfer. The intercalation structure formed by the fusion of MoO\textsubscript{2}, MoS\textsubscript{2} and PANI is conducive to solving the volume expansion problem of molybdenum sulfide in long cycles. Figure 2(b) shows the HRTEM and HAADF-STEM images and corresponding element atlas images for MoO\textsubscript{2}-MoS\textsubscript{2}@PANI. The crystal face lattice fringe in (0 1 1) MoO\textsubscript{2} and (0 0 2) MoS\textsubscript{2} at MoO\textsubscript{2}-MoS\textsubscript{2}@PANI is 0.32 and 0.69 nm, respectively (Fig. 3a) [25–27]. In addition, the crystal plane spacing of (0 0 2) in MoS\textsubscript{2} is usually large, which facilitates the diffusion of Li\textsuperscript{+} between electrolyte penetration and active substances [28, 29]. The HAADF-STEM image of MoO\textsubscript{2}-MoS\textsubscript{2}@PANI and its element mapping image show that elements (Mo, S, O) are evenly distributed (Fig. 2c). MoO\textsubscript{2} and MoS\textsubscript{2} are evenly inserted into the intercalation structure on the surface of PANI, forming a good MoO\textsubscript{2}-MoS\textsubscript{2}@PANI intercalation structure.

Figure 3(a) XRD shows the crystal phase of MoO\textsubscript{2}-MoS\textsubscript{2}@PANI and demonstrates the presence of MoO\textsubscript{2} and MoS\textsubscript{2} in the obtained composites. There is clear evidence of MoO\textsubscript{2} phase formation in the sample with peaks at 25.96, 36.94, 53.94, 60.18, 66.62 and 79.62°. These diffraction peaks are consistent with the (-1 1 1), (-2 1 1), (-3 1 2), (0 3 1), (-1 0 2) and (2 3 1) planes of MoO\textsubscript{2} (PDF#32–0671). There is clear evidence of MoS\textsubscript{2} phase formation in the sample with peaks at 9.5, 43.72 and 60.18°. These diffraction peaks are consistent with the (0 0 2), (1 0 0), (1 0 3) and (1 1 0) planes of MoS\textsubscript{2} (PDF#75-1539). Note that the (0 0 2) peak of MoS\textsubscript{2} is shifted to a lower angle of approximately 9.6°, due to possible ion and molecular insertion [30, 31].

There are two typical characteristic peaks at 1597 and 1345cm\textsuperscript{-1}. The two characteristic peaks are the G band and the D band. This is a good demonstration of the connection between the MoO\textsubscript{2}-MoS\textsubscript{2} hybrid structure and carbon cloth.

The thermal stability of the MoO\textsubscript{2}-MoS\textsubscript{2}@PANI composite was assessed using thermogravimetric analysis (TGA). The thermal imaging graph in Fig. 3c illustrates the weight reduction observed at temperatures surpassing 450°C, stemming from the oxidation process in which MoS\textsubscript{2} transforms into molybdenum oxide (MoO\textsubscript{2}) and sulfur dioxide (SO\textsubscript{2}). The decomposition process exhibits three distinct stages. The slight decrease in weight observed between 30–450°C primarily arises from the evaporation of physically adsorbed water molecules on the carbon material, resulting in a 3.5% weight reduction. Subsequently, the weight loss observed within the 450–550°C range can be attributed to the thermal decomposition of thermally unstable oxygen-containing functional groups, leading to a 13.5% reduction in weight. In the temperature range of 550–730°C, a noteworthy weight loss occurs due to the exothermic removal of remaining oxygen-containing components and the complete degradation of polyaniline, resulting in a 31% reduction in weight. However, 53% residual material remains after this process.

