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Preparation and electrochemical properties of CoS₂/carbon nanofiber composites

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Abstract

Carbon nanocomposites are widely used in hydrogen storage materials and high-capacity electrode materials due to their unique structure and excellent performance. Inspired by Sandwich biscuit, we report a green and convenient method for preparing CoS_2 -carbon nanofiber composites (CoS_2 -CNFs). The CoS_2 -CNFs are prepared by electrospinning technology and hydrothermal process. The structural and morphological properties of CoS_2 -CNFs were characterized through X-ray diffraction, scanning electron microscopy, transmission electron microscope, Raman spectra, and X-ray photoelectron spectroscopy. Meanwhile, the CoS_2 -CNFs reaches 378 F g⁻¹, over 75.6% of initial capacitance is retained as the current density improves from 1 to 10 A g⁻¹ and also exhibits an excellent cycling performance with 89.5% capacitance retention after 1000 times charge/discharge cycles. This result suggests that the CoS_2 -CNFs could yield them potentially promising candidates for future energy storage systems.

Keywords CoS2-CNFs nanocomposite · Electrospinning · Supercapacitors · Electrochemical performance

Introduction

With the rapid development of economy, the increasing energy demand has motivated the desirable search for energy storage material that alternative sources of energy that are environment-friendly, low-cost, and sustainable [1, 2]. As a new type of energy storage device, researchers pay more attention to supercapacitors due to its short charging time and high power density [3-5]. At present, electrode materials can be divided into two major categories, single electrode material and composite electrode material. Single materials include carbon materials, transition metal oxides, conductive polymers, and transition metal sulfides. The core components of supercapacitors are electrode materials. Carbon materials [6–8], transition metal oxides [9–11], conducting polymers, and transition metal sulfides [12] are the main categories of electrode materials. Carbon materials have been widely utilized for supercapacitors due to their high conductivity and

Gaofeng Shi gaofengshi_lzh@163.com extremely good cycle life [13] but their energy densities are insufficient so that it is not suitable for many current special applications. Metal oxides and conductive polymers have high specific capacity, but poor stability and expensive [10, 14]. Transition metal sulfides are inexpensive and have higher capacitive properties than carbon material electrode materials. Therefore, it shows a broad prospect in the field of preparation of tantalum capacitor electrode materials [15–17].

As the development of research, it has been found that single electrode material has certain limitations in certain properties and applications, and needs to be changed and regulated in structure and performance to achieve various intended purposes. For example, metal sulfides load on the surface of a carbon fiber or a carbon nanotube having high specific surface area and good conductivity [18, 19].

Among various transition metal sulfides, cobalt sulfide can form various crystal structures such as CoS_2 , Co_3S_4 , CoS, and Co_9S_8 [20–22]. Zhang [23] reported a facile method for preparing a nanocomposite with CoS_2 nanoparticles in N-doped carbon nanotube hollow frameworks (NCNTFs). The resultant interconnected carbonaceous frameworks provide high conductivity for well-dispersed CoS_2 nanoparticles, with a high specific capacity of 937 mAh g⁻¹ at a current density of 1.0 A g⁻¹. Xia [24] reported an effective strategy to confine CoS_2 nanodots within the graphitic carbon walls of the porous N-

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doping carbon spheres. The CoS₂-in-wall-NCSs showed a large capacity of 1165.4 mAh g⁻¹ at 200 mA g⁻¹ Zhang [25] reported a spongy CoS₂/carbon composite assembled from CoS₂ nanoparticles homogeneously anchored on a spongy carbon matrix was synthesized through a facile freeze-drying method and a hydrothermal process. It delivers a high specific capacity of 610 mAh g⁻¹ at 500 mA g⁻¹ after 120 cycles in LIBs. Xu [26] reported self-assembled interwoven CoS₂/carbon nanotubes (CNTs)/graphene (CCG) composite with hierarchical architecture was synthesized via a facile hydrothermal reaction. It showed a high initial discharge capacity of 993 mAh g^{-1} at a current density of 100 mA g^{-1} . Zhang [27] reported Co₉S₈@C nanospheres with a 5-nm carbon shell, and 50-nm Co₂S₈ core had been synthesized by a facile hydrothermal method followed by an annealing process. The Co₉S₈@C electrode shows capacities of 601 mAh g^{-1} , at current density of 0.05 A g^{-1} . Hu [28] reported CoS-NP/CoS-NS DSNBs with double-shell hollow structure was synthesized by using the framework of Cobased zeolite imidazole (ZIF-67) nano-cube. CoS-NP/CoS-NS DSNBs can be operated stably in a wide potential range of 1.6 V with greatly enhanced energy density and power capability. At a current density of 1 A g^{-1} , its specific capacitance can reach 980 F g^{-1} , and it was stable for 10,000 cycles with a capacitance retention of 88%.

