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To cite this article: Xiaowei Shen et al 2020 Nanotechnology 31 485403

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Nanotechnology 31 (2020) 485403 (9pp)

## Strongly trapping soluble lithium polysulfides using polar cysteamine groups for highly stable lithium sulfur batteries

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Received 19 June 2020, revised 3 August 2020 Accepted for publication 21 August 2020 Published 18 September 2020



#### Abstract

Sulfur has become one of the most promising positive electrode materials for lithium sulfur batteries due to its high theoretical capacity and high energy density (2500 Wh kg<sup>-1</sup>). The use of common nonpolar carbon/sulfur composites has proved to be a good way to improve the performance, but they still cannot efficiently trap highly polar lithium polysulfides due to the weak interactions between nonpolar carbon and polar polysulfides. Herein, we report a new strategy of using polar cysteamine groups to trap polar polysulfides, leading to greatly enhanced capacity of ~920 mAh g<sup>-1</sup> at 1 C with a high Coulombic efficiency of ~99.1%, and a long cycle life of over 600 cycles with a capacity retention higher than 80%. Importantly, in situ UV/Vis spectroscopy was employed to identify intermediates during cycling, which demonstrates the constructed unique polar cysteamine functionalized carbon nanotubes (CNTs) can greatly reduce the production of polysulfides and suppress the shuttle effect. The broken-bond model of linear polysulfane during cycling was further demonstrated by density functional theory calculations. The present strategy of using polar cysteamine-functionalized CNTs to trap soluble intermediates is promising and has significant potential for the development of highly efficient lithium sulfur batteries.

Supplementary material for this article is available online

Keywords: Li-S batteries, shuttle effect, polar polysulfides, in-situ UV/Vis spectroscopy

(Some figures may appear in color only in the online journal)

#### 1. Introduction

Lithium-ion batteries (LIBs) are one of the most important power sources for battery-powered devices ranging from portable electronics to electric vehicles (EVs) [1, 2]. Traditional LIBs have reached bottlenecks in the applications of energy storage as they have approached their theoretical energy density limits in recent years, which are still not satisfying the energy requirement of EVs for the future [3-5]. Lithium sulfur (Li-S) batteries that utilize elemental sulfur (S<sub>8</sub>) as a cathode active material have been extensively studied as one of the most promising alternatives to LIBs because they deliver extremely high theoretical capacity of ~1675 mAh g<sup>-1</sup> and specific energy density of ~2500 Wh kg<sup>-1</sup> through the redox reaction of  $S_8 + 16Li^+ + 16 \times e^- \rightarrow 8Li_2S$ , which is superior to conventional commercialized LIBs. There are also other advantages of elemental sulfur such as light weight, low cost, high natural abundance, nontoxicity and environmental friendliness [1, 6–9]. However, the practical applications of Li-S batteries have suffered from several obstacles. The first is the insulating nature of sulfur  $(5 \times 10^{-30} \text{ S cm}^{-1})$ that requires a large amount of electrochemically inactive conductive additives to improve the poor conductivity [5, 10]; another problem is the dissolution of lithium polysulfides (LiPS) (Li<sub>2</sub>S<sub>n</sub>,  $2 < n \leq 8$ ) in the electrolyte which can lead to a continuous loss of active material from the cathode and a polysulfide shuttle phenomenon. Moreover, the huge volume change of up to 80% on full lithiation is a noteworthy problem. These above-mentioned issues result in a series of drawbacks for Li-S batteries including low coulombic efficiencies, low capacities, rapid capacity fading and poor rate performance [11–16].

To address the above issues, great efforts were focused on enhancing the conductivity of sulfur and suppressing the dissolution of LiPS. One possible and popular approach is to confine sulfur in conductive hosts, for instance, various nonpolar carbon nanostructures, and a number of composites have been constructed and reported including graphene/graphene oxide-sulfur composites [17-20], mesoporous carbon-sulfur composites [21, 22], hollow carbon spheres-sulfur composites [23, 24], and carbon nanotubes (CNTs)/nanofibers-sulfur composites [25-27], which can give rise to higher discharging capacity and cycling performance of Li-S batteries. However, most of them depend on the weak interactions between nonpolar carbon and highly polar polysulfides that can only slow down the sulfur loss in the short term and, as a result, LiPS species still diffuse into the electrolyte due to the existence of an electrical field [28].

