Hierarchical MoS₂ tubular structures internally wired by carbon nanotubes as a highly stable anode material for lithium-ion batteries

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Molybdenum disulfide (MoS₂), a typical two-dimensional material, is a promising anode material for lithium-ion batteries because of its three times the theoretical capacity of graphite. The main challenges associated with MoS₂ anodes are the structural degradation and the low rate capability caused by the low intrinsic electric conductivity and large strain upon cycling. Here, we design hierarchical MoS₂ tubular structures internally wired by carbon nanotubes (CNTs) to tackle these problems. These porous MoS₂ tubular structures are constructed from building blocks of ultrathin nanosheets, which are believed to benefit the electrochemical reactions. Benefiting from the unique structural and compositional characteristics, these CNT-wired MoS₂ tubular structures deliver a very high specific capacity of ~1320 mAh g⁻¹ at a current density of 0.1 A g⁻¹, exceptional rate capability, and an ultralong cycle life of up to 1000 cycles. This work may inspire new ideas for constructing high-performance electrodes for electrochemical energy storage.

INTRODUCTION

Lithium-ion batteries (LIBs) have been widely used in consumer electronics (1, 2). However, the rapidly growing demand for electric vehicles, hybrid electric vehicles, and large-scale electric grid energy storage has triggered an urgent pursuit for advanced batteries with much higher energy density (3, 4). Metal sulfides represent an interesting class of electrode materials for LIBs because of their high abundance, low cost, and intriguing properties (5–13). Among them, molybdenum disulfide (MoS₂), a typical two-dimensional (2D) material, has been considered as a promising anode material for LIBs because of its high specific capacity from a four-electron transfer per formula unit (11–13). However, like many other electrode materials, MoS₂-based anodes are plagued with two main challenges that cause low rate capability and fast capacity decay: the low intrinsic electric conductivity and the large strain upon cycling (14). To tackle these challenges, two typical strategies have been exploited to improve the electrochemical performance of MoS₂-based electrodes. One is to synthesize nanostructured MoS₂ materials that can relax the strain upon cycling, therefore maintaining the structural stability and decreasing the barrier for lithium intercalation (12). The other is to grow the poorly conductive MoS₂ on carbonaceous supports, such as graphene, to improve the electron and ion transport (11, 14–16). In particular, one-dimensional (1D) carbon-MoS₂ nanocomposites have been studied in view of their enhanced ion and electron transport properties (13, 17–20). However, two major constraints remain in these carbon-MoS₂ nanocomposites. First, the electrolyte needs to diffuse through the surface of carbon materials to react with the MoS₂ underneath, thus limiting the rate capability of the electrode (11). In addition, these nanocomposites usually contain a significant amount (>30 wt %) of barely active carbon materials, which not only decreases the mass loading of MoS₂ but also more seriously overconfines the electrodes, thus causing mechanical strain again (13, 14). Thus, it is highly desirable to develop a better 1D structure of the MoS₂/carbon composite with high specific capacity and excellent cycling stability.

Here, we design a novel strategy to synthesize porous hierarchical MoS₂ tubular structures constructed from ultrathin nanosheets and wire the interior of these tubular structures with aligned carbon nanotubes (CNTs) to enhance the electric conductivity. The overall synthesis approach involves the following steps, as schematically shown in Fig. 1. First, carboxylic groups are introduced onto multiwalled CNTs (fig. S1) by refluxing the CNTs in acid. The CNTs are then embedded into polycrylonitrile (PAN) nanofibers by an electrospinning method (Fig. 1A) (21). The abundant –CN functional groups in PAN could coordinate with the carboxylic acid groups on CNTs, forming a good/homogeneous mixture. During the electrospinning process, the CNTs align along the streamlines of the electrospinning solution owing to the elongation and surface tension of the fluid jet (22, 23). As a result, a flexible tube-in-fiber structure with CNTs aligned in PAN fibers is obtained. A protective layer of CoS₂ is grown onto the CNT/PAN tube-in-fiber composite by a combined precipitation and sulfidation process to prevent the damage of structure during the synthesis process and maintain the 1D morphology of the final materials (Fig. 1, B and I, and fig. S2). Next, a facile hydrothermal approach is used to grow ultrathin MoS₂ nanosheets on the composite and completely remove the PAN simultaneously, forming the tubular MoS₂ structure (Fig. 1B, II). Then, the composite is heated in N₂ (95%)/H₂ (5%) at 800°C for 2 hours to increase the crystallinity of MoS₂. Meanwhile, the protective layer of CoS₂ is reduced to form Co nanoparticles (Fig. 1B, III) (24, 25). Finally, the Co nanoparticles are dissolved by acid treatment, thus generating some pores on the wall of MoS₂ nanotubes, to obtain CNT-wired porous hierarchical MoS₂ nanotubes consisting of ultrathin nanosheets (Fig. 1B, IV). As expected, the CNT-wired MoS₂ hierarchical tubular structures exhibit remarkable electrochemical performance with high specific capacity, outstanding rate capability, and an ultralong cycle life when evaluated as an anode material for LIBs.
RESULTS