Therefore, it can be used to meet the different needs of various industries and attract people's attention. The combination of CoS_2 and carbon materials can not only make up for the shortcomings of single materials, but also activate the synergistic effects of different materials, thereby significantly improving the electrochemical properties and cycle stability of electrode materials [29, 30].

Herein, we demonstrate a successful fabrication of a CoS_2 carbon nanofiber composite prepared by hydrothermal synthesis. The carbon fiber prepared by the electrostatic method is used as a substrate for supporting CoS_2 , which not only can increase the large specific surface area but also can provide more electrochemical active sites for ion intercalation or deintercalation, thereby improving electrochemical performance. The resultant CoS_2 -CNFs materials demonstrate high specific capacitance (378 F g⁻¹ at the current density of 1 A g⁻¹), good cycle stability (the capacitance retention of 89.5% over 1000 cycles), and excellent rate capability, which capacitance remains up to 286 F g⁻¹ at the current density of 10 A g⁻¹.

Experimental

Reagent

Polyacrylonitrile (PAN), cobalt acetate, and thioacetamide were purchased from Macklin, (Shanghai, China); N, Ndimethylformamide (DMF) (Tianjin Tianxin Fine Chemical Development Center); ethylene glycol (Tianjin Chemical Reagent Third Factory); absolute ethanol (Tianjin Damao Chemical Reagent Factory); acetylene black (Tianjin Youmeng Chemical Technology Co., Ltd); foam nickel (Kunshan Tengerhui Electronic Technology Co., Ltd.); and polytetrafluoroethylene (PTFE) (Guangzhou Songbai Chemical Reagent Co., Ltd.)

Preparation of carbon nanofibers

The polymer solution for electrospinning was prepared by mixing 1.0 g of PAN in 10 ml of N, N-dimethylformamide (DMF) solution. The blend was kept under magnetic stirring for 6 h to form a colorless viscous liquid. A plastic syringe with a 20-gauge stainless steel needle was filled with the prepared spinning solution and then connected to the highvoltage anode. No syringe pump was used during the spinning process. A tin foil-coated cylinder served as a nanofiber collector. The distance from the tip of the needle to the collector was 20 cm. The advancing speed was 0.12 mm min^{-1} . The negative high pressure was -2 kV. The positive high pressure was 15 kV. And the room temperature was 25 °C. The nanofiber film by the above electrospinning was fixed on the magnetic boat to ensure the tension of the film. The obtained fibers were placed in a muffle furnace and pre-oxidized in air at 260 °C for 1 h, with a heating rate of 1 °C min⁻¹. Then, the material was carbonized in nitrogen with a heating rate of 2 °C min⁻¹, held at 800 °C for 1 h, and cooled to room temperature. Under these conditions, PAN-based carbon nanofibers were obtained.

Preparation of CoS₂/carbon nanofiber composite

Firstly, the carbon fiber prepared was carboxylated so that it had a mass of oxygen-containing functional groups on the surface. Then 30 mg carbon fibers carboxylated was dispersed in 50 ml glycol solution with ultrasonication for 30 min. After complete mixing, 10 mmol thioacetamide (CH₃CSNH₂) and 1 mmol Co(CH₃COO)₂·4H₂0 were added to the solution and then magnetic stirring for 1 h to form homogeneous solution. The mixture was moved into a Teflon-lined autoclave, sealed, and heated maintained at 150 °C for 12 h in an oven, followed by natural cooling to room temperature. After cooled down, the resulting black solid product washed with deionized water and ethanol many times and dried in vacuum at 60 °C for 12 h. For properties comparison, pure CoS₂ were prepared to follow the similar procedure in the absence of PAN-based carbon fiber. The entire preparation process is shown in Scheme 1.