In this work, we report a new strategy to functionalize CNTs by using polar cysteamine to trap highly polar long chain LiPS, leading to greatly enhanced capacity and stability for Li-S batteries. The reasons CNTs are selected as the carbon host are that CNTs exhibit high aspect ratios, high surface area, extremely high conductivity and low density, as well as having a low cost [1, 29]. Polar cysteamine, which has a special structure with an amino group at one end and a sulfydryl group at the other end, was connected to CNTs. Sulfur was then covalently attached to the sulfydryl groups via ring-opening reaction. The constructed cysteamine-functionalized CNTs/S (CFCS) can effectively restrain the production of LiPS and the polysulfides shuttle effect. In situ UV/Vis spectroscopy is used to explore the reaction mechanism during cycling, which detect that the short-chain polysulfides are the main products in the electrolyte, while polar long-chain polysulfides are strongly trapped by the polar cysteamine functionalized CNTs. These findings are further verified by density functional theory (DFT) calculations. As a result, the Li-S batteries with CFCS cathodes exhibit excellent long-term cycling performance with high capacity retention of over 80% for up to 600 cycles.

#### 2. Materials and methods

#### 2.1. Fabrication of CNTS-SH

Hydroxyl- and carboxyl-functionalized CNTs (HCCNTs) were prepared according to the modified Hummer's method. Briefly, 100 mg CNTS was dispersed in a solution containing concentrated sulfuric acid (40 ml) and concentrated nitric acid (20 ml). The mixture was cooled down to 0 °C, followed by slowly adding 6 g KMnO<sub>4</sub>. Then, the reaction system was transferred to a water bath and kept at 35 °C for 6 h. Subsequently, 300 ml distilled water was added to dilute the mixture, and H<sub>2</sub>O<sub>2</sub> solution (30 wt%) was dropwise added with constant stirring until no gas bubbles evolved. The product was collected by centrifugation and washed with HCl solution (10 wt%) several times, and then dried at 60 °C overnight. Afterwards, 60 mg peroxided CNTs were put into a round bottom flask containing 60 ml cysteamine solution  $(0.11 \text{ mg ml}^{-1})$  and kept at 95 °C. After 6 h, the cysteamine functionalized CNTs were obtained (CNTs-SH) by several filtration-rinse cycles until the filter liquor became neutral and was then dried at 60 °C.

#### 2.2. Preparation of CFCS

The CFCS powder was synthesized by using the cysteamine functionalized CNTs and sulfur powder as the starting materials in the weight ratio 1:3, the starting materials were mixed and then heated at 160 °C for 10 h and 245 °C for another 2 h under an argon atmosphere. Finally, the product was further annealed at 155 °C in an Ar flow for 2 h to remove the uncombined sulfur and achieve CFCS samples. As a contrast sample, CNTs/S was prepared by the mixture of CNTs and sulfur heated at 160 °C for 12 h in the weight ratio 1:3.

#### 2.3. General characterization

The morphology of the materials was observed using field emission transmission electron microscopy (FETEM, FEI Tecnai G2 F20 S-TWIN TMP, Hongkong). Elemental analysis was performed on an x-ray photoelectron spectrometer (XPS, Kratos Axis Ultra Dld, Japan). Thermogravimetric-differential thermal analysis (TGA, SDT 2960, TA Instruments, USA) was used to determine the sulfur content of the material. Raman spectra were recorded on a HR800 (HORIBA Jobin Yvon) Raman spectrometer.

#### 2.4. Electrochemical characterization

Coin cells (CR2025) were assembled using lithium foil as the anode, Celgard 2400 as the separator, 1.0 M LiTFSI in DOL/DME (1:1 by volume) with 1 wt % LiNO<sub>3</sub> and 0.02 M Li<sub>2</sub>S<sub>8</sub> as the electrolyte, and a cathode with 70% as-prepared CFCS powder, 20% acetylene black, and 10% polymer binder for each cell. The sulfur loading per electrode can be as high as ~2.5 mg cm<sup>-2</sup>. The battery assembly was done in an



**Figure 1.** Schematic illustration of the design and synthetic process of CFCS sample. The CNTs were oxidized by the modified Hummer's method, and the sulfydryl groups were grafted to CNTs via a reaction between cysteamine and the hydroxyl and carboxyl functional groups on the CNTs. In the next step, sulfur was covalently loaded to the cysteamine functionalized carbon nanotube composite.