Synthesis and characterizations of CNT-wired hierarchical MoS₂ tubular structures (CNT/MoS₂ hybrids)

Figure 2A shows a typical field-emission scanning electron microscopy (FESEM) image of the CNT/PAN composite nanofiber with a smooth surface and a diameter of ~200 nm. The transmission electron microscopy (TEM) image shown in Fig. 2B confirms a tube-in-fiber structure with a single CNT well aligned along the axis of the nanofiber. The surface of the nanofibers becomes rougher after refluxing in the ethanol solution of (CH₃COO)₂Co·4H₂O (fig. S3), suggesting the successful deposition of Co acetate hydroxide with a tetragonal phase (26), as confirmed by powder x-ray diffraction (XRD) (fig. S4). The easy deposition of Co acetate hydroxide onto the tube-in-fiber composite could be mainly ascribed to the existence of abundant –CN functional groups in PAN. After sulfidation treatment in thioacetamide (TAA) solution, the outer layer of Co acetate hydroxide can be transformed to CoSₓ as a protective layer, whereas the 1D morphology is perfectly retained (Fig. 2C). The well-defined CoSₓ layer on the surface of the CNT/PAN nanofiber can be easily identified (Fig. 2D). Energy-dispersive x-ray spectroscopy (EDX) and XRD results show that the shell mainly consists of amorphous CoSₓ (figs. S5 and S6I). After a facile hydrothermal process, the surface of the composite is uniformly covered with MoS₂ nanosheets (Fig. 2E). This process is accompanied by complete removal of PAN, leading to the formation of the tubular structure. In addition, the CNTs remain well aligned in the core, yielding an interesting CNT-in-tube structure (Fig. 2, F and G). The as-synthesized CNT/MoS₂-CoSₓ hollow structures are further annealed to increase the crystallinity of MoS₂ (fig. S6II). FESEM (Fig. 2H) and TEM (Fig. 2I) images show that the 1D hollow morphology is well maintained, with negligible size change after annealing. Some particles can be observed on the wall of MoS₂ nanotubes (Fig. 2I). High-resolution TEM (HRTEM) analysis reveals that they have an interplanar distance of 0.205 nm corresponding to the Co (111) plane, suggesting that the CoSₓ layer has been reduced into Co nanoparticles during the annealing process. XRD analysis (fig. S6III) shows two sets of diffraction peaks that can be assigned to the hexagonal MoS₂ and Co (Joint Committee on Powder Diffraction Standards (JCPDS) card nos. 37-1492 and 15-0806).

