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## Fabrication of a novel TiO<sub>2</sub>/S composite cathode for high performance lithium–sulfur batteries

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Sulfur is an attractive cathode material with a high specific capacity of 1675 mA h g<sup>−1</sup>, but its rapid capacity decay due to polysulfide dissociation presents a significant technical challenge. Here, we present the fabrication of a TiO<sub>2</sub>/S composite cathode by encapsulating elemental sulfur into TiO<sub>2</sub> nanotube hosts for high performance lithium–sulfur batteries. A high capacity of 913 mA h g<sup>−1</sup> has been achieved at a rate of 0.2C in the initial cycle for the TiO<sub>2</sub>/S composite cathode with a sulfur content of 65 wt% and the reversible capacity remains as high as 851 mA h g<sup>−1</sup> after 100 cycles. The improvements of electrochemical performances were attributed to the good dispersion of sulfur in the TiO<sub>2</sub> nanotubes and the excellent adsorbing effect on polysulfides of TiO<sub>2</sub>.

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## Introduction

The emerging fields of electric vehicles and hybrid electric vehicles demand significant improvement of rechargeable battery technologies to achieve higher energy densities.<sup>1–3</sup> Unfortunately, the energy density and cycle life of the presently available lithium-ion battery (LIB) remain insufficient for many of the aforementioned applications.<sup>4,5</sup> Lithium–sulfur (Li–S) batteries have been reported as one of the highly promising rechargeable lithium batteries due to the high theoretical capacity (1675 mA h g<sup>−1</sup>), high energy density (2600 W h kg<sup>−1</sup>), low cost, and natural abundance of sulfur.<sup>4–6</sup> Although this battery system has been attracting attention for more than two decades, it has not been commercialized on a large scale due to several unsolved problems. It is known that sulfur particles suffer from the problems of: (a) poor electronic conductivity, (b) dissolution of intermediate polysulfides (creating an internal “shuttle effect”), and (c) large volumetric expansion (~80%) upon lithiation, which result in a rapid capacity decay and low coulombic efficiency.<sup>7–11</sup> Therefore, enhancing the ionic/electronic conductivity and trapping the polysulfides to prevent the dissolution are critical to develop high energy density and long-lasting Li–S batteries.

To tackle the issues, sulfur is always combined with porous substrates through proper structural designs (surface coating and/or sulfur loading) to effectively confine sulfur on the

cathode side and limit dissolution of polysulfides in electrolyte. These substrates include mesoporous carbon,<sup>12,13</sup> microporous carbon,<sup>14</sup> graphene,<sup>15,16</sup> porous carbon fibers,<sup>13,17,18</sup> polymer additives,<sup>19,20</sup> and metal oxides<sup>21–23</sup> that limit the dissolution of polysulfides through both physical and chemical interactions.

Recently, the advance in design and synthesis of the suitable porous substrates with a strong ability to chemically absorb sulfur species is particularly attractive.<sup>24</sup> For example, Wang *et al.* demonstrated noticeable enhancements in the cycling stability caused by nitrogen doping promoted chemical adsorption in a series of nitrogen-doped nanocarbon based cathodes.<sup>24–26</sup> Meanwhile, metal oxides, such as TiO<sub>2</sub>,<sup>7</sup> Ti<sub>4</sub>O<sub>7</sub>,<sup>21</sup> and MnO<sub>2</sub>,<sup>27</sup> were also proved to be an efficient intermediary to form the strong chemical bonding between polysulfides and metal oxides. As a result, these semiconducting or metallic oxides have been introduced into the cathode as high-performance sulfur host materials.