Structure characterization

The structure of the as-prepared samples was tested by X-ray diffractometer (XRD, MSA-XD2, Rigaku, Japan) in the 20



Scheme 1 Schematic illustration for preparation of CoS2-CNFs

range of 5 to 80°. The X-ray photoelectron spectroscopy (XPS) spectra were acquired on a scanning X-ray photoelectron spectrometer (Thermo Scientific, USA) with monochromatized Al K α X-ray source. The surface structure of the sample was observed by cold field emission type scanning electron microscope (SEM, JSM-6701FJapan Electron Optics Co., Ltd.). The microstructures of samples were imaged by transmission electron microscopy (TEM, JEOL JEM-2010). Raman spectrum was evaluated by spectrometer (JYHR800, Micro-Raman).

Electrochemical characterization

The electrochemical performance measurements were carried out on a CHI660E electrochemical work station (CHI660E, Shanghai Chenhua Instrument Co., Ltd.) in 6 M KOH aqueous electrolyte with a conventional three-electrode configuration. In order to prepare a working electrode, 80 wt% active material, 15 wt% carbon black as a conductive additive and 5 wt% polytetrafluoroethylene (PTFE) binder were mixed uniformly, using anhydrous ethanol as the solvent [31]. The paste was then loaded onto a piece of nickel foam (2.0 \times 1.0 cm) with a coating area of 1 cm \times 1 cm and dried at 65 °C for 12 h in a vacuum oven. Then, the electrode sheet was formed under a pressure of 5 MPa for 1 min. Cyclic voltammetry (CV), galvanostatic charge-discharge (GCD), and electron impedance spectroscopy (EIS) were performed on an electrochemical workstation using a saturated calomel electrode (SCE) and a platinum foil as a reference electrode and a counter electrode, respectively. The specific capacitance (F g^{-1}), was calculated using the following formulae:

$$C = \frac{I\Delta t}{m\Delta V} \tag{1}$$

Where *I* denotes the discharge current, Δt is the discharge time, *m* is the mass load, and ΔV is the potential window of discharge [32, 33].

Results and discussion

The phase composition and crystal structure of the material can be analyzed by XRD diffraction. The crystallographic structures of pure CoS₂ and as-prepared CoS₂-CNFs were analyzed by X-ray powder diffraction (XRD), as shown in Fig. 1a. Compared with the standard pattern of JCPDS No.41-1471, for the pure CoS₂ and as-prepared CoS₂-CNFs, the diffraction peaks appear at $2\theta = 27.884^{\circ}$, 32.303° , 36.236°, 39.828°, 46.320°, and 54.942° corresponding to the (111), (200), (210), (211), (220), and (311), demonstrating that the as-prepared samples are highly pure [34-36]. In addition, the diffraction peaks appeared at 23.5° for CoS2-CNFs, corresponding to the (002) crystal plane of the graphite layer. Furthermore, the intense and sharp peaks indicate that the as-prepared CoS2 samples are well-crystalline. In order to further verify whether the sample of CNFs and CoS2 were combined or not, Raman spectroscopy tests were carried out on the CoS₂-CNFs, CNFs, and CoS₂ respectively, as shown in Fig. 1b. It can be seen from the figure that, compared with the pure CoS₂ and CNFs, the characteristic peaks of CoS₂-CNFs were not only observed at 670 cm⁻¹, which belongs to the characteristic peaks of CoS_2 , but also at 1345 cm⁻¹ and 1597 cm⁻¹, which belong to the D peak and G peak of carbon materials [29, 30]. It indicated that CoS_2 has successfully combined with CNFs. D peak represents the disordered structure of carbon material and G peak represents the graphitized structure [37]. The intensity ratio of D band to G band (ID/IG) can reflect the degree of structural graphitization in the carbon materials. Compared to pure CNFs, CoS2-CNFs exhibits an increased ID/IG intensity ratio, indicating that the degree of graphitization of carbon material in the composite increased.

To further identify the phase composition of the composites, the elemental composition and chemical states of the composites, XPS measurements were conducted. Figure 2 shows the XPS full spectrum of the composite and the highresolution spectrum of the four elements of Co, S, C, and O. The relative contents of each element are shown in Table 1.



Fig. 1 (a)XRD pattern of CNFs, CoS2-CNFs and CoS2; (b) Roman spectrum of CNFs, CoS2-CNFs and CoS2.