The Co nanoparticles are removed by acid treatment to generate some pores on the wall of MoS₂ tubular structures without affecting the overall morphology of the CNT/MoS₂ nanohybrid (Fig. 3A). The crystallographic structure and phase purity of the nanohybrid are characterized by XRD (Fig. 3B). All the diffraction peaks can be perfectly indexed to the hexagonal MoS₂ (JCPDS card no. 37-1492) with no residues or impurity phase. The composition of the nanohybrid is further examined by EDX (Fig. 3C). The Mo/S atomic ratio of the hybrid is determined to be around 1:1.87, which is close to the stoichiometric composition. It also confirms that the Co particles have been completely removed after the acid treatment compared to the EDX spectrum before the acid treatment (fig. S7). Figure 3 (D and E) shows that a single CNT with a diameter of ~35 nm aligns with the axis of MoS₂ tubular structures and attaches to the inner wall of the tubular structure. In addition, the wall of the MoS₂ tubular structures is about 70 nm thick. A closer examination (Fig. 3, F and G) reveals that the MoS₂ nanosheets are 1.1 to 3.3 nm thick, corresponding to only two to five layers of MoS₂. X-ray photoelectron spectroscopy (XPS) study demonstrates the existence of Mo, S, and C in the prepared materials (fig. S8A). The binding energies at 229.4 and 232.5 eV in the Mo 3d–S 2s spectrum are ascribed to Mo 2d₃/₂ and Mo 2d₅/₂, confirming the chemical state of Mo⁴⁺ in MoS₂ (fig. S8B). The binding energies of S 2p₁/₂ and S 2p₃/₂ bands are located at 162.2 and 163.3 eV, respectively, which are due to the S²⁻ state in MoS₂ (fig. S8C). The high-resolution XPS spectrum of C 1s further confirms that the synthesized materials contain CNTs (fig. S8D) (27–31). The CNT content in the as-synthesized 1D CNT/MoS₂ hollow nanohybrid is determined to be about 10.7 wt % (fig. S9). With the hollow tubular structure and ultrathin nanosheets, the CNT/MoS₂ nanohybrids show a high surface area of ~200 m² g⁻¹, with the pore sizes mostly below 25 nm (fig. S10).

Without the introduction of CNTs, similar hierarchical MoS₂ tubular structures can be obtained (figs. S11 and S12), and irregular MoS₂
Fig. 2. Structural characterizations of the intermediate products. (A to I) FESEM, TEM, and HRTEM images of the CNT-in-PAN nanofibers (A and B), the CNT/PAN-CoSₓ nanofibers (C and D), the CNT/MoS₂-CoSₓ tubular structures (E to G), and the CNT/MoS₂-Co tubular structures (H and I).

Fig. 3. Characterizations of the CNT/MoS₂ tubular nanohybrid. (A) FESEM image. (B) XRD pattern. a.u., arbitrary units. (C) EDX spectrum. at %, atomic percent. (D) FESEM image. (E and F) TEM images. (G) HRTEM image.
flakes are synthesized under the same hydrothermal conditions in the absence of any templates (fig. S13). The thickness of the MoS2 shell that is wired (or not wired) by CNTs can be easily controlled by varying the concentration of the Mo precursor in the synthesis solution (figs. S14 and S15). The type of CNTs can also be varied inside MoS2 tubular structures. For example, CNTs with a smaller diameter of ~15 nm can be similarly aligned inside the MoS2 shell (fig. S16). The number of CNTs in each MoS2 tubular structure can be systematically controlled by altering the amount of CNTs in the PAN matrix. As shown in Fig. 4 (A to C), two strands of CNTs can be clearly observed in a single MoS2 tubular structure. The number of CNTs aligned in a single MoS2 tubular structure can be controlled to be predominantly three (Fig. 4, D to F) or even four (Fig. 4, G to I). All these results show that the designed strategy is highly effective.

**Electrochemical evaluation of the hollow nanohybrids**

The CNT/MoS2 nanohybrid is evaluated as an anode material for LIBs, demonstrating its promising application. Figure 5A shows typical galvanostatic charge-discharge voltage profiles of the hybrid in the voltage range of 0 to 3 V versus Li/Li+. Two voltage plateaus located at 1.1 and 0.7 V can be clearly seen in the first discharge process, which can be attributed to the insertion of Li⁺ into the interlayer lattice of MoS2 to form LiₓMoS2 and a conversion reaction process between LiₓMoS2 and Li⁺, respectively (32–34). A pronounced peak at around 2.3 V can be assigned to the delithiation of LiₓS to S in the first charge process. A different discharge profile with two voltage plateaus located at ~1.9 and 1.3 V is observed in the following discharge process, suggesting a multistep lithium insertion mechanism after the first cycle (19, 35, 36). Typical cyclic voltammograms of the nanohybrid with representative cathodic/anodic peaks (fig. S17A) are in agreement with the above charge-discharge profiles. From Fig. 5A, the first reversible capacity of the CNT/MoS2 hollow nanohybrid is 1320 mAh g⁻¹, which is much higher than that of MoS2 nanotubes (1150 mAh g⁻¹; fig. S17D) and MoS2 flakes (750 mAh g⁻¹; fig. S18). The irreversible capacity of 531 mAh g⁻¹ in the first cycle corresponding to a Coulombic efficiency of 71.3% could be due to some irreversible processes, such as the formation of the solid-electrolyte interface film and the decomposition of electrolyte (37–39).