Hence, in this work, we design and fabricate a novel structured cathode for Li–S batteries, with sulfur encapsulated in a TiO<sub>2</sub> nanotube host, as illustrated in Fig. 1. In this cathode, TiO<sub>2</sub> nanotubes were prepared by an improved hydrothermal process and a subsequent thermal treatment,<sup>28,29</sup> and the TiO<sub>2</sub>/S composites were prepared by a typical melt-diffusion strategy. Electrochemical measurements indicate that the TiO<sub>2</sub>/S composite exhibits excellent cycling stability, which is mainly attributed to the significant roles that the TiO<sub>2</sub> nanotubes played during the electrochemistry reactions. The TiO<sub>2</sub> nanotubes can prevent the polysulfides from dissolving in electrolyte and minimize the “shuttle effect”; at the same time, can promote the interaction between TiO<sub>2</sub> and S, which was believed to be an electrostatic attraction (S–Ti–O) that improved the surface adsorption of polysulfides onto TiO<sub>2</sub> surfaces.<sup>13,30</sup>

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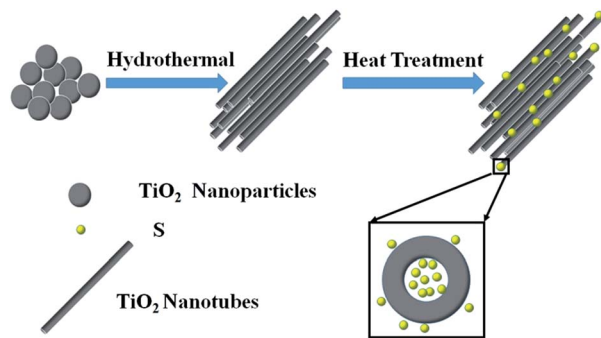


Fig. 1 Schematic illustration of the assembled  $\text{TiO}_2/\text{S}$  composites for improving cathode performance.

## Experimental

### Fabrication of $\text{TiO}_2$ nanotubes

The  $\text{TiO}_2$  nanotubes were synthesized by a hydrothermal method.<sup>29</sup> In a typical process, 0.4 g of  $\text{TiO}_2$  powder was dispersed into 60 mL of NaOH solution (10 M) with continuous stirring for 10 min. After that, the obtained solution was transferred into 100 mL Teflon-lined stainless-steel autoclave, which was put inside a silicon oil bath on a hot plate and the reaction temperature was set at 150 °C for 24 h while the stirring rate is 800 rpm. After reaction, the autoclave was taken out from the oil bath and cooled to room temperature. The product, sodium titanate, collected by vacuum drawing and filtering, was washed with deionized water for several times to reach a pH value of 9. After that, the sodium titanate was subjected to a hydrogen ion exchange process in a diluted  $\text{HNO}_3$  solution (0.1 M) for three times. Finally, the suspension was filtered again, washed with deionized water for several times until a pH value of 7 was reached, generating the hydrogen titanate nanotube. Then the hydrogen titanate nanotube was heated at 450 °C for 2 h in a muffle furnace and the  $\text{TiO}_2$  nanotubes was obtained after cooling down to room temperature.

### Preparation of $\text{TiO}_2/\text{S}$ composites

To prepare  $\text{TiO}_2/\text{S}$  composites, elemental sulfur was mixed with  $\text{TiO}_2$  nanotubes while the mass ratio could be controlled. In a typical experiment, the  $\text{TiO}_2$  nanotubes and elemental sulfur were mixed with a mass ratio of 1 : 1.05 (1 : 2.05). Then the mixtures were heated at 155 °C for 10 h in a sealed vessel filled with argon gas. After cooling down, the  $\text{TiO}_2/\text{S}$  composites with a mass ratio of 1 : 1 (1 : 2) were obtained.

### Characterization

X-ray diffraction (XRD) patterns were measured on an X'Pert PRO MPD. Cu K line was used as a radiation source with  $\lambda = 0.15418$  nm. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) measurements were carried out with Quanta 600 FEG and FEI Tecnai F30G<sup>2</sup>, respectively. The  $\text{N}_2$  adsorption-desorption were determined by Brunauer-Emmett-Teller (BET) measurements using an ASAP-2020 surface area analyzer. The sulfur content of  $\text{TiO}_2/\text{S}$  was

determined by a thermal gravimetric analysis (TGA/SDTA851, Switzerland) from room temperature to 500 °C at a ramping rate of 10 °C  $\text{min}^{-1}$  in air flow.