Figure 2a gives XPS survey spectrum of the CoS_2 -CNFs. The detected elements are Co, S, C, and O as expected for CoS_2 -CNFs. Firstly, the peak of C element in the composite was fitted by peak splitting method. The spectra can be fitted into four peaks for carbon atoms in four different functional groups. The C1s XPS spectra of CoS_2 -CNFs were presented in Fig. 2b. The peak of C1s spectrum at 284.7 eV, 288.6 eV, and 286.4 eV correspond to C = C-C, C = O, and C-O respectively, which are both carbon and oxygen peaks. The peak at

284.9 eV is C-S, indicating that the composite contains a small amount of sulfur embedded in the carbon lattice [38]. The Co2p spectra of CoS₂-CNFs is shown in Fig. 2c; the peaks located at 779.2 eV and 794.5 eV are assigned to the Co2p_{2/3} and Co2p_{1/2} spin-orbit lines of CoS₂ [35]. The main peak at the binding energy of 779.9 eV is attributed to the presence of Co-S bond, while the peak located at higher binding energy is related to the Co2p_{1/2} level [34]. The S2p spectrum in Fig. 2d shows that the characteristic peaks at 162.5 eV indicate the



Fig. 2 XPS spectra of CoS_2 -CNFs: (a) survey spectrum, (b) C1s, (c) Co2p, (d) S2p.

Table 1	Surface element content of CoS2-CNFs								
Sample	C (%)	O (%)	Co (%)	S (%)					
CoS ₂ -CN	Fs 70.1	9.73	6.02	14.15					

existence of $S_2^{2^-}$ -dimer in the CoS₂-CNFs [39]. At the same time, a small characteristic peak appeared at 168.5 eV corresponds to O-S bond, which may originate from the surface absorption of the samples exposed to air in the post-treatment process [40, 41]. Moreover, according to Table 1, the Co:S ratio of 6.02%:14.15%, closing to 1:2, which further confirms that the metal sulfide in the generated composite material exists in the form of CoS₂.

In order to verify whether CoS_2 had been loaded onto carbon fiber, we observed changes of the structure of the carbon fiber by SEM and TEM, as shown in Fig. 3. Figure 3(a) was the SEM diagram of the PAN-based nanofiber membrane prepared by electrospinning. It can be seen from the figure that the nanofiber membrane prepared was uniformity distributed with a diameter of about 160 nm. Figure 3(b) showed the carbonized PAN-based CNFs fiber. As can be seen from the figure, the surface of the material remains fibrous and smooth. The SEM diagram of the pure CoS_2 synthesized by hydrothermal method was shown in Fig. 3(c). The CoS_2 particles prepared had uniform distribution with the size of 50–100 nm. The SEM of the synthesized composite CoS_2 -CNFs was shown in Fig. 3(d). The sample showed fibrous structure, and there were many fine particles on the surface of the fiber. It indicated that during the hydrothermal process, Co²⁺ resolved from cobalt acetate combined with the sulfur in the free state of thioacetamide to generate CoS₂ particles, due to the high temperature of the system. Thereby, the resultant CoS₂ was attached to the surface of CNFs. Compared Fig. 3(c) with Fig. 3(d), the size of CoS₂ in CNFs was significantly reduced, which can be attributed to the rich oxygen-containing groups on the carbon nanofiber providing sufficient nucleation sites during the hydrothermal process and effectively protecting CoS_2 against aggregation. Figure 3(e) is TEM images of CoS₂-CNFs composite. Obviously, we successfully loaded CoS₂ particles onto the surface of carbon nanofiber, but the distribution is less, which may be caused by the loss of sulfur source due to the high temperature during the hydrothermal process. Figure 3(f) and Fig. 3(g) showed HRTEM of CoS₂-CNFs composite. Figure 3f demonstrated the lattice fringe spacing was 0.167 nm \pm 0.2 nm and 0.248 nm \pm 0.2 nm, corresponding to the (311) and (210) crystal surfaces of CoS_2 , respectively. From the perspective of diffraction ring (Fig. 3g), we detected the crystal surfaces of CoS_2 (111), (200), (210), (220), and (311) (JCPDS No.41-1471), It proved that the CoS₂ particles anchor onto the surface of CNFs.