The cycling performance of the CNT/MoS2 nanohybrid electrode is presented in Fig. 5 (B and C). As shown in Fig. 5B, the CNT/MoS2 nanohybrid electrode delivers a reversible specific capacity of ~1100 mAh g⁻¹ at 0.5 A g⁻¹ with no significant decay of capacity after 200 cycles. On the other hand, the MoS2 nanotube electrode exhibits a lower specific capacity of around 870 mAh g⁻¹ (fig. S17E). Both CNT/MoS2 and MoS2 tubular structures show greatly enhanced lithium storage performance as compared with the MoS2 flake electrode (fig. S18). As shown in the

**Fig. 4. Control of the number of CNTs in the CNT/MoS2 tubular nanohybrids.** (A to I) FESEM (A, D, and G) and TEM images (B, E, and H) and schematics (C, F, and I) of the CNT/MoS2 tubular structures with different numbers of CNTs. Double (A to C), triple (D to F), and quadruple (G to I) CNTs in each MoS2 tubular structure are shown.
inset of Fig. 5B, this CNT/MoS2 hybrid electrode also shows exceptional rate capability. At current densities of 0.5, 1, 2, 3, 4, 5, and 10 A g\(^{-1}\), the reversible capacities of the CNT/MoS2 nanohybrid are ~1115, 1000, 926, 867, 815, 776, and 670 mAh g\(^{-1}\), respectively. When the current density is reduced back to 0.5 A g\(^{-1}\) from 10 A g\(^{-1}\), a high capacity of 1145 mAh g\(^{-1}\) can be immediately resumed. Moreover, the CNT/MoS2 hybrid electrode also shows excellent cycling stability at a very high current density of 5 A g\(^{-1}\) (Fig. 5C). A remarkably reversible capacity of ~800 mAh g\(^{-1}\) can be retained even after 1000 cycles. The Coulombic efficiency at both low and high current densities for the CNT/MoS2 and MoS2 electrodes is nearly 100% after the first few cycles (Fig. 5, B and C, and fig. S17B). To investigate the structural stability of the materials, we carried out a postmortem study by FESEM and TEM examinations. Clearly, the size, shape, and structural integrity of both the 1D CNT/MoS2 nanohybrid (Fig. 5, D and E, and fig. S19) and the MoS2 nanotube (fig. S20) are still well retained, with only some changes in the MoS2 nanosheets. Meanwhile, the MoS2 flakes suffer from great structural degradation after cycling (fig. S21). These results demonstrate the great structural advantages of such 1D tubular structures. Electrochemical impedance spectroscopy (fig. S22) analysis shows that the CNT/MoS2 hybrid manifests the lowest charge transfer resistance for Li\(^+\) ion insertion and extraction (40). Furthermore, the resistance of the prepared nanohybrid is lower than that of other MoS2/carbon composite electrodes (table S1).

**DISCUSSION**

The designed strategy for synthesizing the CNT/MoS2 tubular nanohybrids presented in this work is facile and easily reproducible. The simple electrospinning synthesis of a 1D tube-in-fiber structure with aligned CNTs produces a novel template. This provides an alternative route for preparing functional tubular materials internally wired by CNTs. The introduction of the protective CoS\(_x\) layer onto the surface of polymeric fibers overcomes the inherent disadvantages of polymer templates, such as low stability under harsh conditions, to maintain the 1D morphology of the material during the hydrothermal process. In addition, such a protective layer serves as a sacrificial component to produce pores on the wall of MoS2 nanotubes in the final products. The polymer adopted in this work can be simply removed during the MoS2 deposition process to create the tubular structure. Several important parameters that influence the electrochemical properties of the hybrids, including the thickness of MoS2 shells, the type of CNTs,
and the number of CNTs in each MoS₂ tubular structure, can be well controlled by altering their corresponding precursors in the starting materials.