In order to analyze the elemental composition and surface electronic states of MoO\textsubscript{2}-MoS\textsubscript{2}@PANI, the XPS studies on MoO\textsubscript{2}-MoS\textsubscript{2}@PANI have been carried out. It is found that Mo 3d, S 2p, C 1s and O 1s XPS are perfectly combined, and the four elements Mo, S, O and C can be found obviously, and the existence
of MoO$_2$, MoS$_2$ and C is proved. The XPS energy spectrum shown in Fig. 4a shows the Mo, S, O, and C
signals in the MoO$_2$-MoS$_2$@PANI structure. According to the Mo 3d XPS diagram (Fig. 4b), it can be
concluded that Mo 3d$_{3/2}$ and Mo 3d$_{3/2}$ of Mo (IV) are the main peaks, and their binding energies are
232.86 eV and 229.59 eV, respectively. A very faint peak at 226.65 eV was also observed, attributed to S
2s in the MoS$_2$ component. One of the peaks at 236.1 eV is Mo 3d$_{3/2}$ of Mo (VI), due to the slight
oxidation of the Mo element in the air [32, 33]. Figure 4c shows the S2p XPS of the sample, and the peaks
of 163.7 and 162.4 eV in the spectrum are mainly the S 2p$_{1/2}$ and S 2p$_{3/2}$ spectra of MoS$_2$ [12]. C 1s XPS
for MoO$_2$-MoS$_2$@PANI (Fig. 4d) confirms the presence of carbon-oxygen bonds. The C-C bond belonging
to MoO$_2$-MoS$_2$@PANI is at 284.7 eV, while the peaks at 288.9 and 286.6 eV fit to the O = C-O and C-O-C
bonds, respectively [6]. The XPS spectrogram of O 1s is shown in Fig. 4e. The peak of 530.47 eV is the
Mo-O bond energy in MoO$_2$. The other peak is 531.46e, which is the S-O bond caused by partial oxidation
of the S element [33].

The electrochemical performance assessment of MoO$_2$-MoS$_2$@PANI as an active electrode material in
lithium-ion batteries involved conducting cyclic voltammetry (CV) measurements within the voltage range
of 0.01-3V at a scan rate of 0.1 mV s$^{-1}$, as illustrated in Fig. 5(a). In comparison to the MoS$_2$ component,
the MoO$_2$ component, present at a significantly lower weight ratio, exhibited diminished peaks at
1.27/1.41 V and 1.55/1.7 V (Fig. 5a). Conversely, the MoS$_2$ component displayed stronger peaks at 1.07
V and 1.89/2.28 V. The first cathodic/anodic scan demonstrated highly reversible peaks at 1.27/1.41 V
and 1.55/1.7 V, reflecting phase changes determined by subsequent equations (1) and (2).

$$xLi^{++}MoO_2 + xe^- \rightarrow Li_xMoO_2 \quad (1)$$

$$(4-x)Li^{++}Li_xMoO_2 + (4-x) e^- \rightarrow 2 Li_2O + Mo \quad (2)$$

The peak at 1.03 V was assigned to the lithiation reaction of the MoS$_2$ component during the initial cycle,
as described by subsequent Eq. (3).

$$xLi^{++}MoS_2 + xe^- \rightarrow Li_xMoS_2 \quad (3)$$

$$Li_2S + 2Li^+ + 2e^- \quad (4)$$

Subsequent scans revealed overlapping peaks resulting from the reversible lithiation/delithiation process
of the MoO$_2$ component, coinciding with the peaks observed in the first cycle. The peaks arising from the
lithiation/delithiation of the molybdenum disulfide component exhibited phase transitions throughout
successive cycles. Notably, the initial peak at 1.03 V weakened, while a novel peak at 1.89 V emerged in
subsequent cycles. The peak pair at 1.89/2.28 V was attributed to the redox reaction of the Li-S battery
system, following Eq. (4) [34]. Additionally, a prominent peak at 0.5 V during the initial lithiation process
indicated the growth of a solid electrolyte interface (SEI) film on the electrode material, gradually
diminishing in intensity during the second and third lithiation curves, suggesting the formation of a relatively stable SEI film.

In our assessment of the lithium storage capacity of the MoO$_2$-MoS$_2$@PANI sample, which serves as a negative electrode material for lithium-ion batteries, we examined the charge/discharge behavior during the 1st, 2nd, and 3rd cycles, as presented in Fig. 5(b). The 1st DC curve displayed a distinct potential plateau at 0.7 V, corresponding to the characteristic lithiation of the MoS$_2$ component with Li$_2$S. Subsequently, on the discharge/charge curves, we observed another potential plateau at 2.3 V, which aligns with the Li-S battery system (as described by Eq. 4). The MoO$_2$-MoS$_2$@PANI sample exhibited an initial capacity of 1642 mAh g$^{-1}$ (discharge) and 1244.7 mAh g$^{-1}$ (charge). The presence of an irreversible capacity loss and lower coulombic efficiency (CE) of 75.81% primarily stemmed from the formation and growth of the solid electrolyte interface (SEI) film during the initial discharge process. However, in the subsequent cycles, the CE values notably improved to 95.43% and 96.39% during the second and third cycles, respectively.