To determine the percentage of CoS_2 in the CNFs, thermogravimetric analysis (TGA) was carried out from room temperature to 900°C at a heating rate of 10 °C·min⁻¹ in air. As



Fig. 3 SEM images of the PAN fiber (**a**), carbonized PAN fiber (**b**), CoS_2 nanoparticles (**c**), CoS_2 -CNFs composite (**d**), TEM image of CoS_2 -CNFs composite (**e**), HRTEM image of CoS_2 -CNFs composite (**f**), and CoS_2 -CNFs composite HETEM diffraction ring diagram (**g**)



Fig. 4 TGA curve of CoS₂-CNFs composite

shown in Fig. 4, there were two stages of weight loss for CoS_2 -CNFs. The first stage at below 477.3 °C was attributed to the oxidation of CoS_2 in the composite. The second continuous weight loss in the range of 477.3 °C–580.3 °C resulted from the combustion of CNFs in air. Finally, the weight percentage of the CoS_2 determined to be about 20%. All these



results indicated that the obtained sample was CoS_2 and CNFs composite named CoS_2 -CNFs.

Electrochemical property testing was an important method to characterize electrode materials. We applied the electrochemical workstation to test the electrochemical properties of the composite material CNFs, CoS₂, and CoS_2 -CNFs. Figure 5(a) showed a cyclic voltammogram of the CNFs, CoS₂, and CoS₂-CNFs with a voltage range of -0.2 to 0.5 V and a scan rate of 20 mV s⁻¹ using 6 M KOH solution as the electrolyte. As can be seen from the figure, CoS₂ and CoS₂-CNFs appeared two pairs of redox peaks, indicating that the electrode materials mainly stored electric energy with a pseudocapacitive energy storage mechanism. However, no significant redox peak was found in the electrode materials prepared by CNFs, indicating that the energy storage mechanism was double-layer capacitance. At the same scan rate, compared with CNFs, CoS₂, and CoS₂-CNFs, it was easy to find that CoS₂-CNFs composite material had a larger integral area, indicating its capacitance performance was better. Figure 5(b)showed the GCD of CNFs, CoS₂, and CoS₂-CNFs composite at the current density of 1 A g^{-1} , with the potential window from -0.1 to 0.4 V. It can be seen from the figure



Fig. 5 Electrochemical performance of CNFs, CoS_2 , and CoS_2 -CNFs. (a) CV curves for CNFs, CoS_2 , and CoS_2 -CNFs at a scan rate of 20 mV s⁻¹. (b) Galvanostatic charge-discharge curves of all the samples at the current density of 1 A g⁻¹. (c) CV curves for CoS_2 -CNFs at scan rates ranging from 5 to 50 mV s⁻¹. (d) Galvanostatic charge-discharge

curves of CoS_2 -CNFs at different current densities. (e) Specific capacitance of the samples versus various current densities from 1 to 10 A g⁻¹. (f) Electrochemical impedance spectra (EIS) of the CNFs, CoS_2 , and CoS_2 -CNFs. (g) CNFs, CoS_2 , and CoS_2 -CNFs in specific capacitance retention rates at the current density of 2 A g⁻¹ after 1000 cycle



Fig. 5 continued.

that the charge and discharge time of CoS2-CNFs was the longest, which indicated its excellent capacitance. At 1 A g^{-1} current density, the specific capacitances tested for CNFs, CoS_2 , and CoS_2 -CNFs were 14 F g⁻¹, 213.6 F g^{-1} , and 378 F g^{-1} respectively. Compared with CNFs and pure CoS₂, the capacitance of CoS₂-CNFs composite material was greatly improved. Figure 5(c) showed the CV curve of CoS2-CNFs at different scanning rates from 5 to 50 mV s⁻¹ in the potential window from -0.2to 0.5 V. As can be seen from the figure, the position of the redox peak varied continuously with the increase of the scanning speed, but the shape of the CV curves was maintained, indicating the excellent rate performance. According to the two pairs of redox peaks observed in the figure, we described the energy storage mechanism of the composite under alkaline conditions. Two pairs of redox peaks may come from the reversible Faradic redox processes of $Co^{2+} \leftrightarrow Co^{3+}$ and $Co^{3+} \leftrightarrow Co^{4+}$ occurring within the electroactive materials. The redox reactions mediated by OH^- on the electrode can be described as the following formulas [42].

$$CoS_2 + OH^{-} \rightleftharpoons CoS_2OH + H_2O + e^{-1}$$
(2)

$$CoS_2OH + OH = CoS_2O + H_2O + e^{-1}$$
(3)