By virtue of the unique tubular structure, the 1D CNT/MoS₂ nanohybrid exhibits exceptional electrochemical performance as the anode for LIBs. To the best of our knowledge, the performance of this nanohybrid is significantly better than that of other MoS₂-based anodes (table S2). The superior performance of our CNT/MoS₂ tubular nanohybrid might be due to the following aspects, as illustrated in Fig. 5F. First, the good organization of ultrathin MoS₂ nanosheets and the 1D porous tubular structure enable a short diffusion distance for fast Li⁺-ion diffusion, stable structural integrity that effectively buffers the mechanical stress during the charge-discharge process, and a sufficiently large electrode/electrolyte interface for the rapid charge transfer reaction (41–43). Second, both the MoS₂ nanotubes and the interior CNTs can act as channels for electron transport (44, 45). Third, the CNTs not only serve as a conductive path but also help to enhance the structural stability of the overall electrode during the lithiation/delithiation process (13).

In summary, we report an original strategy for synthesizing an interesting tubular nanohybrid of porous MoS₂ nanotubes constructed from ultrathin nanosheets wired by CNTs. This strategy relies on the successful alignment of CNTs in electrosyn polymeric nanofibers. The various important factors that influence the electrochemical performance of the electrode, such as the shell thickness of MoS₂ tubular structures and the number of CNTs inside each MoS₂ tubular structure, can be systematically adjusted. Benefiting from the advantageous structure, the CNT/MoS₂ tubular nanohybrid exhibits remarkable electrochemical performance as anode materials in LIBs with a very high specific capacity of up to 1300 mAh g⁻¹, outstanding rate capability, and an ultralong cycle life of up to 1000 cycles. Such a strategy could be readily extended to other materials for the development of high-performance electrodes for better LIBs.

MATERIALS AND METHODS

Synthesis of the CNT/PAN tube-in-fiber composite

The mixture solution was prepared by adding 1.5 g of PAN (Sigma-Aldrich) and a certain amount of functionalized CNTs (obtained by reflux in HNO₃ at 80°C for 1 hour) in 19 ml of dimethylformamide (Sigma-Aldrich) solvent. The applied working voltage, flow rate, and distance between the needle and the collector were fixed at 13 kV, (Sigma-Aldrich) solvent. The applied working voltage, flow rate, and distance between the needle and the collector were fixed at 13 kV, respectively.

Synthesis of a protective layer of CoSₓ onto the CNT/PAN tube-in-fiber composite

Cobalt acetate tetrahydrate (0.774 g) (Sigma-Aldrich) was dissolved in 100 ml of ethanol, followed by the addition of 100 mg of the as-prepared CNT/PAN tube-in-fiber composite into the solution. After sonication for 20 min, the above mixture was heated to 80°C in an oil bath for several hours to grow Co acetate hydroxide onto the CNT/PAN composite. The obtained CNT/PAN-Co acetate hydroxide composite and 0.13 g of TAA (Sigma-Aldrich) were dispersed in 40 ml of ethanol, transferred to a 100-ml Teflon-lined stainless steel autoclave, and then heated to 120°C for 12 hours to obtain the CNT/PAN-CoSₓ composite.

Synthesis of the hierarchical MoS₂ tubular structures wired by CNTs (CNT/MoS₂ nanohybrids)