The rate performance of electrode materials holds significant importance in practical applications. Figure 5(c) demonstrates the cycling behavior of MoO$_2$-MoS$_2$@PANI, MoO$_2$-MoS$_2$@PANI-1, MoO$_2$-MoS$_2$@PANI-2, and MoO$_2$-MoS$_2$@PANI-3 samples, which were subjected to cycling from 0.1 A g$^{-1}$ to 2 A g$^{-1}$ and then back to 0.1 A g$^{-1}$. At current densities of 0.1, 0.2, 0.5, 1, 1.5, and 2 A g$^{-1}$, the MoO$_2$-MoS$_2$@PANI electrode exhibited discharge capacities of 900, 766, 660, 580, 519, and 464 mAh g$^{-1}$, respectively. Upon returning to a current density of 0.1 A g$^{-1}$, the specific capacity of MoO$_2$-MoS$_2$@PANI reached 785 mAh g$^{-1}$. In comparison to the other three materials, the MoO$_2$-MoS$_2$@PANI electrode displayed favorable electrochemical reversibility and structural stability. This exceptional rate cycling performance can be attributed to the integrated structure comprising MoS$_2$, MoO$_2$, and polyaniline components. The distinctive framework formed by the intercalated MoS$_2$ and MoO$_2$ within polyaniline plays a vital role in restraining the pulverization of MoS$_2$/MoO$_2$ and facilitating abundant conductive pathways during the charge/discharge processes.

Figure 6(a) illustrates the cyclic performance of MoO$_2$-MoS$_2$@PANI, MoO$_2$-MoS$_2$@PANI-1, MoO$_2$-MoS$_2$@PANI-2, and MoO$_2$-MoS$_2$@PANI-3 at a current density of 100 mA g$^{-1}$ over 500 cycles. Initially, the capacity of MoO$_2$-MoS$_2$@PANI decreased before gradually recovering, eventually reaching an output of 860 mAh g$^{-1}$ at the 500th cycle. This behavior can be ascribed to two possible factors: during the activation process, the presence of MoO$_2$ [35] enables the pulverized MoS$_2$ component to remain intercalated on the surface of polyaniline, preserving its activity rather than dissolving into the electrolyte. In contrast, MoO$_2$-MoS$_2$@PANI-1, MoO$_2$-MoS$_2$@PANI-2, and MoO$_2$-MoS$_2$@PANI-3 exhibited a declining capacity trend, delivering outputs of 328 mAh g$^{-1}$, 458 mAh g$^{-1}$, and 606 mAh g$^{-1}$, respectively, after 1000 cycles.
Figure 6(b) illustrates the cyclic performance of MoO$_2$-MoS$_2$@PANI, MoO$_2$-MoS$_2$@PANI-1, MoO$_2$-MoS$_2$@PANI-2, and MoO$_2$-MoS$_2$@PANI-3 under a current density of 2A g$^{-1}$ for 1000 cycles. Initially, the capacity of MoO$_2$-MoS$_2$@PANI decreased, followed by a gradual stabilization and a slight increase, resulting in an output of 490 mAh g$^{-1}$ at the 1000th cycle. The formation of an interconnected network of nanoscale particles, facilitated by the uniform doping and intercalation of MoO$_2$ and MoS$_2$ on the surface of polyaniline, effectively accommodated the pulverization of MoO$_2$-MoS$_2$ and yielded exceptional reversible capacity. In contrast, MoO$_2$-MoS$_2$@PANI-1, MoO$_2$-MoS$_2$@PANI-2, and MoO$_2$-MoS$_2$@PANI-3 exhibited a decreasing capacity trend, with respective outputs of 112 mAh g$^{-1}$, 259 mAh g$^{-1}$, and 407 mAh g$^{-1}$ at the 1000th cycle.