Figure 2. (a) The Raman spectra of CNTs, HCCNTs, CNTs–SH and CFCS materials; (b) TEM images of CNTs; (c) The HAADF-STEM image of CNTs–SH and (d) corresponding element mapping of carbon, nitrogen and sulfur.

argon-filled glove box with H<sub>2</sub>O and O<sub>2</sub> less than 0.1 ppm. The galvanostatic charge-discharge test was tested within a voltage window of 1.6–2.6 V (vs. Li<sup>+</sup>/Li) by using a battery testing system (LAND CT 2001A, Wuhan, China). Cyclic voltammetry (CV) measurements were conducted at 0.1 mV s<sup>-1</sup> within the range of 1.6–2.6 V on a CHI 660E (Chenhua Shanghai, China) electrochemical workstation.

#### 2.5. in-situ UV/Vis analysis

A fenestrated 2025-type coin with a sealed glass cover was used to prepare the battery. The configuration of the assembled cell was similar to a common battery. The lithium wafers were punched at the same size as the testing window by the beam, which meant that the UV/Vis spectroscopy of the electrolyte could be obtained without any interference and obstruction. UV–vis absorption spectra were recorded on a UV Lambda 750 UV/Vis/NIR spectrometer equipped with an integrating sphere between 200 nm and 800 nm. Galvanostatic cycling tests of the first cycle were carried out at a current density of 0.5 C.

#### 2.6. Computational method

The Atomistix Toolkit (ATK<sup>®</sup>) was used to simulate the covalent interactions, which were performed by utilizing the model and density-functional theory (DFT). In the present calculations, the periodic-boundary-condition was used with a large super cell of  $30 \times 30 \times 30$  Å3. Also, the Brillouin zone was sampled by  $1 \times 1 \times 1$  k-points using the Monchorst-Pack scheme during the geometry optimization.

#### 3. Experimental results and discussion

Figure 1 provides a schematic of the synthetic procedure of CFCS. Briefly, CNTs are firstly functionalized by the modified Hummer's method, and HCCNTs are obtained. Then, the sulfydryl groups are covalently grafted to HCCNTs via the reaction between cysteamine and carboxyl functional groups to form CNTs-SH composites. In the next step, the S8 ring opens and is loaded to CNTs-SH composites by sulfydryl groups. The total sulfur content in CFCS is determined to be ~58 wt% by TGA analysis (figure S1, available online at https://stacks.iop.org/NANO/31/485403/mmedia) [28]. More detailed procedures are described in the experimental section. Multiple analytical tools are employed to demonstrate the covalent attachment of cysteamine to CNTs. Raman spectroscopy is a powerful method to investigate the atomic structure of carbons and further characterize the CNTs-SH composites. Usually, the D band located at ~1350  $\text{cm}^{-1}$  indicates the presence of defects, as well as disordered and amorphous carbon and the G band centered at ~1580 cm<sup>-1</sup> originates from the graphitic nature of the CNTs. The intensity ratio of I<sub>D</sub>/I<sub>G</sub> reveals the degree of graphitization. A significant decrease in the intensity ratio of ID/IG is observed after



Figure 3. (a) XPS survey spectrum of CNTs, HCCNTs, the CNTs–SH and CFCS; C 1s XPS spectra of (b) CNTs, (c) HCCNTs and (d) CNTs–SH, respectively.

the functionalization of CNTs (Figure 2(a)). After reaction with cysteamine, the I<sub>D</sub>/I<sub>G</sub> ratio is increased again, indicating an increase of sp<sup>3</sup> carbons on the nanotubes, which implies the carboxyl functional groups on the CNTs are replaced by groups originating from cysteamine. It is predictable that CFCS has similar Raman spectra with that of CNTs-SH, indicating no additional defects are generated. Fourier transform infrared spectroscopy (FTIR) was further conducted to reveal the variation of different materials as demonstrated in figure S2. The broad peaks at  $\sim$ 3475 cm<sup>-1</sup> and  $\sim$ 1590 cm<sup>-1</sup> are ascribed to disturbance of moisture. The stretching vibration of hydroxyl (~3650  $\text{cm}^{-1}$ ) and carboxyl (~1760  $\text{cm}^{-1}$  and the broad peak at ~2810 cm<sup>-1</sup>) in HCCNTs indicates the oxidation of CNTs. The peak located at ~1502 cm<sup>-1</sup> is attributed to the stretching vibration of N-H, while those at 3490 cm<sup>-1</sup> and 1180 cm<sup>-1</sup> of CNTs-SH and CFCS are derived from amide groups, which suggests that sulfydryl groups were covalently grafted to HCCNTs. Figure 2(b) shows the image of multi-walled CNTs, which essentially comprise multilayered graphene rolled into a co-axial nanostructure, and its inset shows the thick tube wall, proving an amount of defects caused by the interaction between the layers. Figures 2(c) and S3 display the morphology of CNTs-SH, which reveal that the nanotubes change into sheet structure to a large extent after oxidization. Figure 2(d) is the element mapping of CNTs-SH of C, N and S elements. The well dispersed distributions further demonstrate the covalent connections of sulfydryl groups with the CNTs.