According to the former formulas, the peak of O1 to R1 represented the redox reaction between CoS_2 and CoS_2OH (as shown in Eq. 2), while O2 to R2 represented the transformation between CoS_2OH and CoS_2O (as shown in Eq. 3). With the increase of scanning rate, the potential of anode and cathode peaks moved to positive and negative directions respectively. That might be due to the inability to neutralize the electric charges during the redox reaction, which limited the ion diffusion rate. Figure 5d showed the GCD of CoS_2 -CNFs composite at different current

Table 2 Specific capacitance of CoS_2 -CNFs (F g⁻¹)

Sample	C(F/g) (1A/g)	C(F/g) (2A/g)	C(F/g) (3A/g)	C(F/g) (4A/g)	C(F/g) (5A/g)	C(F/g) (6A/g)	C(F/g) (7A/g)	C(F/g) (8A/g)	C(F/g) (9A/g)	C(F/g) (10A/ g)
CoS ₂ -CNFs	378	358	343.2	332.8	322	313.2	305.2	296	293.4	286

densities. The specific capacitance of electrode materials at different current densities was shown in Table 2.

The rate performance was an index to evaluate the practical application of capacitors and had important reference for the actual large current quick charge and discharge. Figure 5(e)showed the specific capacitance of CNFs, CoS₂, and CoS₂-CNFs at the different current density. When the current density increased from 1 to 10 A g^{-1} , the specific capacitances of CNFs, CoS₂, and CoS₂-CNFs samples had increased. The capacitance retention values were 28.5%, 72.1%, and 75.6%, respectively. It showed that by loading CoS_2 onto CNFs surface, the conductivity of CoS2 decreased and the rate performance of CoS2-CNFs was improved. The electrochemical conductivity behavior of CNFs, CoS2, and CoS2-CNFs were investigated by electron impedance spectroscopy (EIS) analysis as shown in Fig. 5(f). The impedance plots included a high frequency component (partial semicircle), a lowfrequency component (straight slopping line along the imaginary axis), and a transition zone between two regions [43]. It can be seen from the figure that the slope of CoS₂-CNFs in the low frequency region was larger than that of the pure CoS_2 , which indicated that CoS₂-CNFs composite had a strong ion diffusion ability, excellent capacitance, and low diffusion resistance. In high frequency area, the curve and the resistance of the X axis intersection of representative system, interfacial charge transfer resistance of the CoS₂-CNFs is only 0.59 Ω and much smaller than that of the CoS_2 (0.75 Ω). In practical application, the cycle life of electrode material was also an important index to evaluate electronic devices. High cyclic stability was important for electrode materials. Figure 5(g)showed the CoS₂ and CoS₂-CNFs cycle characteristics at a current density of 2 A g^{-1} with 1000 cycles of charge/discharge. With the increase of charge and discharge time, the capacitance decreased continuously. For the electrode with pure CoS₂, the capacitance retention rate was 78.3% after 1000 cycles, while the electrode with CoS₂-CNFs, the capacitance retention rate was 89.5% after 1000 cycles. The excellent cycling stability of the CoS₂-CNFs electrode can be attributed to the existence of carbon fiber in CoS₂-CNFs, which improved stability of the electrode material.

Conclusions

In summary, CoS_2 -CNFs composite with a unique nanostructure had been synthesized by a facile in one-pot hydrothermal route. The CoS_2 -CNFs composite not only enhanced the energy density of a single electrode, but also improved the cycle stability of pure CoS_2 . The improvement in cycling stability was attributed to the introduction of the carbon nanofiber. The surface morphology of nanostructures can provide more electrochemical active sites for ion implantation or deimplantation, thus improving the electrochemical properties. The carbon nanofiber anchored CoS₂ via chemical binding, which much more effectively inhibited the shuttle effect than physical confinement alone. Meanwhile, the carbon nanofiber was generated on the surface of the composite CoS₂ particles, buffering volumetric changes during cycling and further restraining the shuttle of polysulfides. Additionally, the carbon nanofiber offered a primarily continuous charge transfer pathway. The CoS₂-CNFs exhibited excellent performance with a high specific capacitance of 378 F g^{-1} at a current density of 1 A g^{-1} . After charging and discharging for 1000 cycles at a current density of 2 A g^{-1} in an aqueous electrolyte of 6 M KOH, the capacitance retention value was maintained at 89.5%, which was far superior to the pure CoS_2 (78.3%) electrode material. The remarkable electrochemical properties of CoS2-CNFs had indicated that it was a promising electrode material for supercapacitors.

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