Figure 7(a) shows the EIS for the MoO$_2$-MoS$_2$@PANI, MoO$_2$-MoS$_2$@PANI-1, MoO$_2$-MoS$_2$@PANI-2, and MoO$_2$-MoS$_2$@PANI-3 electrodes. Calcination of the polyaniline enhances electron transfer to a greater extent compared to non-calcined samples. Moreover, the addition of 3 mL of aniline shows a superior effect on promoting electron transfer compared to 1.5 mL or 6 mL. The MoO$_2$-MoS$_2$@PANI electrode consistently exhibits lower charge transfer resistances compared to the control group. These findings indicate that the MoO$_2$-MoS$_2$@PANI electrode, in comparison to the MoO$_2$-MoS$_2$@PANI-1, MoO$_2$-MoS$_2$@PANI-2, and MoO$_2$-MoS$_2$@PANI-3 electrodes, displays higher conductivity, leading to improved rate capability.

Figure 7(b) shows the EIS of MoO$_2$-MoS$_2$@PANI electrodes at the 1st and 100th charge/discharge cycles. Following 100 cycles, a pronounced decline in the R$_{ct}$ value was observed in comparison to the pre-cycling state, signifying an augmented conductivity and reduced internal electrochemical resistance of the electrode after cycling. This provides additional evidence of the remarkable rate capability and heightened reversible capacity exhibited by MoO$_2$-MoS$_2$@PANI.

The electrochemical dynamics of the MoO$_2$-MoS$_2$@PANI composite were probed to gain deeper insights into its exceptional rate performance. The cyclic voltammetry (CV) profiles acquired at various scan rates are depicted in Fig. 8a. Within the electrode, two prominent modes of lithium-ion storage prevail: diffusion-controlled Faradaic contribution and surface-controlled non-Faradaic contribution [36–38]. The influence of capacitive effects on Li$^+$ storage can be assessed by Eq. 5:

$$i = a b$$  \( (5) \)

where in the parameters (a and b) showcase variability. The value of b, derived from the slope calculation of the lg $i$ versus lg $v$ curve, spans from 0.5 to 1. At b values of 0.5 or 1, the charge storage is primarily dictated by diffusion-controlled or surface-controlled processes, respectively [39–41]. Analysis of the oxidation and reduction peak currents obtained at different scan rates (Fig. 8b) reveals corresponding b values of 0.69 and 0.59, respectively. These results suggest the concurrent operation of diffusion-controlled and surface-controlled mechanisms within the MoO$_2$-MoS$_2$@PANI electrode. The capacitive behavior of the MoO$_2$-MoS$_2$@PANI electrode can be assessed using Eq. 6:
\[ i(V) = k_1 + k_2 \cdot 1/2 \] (6)

wherein \( k_1 \) and \( k_2 \cdot 1/2 \) correspond to the surface capacitive and diffusion-controlled processes, respectively. Notably, at a scan rate of 2.0 mV s\(^{-1}\) (Fig. 8c), the capacitive contribution represents 88% of the overall capacity of the MoO\(_2\)-MoS\(_2\)@PANI electrode. Furthermore, the proportions of capacitive contribution at scan rates of 0.1, 0.3, 0.5, 0.7, 0.9, 1, and 2 mV s\(^{-1}\) (Fig. 8d) are 34%, 43%, 49%, 55%, 61%, 64%, and 88%, respectively. These findings highlight the dominant role of capacitive contribution in the overall capacity of the MoO\(_2\)-MoS\(_2\)@PANI electrode, thus explaining its remarkable rate performance.