The variation of elemental composition and functional groups are identified by XPS, which is shown in Figure 3(a). For CNTs, only the C 1s signal is detected in the survey spectrum, revealing the high purity of CNTs. The O 1s signal appears in HCCNTs survey spectrum, which is attributed to the hydroxyl and carboxyl groups. After reaction with cysteamine, new peaks located at ~400.2 eV, ~228.2 eV and ~164.2 eV are found in CNTs-SH, corresponding to N 1s, S 2s and S 2p, respectively, suggesting sulfydryl groups have been grafted to CNTs successfully. In addition, in the survey spectrum of CFCS, the intensity of S 2s and S 2p signals increases more substantially than in CNTs-SH, revealing the successful loading of sulfur on CNTs-SH composites. More details can be seen from the higher-resolution spectra of C 1s. The peak centered at ~284.7 eV representing C-C/C = Cis observed in all XPS spectra, and the intensity of the peak in Figure 3(c) weakens evidently compared with Figure 3(b), whereas more new oxygen signals (285.6 eV for C-O, 287.3 eV for C = O and 288.9 eV for O–C = O groups) appear, indicating CNTs are oxidized by the modified Hummer's method. The oxygen-containing groups in the C 1s spectrum of CNTs-SH (Figure 3(d)) then decrease significantly, and the peak intensity corresponding to the sp<sup>2</sup> carbon increases and becomes narrower than Figure 3(c), revealing the removal of oxygen-containing functional groups from CNTs during the reduction process [29-31]. In addition, the peak at 285.8 eV arises from the C-N/C-S bond in cysteamine (Figure 3(d)), providing further evidence that the cysteamine is bonded to



**Figure 4.** (a) The CV measurements of the CFCS electrodes between 1.6 and 2.6 V at scan rates of  $0.1 \text{ mV s}^{-1}$ ; (b) the 1st, 2 nd, 5th, and 20th galvanostatic charge/discharge voltage–capacity profiles at a current density of 0.5 C of CFCS cathodes; (c) the cycling stability of Li-S cells with CFCS as cathodes cycled at different current rate of 0.5 C, 1 C, 1.5 C and 2 C; (d) the long-term cycling performance and Coulombic efficiency of CFCS cathodes at a current density of 1 C.

the CNTs substrate. After covalently binding sulfur, due to the similar carbon chemical environment with CNTs–SH, CFCS exhibits similar C 1s spectra as shown in figure S4. The high-resolution S 2p spectra of CFCS are further studied (figure S5). The dual peaks of S–C bonds at 160.9 and 162.1 eV derive from cysteamine groups. Typical S–S bonds at 163.0 and 164.2 eV are ascribed to the covalent bonding of ring-opened on CNTs by sulfydryl groups. These observations mentioned above are consistent with the conclusions drawn from the survey spectra.

To evaluate the electrochemical performance of CFCS, cyclic voltammetry (CV) is directly investigated using CR2025 coin-type cells versus Li/Li<sup>+</sup>. The first five CV curves are shown in Figure 4(a) between 1.6 and 2.6 V at scan rates of 0.1 mV s<sup>-1</sup>. During the first cycle, two

cathodic peaks are observed at approximately 2.28 and 2.04 V, corresponding to a solid-to-liquid phase transition  $(nS + 2Li^+ + 2e^- \rightarrow Li_2S_n, (4 \le n \le 8))$  and a liquid-to-solid phase transition  $(Li_2S_n + 2(n-1)Li^+ + 2(n-1)e^- \rightarrow nLi_2S (n < 4))$ , respectively. In the first anodic sweep, an oxidation peak at 2.39 V is attributed to the oxidation of lithium sulfide to element sulfur. It is worth noting that the two reduction peaks in the subsequent cycles shift to higher potentials at 2.30 and 2.05 V, respectively, suggesting a reduced polarization after the first activation cycle, and the broad oxidation peak at 2.35–2.40 V indicates the reverse transformation from  $Li_2S_2/Li_2S$  to  $Li_2S_8/S_8$  [32, 33]. Meanwhile, the stable position and intensity of the peaks during the later four CV curves demonstrates robust electrochemical reversibility. The galvanostatic charge-discharge profiles at a current density of