In a typical process, 25 mg of the prepared CNT/PAN-CoSₓ composite was dispersed in 25 ml of water containing glucose (0.1 g), sodium molybdate (Na₂MoO₄·2H₂O, 0.1 g), and thiourea (0.2 g). The mixture was transferred to a Teflon-lined stainless steel autoclave and kept in an electric oven at 220°C for 24 hours. After cooling to room temperature, the black precipitate of CNT/MoS₂-CoSₓ was collected, washed with ethanol, and dried in an oven at 60°C. The collected precipitate was further annealed in N₂ (95%)/H₂ (5%) at 800°C for 2 hours, with a heating rate of 1°C min⁻¹ to increase the crystallinity of MoS₂ and reduce the CoSₓ layer to form Co nanoparticles. The obtained CNT/MoS₂-Co hollow nanohybrid was further treated with HCl to remove the Co nanoparticles to yield the nanohybrid of hierarchical porous MoS₂ nanotubes wired by CNTs. The thickness of the PAN layer, which translates to the diameter of MoS₂ tubular structures, can be controlled by changing the electrospinning conditions, such as the viscosity of the electrospinning solution and the applied working voltage. Porous MoS₂ tubular structures and MoS₂ flakes can also be prepared through a similar route without the addition of CNTs in the PAN matrix and fibrous composite precursors in the starting materials, respectively.

Materials characterization

The materials were characterized by TEM (JEOL, JEM-2010), HRTEM, FESEM (JEOL-6700), XRD (Bruker D2), thermogravimetric analysis (TGA), EDX (Oxford Instruments), and XPS (PHI5600). The nitrogen sorption measurement of the prepared composites was conducted by Autosorb 6B at 77 K.

Electrochemical measurements

The electrochemical tests were evaluated by cycling two-electrode 2032 coin cells with lithium foil as the counter/reference electrode, a Celgard 2400 film as the separator, and the mixed slurry consisting of the prepared CNT/MoS₂ structure, carbon black, and polyvinylidene difluoride in a 70:20:10 weight ratio on copper foil as the working electrode. The CNT/MoS₂ composite electrodes were pressed before assembling into coin cells. The loading density, diameter, and thickness of the prepared electrodes were ~1 mg cm⁻², ~13 mm, and ~60 to 80 μm, respectively. The electrolyte was a 1 M LiPF₆ in a 50:50 (w/w) mixture of ethylene carbonate and diethyl carbonate. The charge-discharge tests were performed on a LAND battery tester at several current densities between the cutoff potentials of 0 and 3 V. Cyclic voltammetry and electrochemical impedance spectroscopy were conducted with a CHI 660C electrochemical workstation.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/2/7/e1600021/DC1

fig. 51. Characterizations of the CNTs.
fig. 52. FESEM images of the MoS₂ material synthesized by the hydrothermal method, with the addition of PAN nanofibers without the CoSₓ protective layer.
fig. 53. FESEM images of the CNT/PAN-Co precursor composite nanofibers.
fig. 54. XRD pattern of the CNT/PAN-Co precursor.
fig. 55. EDX spectrum of the PAN/CNT-CoSₓ composite nanofibers.
fig. 56. XRD analysis of the as-prepared materials.
fig. 57. EDX spectrum of the CNT/MoS₂-Co composite.
fig. 58. XPS spectra of the CNT/MoS₂ tubular nanohybrids.
fig. 59. TGA curves of CNTs, MoS₂ tubular structures, and CNT/MoS₂ nanohybrid in air.
fig. 60. N₂ sorption analysis of the CNT/MoS₂ tubular nanohybrids.
fig. S11. Characterizations of porous MoS2 tubular structures and their corresponding precursors.

fig. S12. XRD and EDX analysis of the MoS2 nanotubes.


fig. S14. TEM and FESEM characterizations of as-prepared porous MoS2 nanotubes.

fig. S15. TEM images of the CNT/MoS2 tubular nanohybrids with different MoS2 shell thicknesses.

fig. S16. TEM images of the MoS2 nanotubes internally wired by CNTs with a smaller diameter.

fig. S17. Electrochemical characterizations of the CNT/MoS2 tubular nanohybrids and MoS2 tubular structures.

fig. S18. Electrochemical characterizations of the MoS2 flakes.

fig. S19. Postmortem characterizations of the CNT/MoS2 tubular nanohybrids after cycling.

fig. S20. Postmortem characterizations of porous MoS2 nanotubes after cycling.

fig. S21. Postmortem characterizations of the MoS2 flakes after cycling.

fig. S22. Nyquist plots of the prepared samples.

table S1. Resistance of different MoS2/carbon composite electrodes.

table S2. Electrochemical performance of different MoS2-based electrodes.

REFERENCES AND NOTES


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