3. Conclusions

In summary, the successful synthesis of the interconnected intercalated structure of MoO\(_2\)-MoS\(_2\)@PANI as a negative electrode material for lithium-ion batteries (LIBs) has yielded promising results. Through the intercalation of MoS\(_2\) and MoO\(_2\) within polyaniline, a conductive pathway is established, effectively preventing the pulverization of MoO\(_2\) during charge/discharge cycling. The capacity enhancement observed during the lithium-ion insertion/extraction process is primarily attributed to the presence of MoO\(_2\), while the intercalated MoS\(_2\) remains embedded within the surface structure of polyaniline, maintaining its integrity without dissolution into the electrolyte. Remarkably, when applied to sodium-ion batteries (LIBs) at a current density of 0.1 A g\(^{-1}\), the MoO\(_2\)-MoS\(_2\)@PANI electrode exhibits excellent stability and demonstrates outstanding performance, achieving a remarkable capacity of 860 mAh g\(^{-1}\) at the 500th cycle. The heterogeneous structure of the MoO\(_2\)-MoS\(_2\)@PANI composite material not only facilitates shorter pathways for efficient electron/ion transfer but also displays adaptability to withstand sample pulverization during cycling. The collaborative effect of MoO\(_2\), MoS\(_2\), and polyaniline synergistically contributes to the exceptional electrochemical performance of this electrode material.

Declarations

Ethical Approval

This study is applicable for both human and/or animal studies and complies with Ethical committees, Internal Review Boards and guidelines. When applicable, we consent to participate and consent to publish are also required.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' contributions
Huanting Xu: Conceptualization, Methodology, Writing - original draft. Chaokui Jiang: Data curation, Writing - original draft. Wenbin Ye: Validation. Deping Xiong: Writing - review & editing. Li Chen: Writing - review & editing. Zuyong Feng: Writing - review & editing. Kunhua Wen: Writing - review & editing. Zhaoying Li: Writing - review & editing. Miao He: Writing - review & editing, Funding acquisition.

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Availability of data and materials

This declaration is “not applicable”.

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**Figures**

![Figure 1](image-url)

**Figure 1**

Making process of the MoO$_2$-MoS$_2$@PANI nanocomposite
Figure 2

SEM images of (a) MoO$_2$-MoS$_2$@PANI; (b) HRTEM of MoO$_2$-MoS$_2$@PANI, (c) HAADF-STEM image of MoO$_2$-MoS$_2$@PANI and the corresponding elemental mapping images (C, O, Mo, S)
Figure 3

(a) XRD patterns of MoO$_2$-MoS$_2$@PANI; (b) Raman spectra of MoO$_2$-MoS$_2$@PANI samples; (c) TGA curve of MoO$_2$-MoS$_2$@PANI
Figure 4

(a) MoO$_2$-MoS$_2$@PANI XPS survey spectra and corresponding (b) Mo 3d, (c) S 2p, (d) O 1s, (e) C 1s high-resolution spectra
Figure 5

(a) CV curve of MoO$_2$-MoS$_2$@PANI at the scanning rate of 0.1 mV s$^{-1}$; (b) Discharge-charge voltage curve MoO$_2$-MoS$_2$@PANI (c) Discharge capacities of MoO$_2$-MoS$_2$@PANI, MoO$_2$-MoS$_2$@PANI-1, MoO$_2$-MoS$_2$@PANI-2, MoO$_2$-MoS$_2$@PANI-3 at different current densities
Figure 6

(a) Cyclic performance of MoO$_2$-MoS$_2$@PANI, MoO$_2$-MoS$_2$@PANI-1, MoO$_2$-MoS$_2$@PANI-2, MoO$_2$-MoS$_2$@PANI-3 at 100 mA g$^{-1}$; (b) Cyclic performance of MoO$_2$-MoS$_2$@PANI, MoO$_2$-MoS$_2$@PANI-1, MoO$_2$-MoS$_2$@PANI-2, MoO$_2$-MoS$_2$@PANI-3 at 2A g$^{-1}$. 
Figure 7
(a) EIS of MoO$_2$-MoS$_2$@PANI, MoO$_2$-MoS$_2$@PANI-1, MoO$_2$-MoS$_2$@PANI-2, MoO$_2$-MoS$_2$@PANI-3; (b) EIS of MoO$_2$-MoS$_2$@PANI electrodes at the 1$^{st}$ and 100$^{th}$ charge/discharge cycles.

Figure 8
(a) CV curves of MoO$_2$-MoS$_2$@PANI at different scan rates. (b) log peak current versus log sweep rate plots of redox peaks. (c) CV curves of MoO$_2$-MoS$_2$@PANI at 2.0 mV s$^{-1}$. (d) Contribution ratio of capacitive capacity of MoO$_2$-MoS$_2$@PANI at different scan rates.