**Figure 5.** In situ UV/Vis spectra measured during the first cycle of CFCS cells. In situ UV/Vis spectra during (a) discharge and (c) charge process and corresponded (b) discharge first-order derivatives and (d) charge derivatives. (e) Illustration of S–S bond energy with the initial  $Li^+$  insertion, all the models are shown in the most stable configuration. In the models, the hydrogen (H), carbon (C), nitrogen (N), oxygen (O) and sulfur (S) elements are displayed as spheres in cyan, blue, orange, red and yellow, respectively.

0.5 C (1 C = 1675 mA g<sup>-1</sup>) are shown in Figure 4(b). Consistent with the two cathodic peaks at 2.28 and 2.04 V in the CV curves, two typical plateaus are observed for the Li-S batteries in the first cycle, which are assigned to a two-step reaction of sulfur with lithium during the discharge process. It can be noted that a sluggish plateau of the CFCS electrode can be found in its first discharge process but remain stable during subsequent cycling, which indicates the establishment of efficient diffusion channels for ions and the accelerated kinetics due to the activation process and the wetting of cathode materials with electrolyte [34, 35]. It is remarkable that the initial and second specific discharge capacity is up to 1114 mAh g<sup>-1</sup> and 1083 mAh g<sup>-1</sup>, and after 20 cycles, both discharge and charge capacities are stabilized at about 1000 mAh g<sup>-1</sup>, further indicating excellent cell reversibility. Electrochemical impedance

spectroscopy (EIS) characterizations of CFCS and CNTs/S before and after 50 cycles are conducted as shown in figure S6. The results reveal that before cycling, the CFCS electrode shows a much lower charge transfer resistance (~30  $\Omega$ ) than CNTs/S electrodes (~78  $\Omega$ ), which indicates the poor interface charge transfer in CNTs/S electrode and fast lithium ion diffusion in CFCS electrode. After 50 cycles, a new semicircle in the high-frequency region arises, which could be assigned to the surface film resistance. The obvious higher interfacial resistance in the cell with CNTs/S electrode can be ascribed to the formation of SEI and insulating layer of solid Li<sub>2</sub>S/Li<sub>2</sub>S<sub>2</sub>. In contrast, the cell with CFCS electrode exhibits lower interfacial resistance value after cycling, which indicates less soluble polysulfides are generated and diffuse to the anode.

Figure S7 shows the comparison of cycling performance between CNTs/S (the mixture of CNTs and sulfur) and CFCS cathodes at a rate of 1 C. It is evident that the reversible capacity of CFCS was greatly enhanced (~900 mAh  $g^{-1}$ ) and after 100 cycles, the discharge capacity stabilizes at approximately 870 mAh  $g^{-1}$ , corresponding to a supreme capacity retention of 96.6% and a capacity fade rate of 0.033% per cycle. In contrast, the capacity of CNTs/S cathodes delivers only ~750 mAh  $g^{-1}$  during the initial several cycles and descends to 67% within 100 cycles, which corresponded to a high decay rate of 0.33% per cycle, further proving the effectiveness of the chemical interaction of CNTs and sulfur in restraint of the LiPS shuttle. To investigate the rate performance of the as-prepared CFCS, the cathodes were tested at different current rates ranging from 0.5 C to 2 C and fairly stable capacities at various rates are observed clearly (Figure 4(c)). The initial discharge capacity of 1114 mAh  $g^{-1}$  is delivered at 0.5 C. At a higher rate of 2 C, the cathode still afforded a capacity of 874 mAh g<sup>-1</sup> corresponding to 91% capacity retention compared with the second capacity after 100 cycles. The long cycle performance of CFCS cathodes is depicted in Figure 4(d) at a rate of 1 C. It can be see the reversible capacity increased from 780 mAh g<sup>-1</sup> to 920 mAh g<sup>-1</sup> during several cycles. After deep cycling for as many as 600 cycles, a high capacity of 620 mAh  $g^{-1}$  remained which exhibits the stable capacity retention of over 80% with high Coulombic efficiency of nearly 99.1%. The results suggest the CFCS cathodes exhibit excellent cyclic stability, which manifests the covalent interactions between sulfur and CNTs can effectively hinder the polysulfides shuttle phenomenon. In addition, the cycling performance of CFCS electrode is investigated with sulfur loading of 2.5 mg  $cm^{-2}$  at a current rate of 0.2 C (figure S8). The CFCS cells still show good cycling performance with capacity of 950 mAh  $g^{-1}$ and have capacity retention of 84% at 100 cycles, demonstrating the promising and potential practical application for efficient Li-S batteries.

To further explain the excellent properties discussed above, in-situ UV/Vis spectroscopy was employed to investigate LiPS intermediates that is soluble in electrolyte. Changes in the UV/Vis spectra in the range of  $\lambda = 650$  to 400 nm can be expected based on the observed differences in the color of electrolyte [36]. Long-, mid-, and short-chain polysulfides can be distinguished during the cycling process as long-chain polysulfides absorb light at higher wavelengths (towards the IR region) and short-chain polysulfides adsorb light closer to the UV part of the spectrum. A pouched negative electrode shell with a sealed cover glass, pouched lithium wafer, separators, electrolytes, and CFCS cathode was used as cell components to assemble a button cell for measurement. in-situ UV/Vis spectra in the range of 300 and 800 nm is displayed in Figure 5(a), which shows the UV/Vis spectra measured during the first discharge cycle. No significant shift of wavelengths can be seen during discharging, which is displayed in the related first-order derivatives more directly (Figure 5(b)). The derivatives show two characteristic positions peaked at 455 and 510 nm firstly which represent  $Li_2S_2$  and  $Li_2S_4$  [36]. With the proceeding of discharge process, the peaks shifted to  $\lambda = 470$  nm gradually, which is in agreement with the formation of  $Li_2S_3$ . As a contrast, the spectra of CNTs/S cathode as shown in figure S9 displays the reciprocating motion after ~2.08 V, which can be described to the conversion from long-chain to short-chain polysulfides. Figure 5(c) is the UV/Vis spectra measured during the first charge cycle and Figure 5(d) corresponds to the first-order derivative curves, which demonstrate the reverse process of discharging reaction. The complex conversion from short-chain to long-chain polysulfides during the charge process of the CNTs/S cathode is also revealed in figure S10. The findings can be verified by the DFT calculation method, which can investigate broken-bond model of linear polysulfane during cycling quantitatively and are presented in Figure 5(e). Initially, when the lithium atoms dynamically insert into CFCS, the calculations indicate the dissociation energy of the S4-S5 bonds is lower than the cleavage of other S-S bonds and thus are easier to break. After further Li<sup>+</sup> insertion reaction, the S1-S2 bond breaks and Li<sub>2</sub>S<sub>4</sub> forms, which can generate Li<sub>2</sub>S<sub>3</sub>, Li<sub>2</sub>S<sub>2</sub> and Li<sub>2</sub>S with further S-S breakage and Li<sup>+</sup> insert. DFT calculation results are in good agreement with in-situ UV/Vis spectra results.

#### 4. Conclusions

In summary, we demonstrated a new strategy to strongly trap soluble lithium polysulfides by using polar cysteaminefunctionalized CNTs for long-life lithium sulfur batteries. The discharge products during the charging-discharging process were identified by in-situ UV/Vis spectroscopy and theoretically confirmed by DFT calculations indicating the effective trapping of long-chain LiPS by polar groups in the CFCS cathodes. The long-term cycling tests demonstrate that the CFCS exhibits greatly improved capacity retention of over 80% for 600 cycles at high rates of 1 C, and the specific capacity is close to 920 mAh  $g^{-1}$  with a high Coulombic efficiency of nearly 99.1%. The excellent electrochemical performance confirms the polar group-functionalized CNTs can be an effective way to strongly trap soluble lithium polysulfides, which provides a new avenue for practical application for high performance Li-S batteries.

#### **Acknowledgments**

This work was supported by the National Natural Science Foundation of China (Nos. 51622208, 21703149, 51872193, and 5192500409) and Natural Science Foundation of Jiangsu Province (No. BK20181168). We acknowledge the financial support from the scientific research funding for high-level talents (No. 03083052) of Nantong University.

#### **Competing interests**

The authors declare no competing interests.

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