### Electrochemical measurements

The  $\text{TiO}_2/\text{S}$  electrode was prepared by mixing the  $\text{TiO}_2/\text{S}$  composites, acetylene black and polyvinylidene fluoride (PVDF) at a weight ratio of 70 : 20 : 10 in *N*-methyl-2-pyrrolidone (NMP) to form homogeneous slurry under magnetic stirring. The slurry was then plastered onto aluminum foil using a doctor blade, and dried at 60 °C for 24 h in a vacuum oven. The areal mass loading of sulfur is  $\sim 1.1$   $\text{mg cm}^{-2}$ . The electrochemical measurements were performed by two-electrode coin cells (CR 2016) with Li foil as both counter electrode and reference electrode at ambient temperature and polypropylene (PP) film as the separator. The electrolyte was 1 M lithium bis(tri-fluoromethanesulfonyl)imide (LiTFSI) and 0.1 M  $\text{LiNO}_3$  in a mixed solvent of 1,3-dioxolane (DOL) and 1,2-dimethoxyethane (DME) with a volume ratio of 1 : 1. The coin cells were galvanostatically charged-discharged at different current densities between 1.8 and 3.0 V (vs.  $\text{Li/Li}^+$ ) using a CT2001A cell test instrument (LAND Electronic Co, BT2013A, China). The cyclic voltammetry (CV) test and electrochemical impedance spectroscopy (EIS) measurement were performed on electrochemical workstation (Solartron analytical 1400) with a voltage range of 1.8–3.0 V (vs.  $\text{Li/Li}^+$ ) at a scanning rate of 0.1  $\text{mV s}^{-1}$  and a frequency window from 0.01 Hz to 100 kHz while the disturbance amplitude was 5 mV, respectively.

## Results and discussion

### Characterization of prepared $\text{TiO}_2$ nanotubes and $\text{TiO}_2/\text{S}$ composites

Fig. 2 shows the XRD patterns of  $\text{TiO}_2$  nanotubes,  $\text{TiO}_2/\text{S}$  composites, element sulfur, and the mixture of  $\text{TiO}_2$  nanotubes and elemental sulfur. All of the identified peaks can be perfectly indexed to anatase  $\text{TiO}_2$  (JCPDS card no. 21-1272). In the XRD pattern of the mixture of  $\text{TiO}_2$  nanotubes and elemental sulfur, the intense diffraction peaks of crystallized sulfur and anatase  $\text{TiO}_2$  could clearly be observed. In contrast, the diffraction peaks of sulfur become very weak after being encapsulated into the  $\text{TiO}_2$  nanotube hosts, indicating good dispersion of sulfur within the  $\text{TiO}_2$  nanotube host, which is similar to that of carbon/sulfur composites in previous reports.<sup>31</sup> However, because of the high loading of sulfur, some sulfur coating on the surface might nucleate to form sulfur particles.

The SEM images of commercial  $\text{TiO}_2$  particles and  $\text{TiO}_2$  nanotubes are shown in Fig. 3a and b. It can be clearly identified that the typical diameter of the  $\text{TiO}_2$  particles is in range of 100–120 nm (Fig. 3a) while the average diameter of  $\text{TiO}_2$  nanotubes is about 80–100 nm (Fig. 3b). After elemental sulfur encapsulating, the morphology of the  $\text{TiO}_2/\text{S}$  composites (Fig. 3c) becomes continuous and disorganized. To further determine the distribution of elemental sulfur in the  $\text{TiO}_2/\text{S}$  composites, element mappings for the composites had been taken. Fig. 3d–f show the element mappings for sulfur, titanium



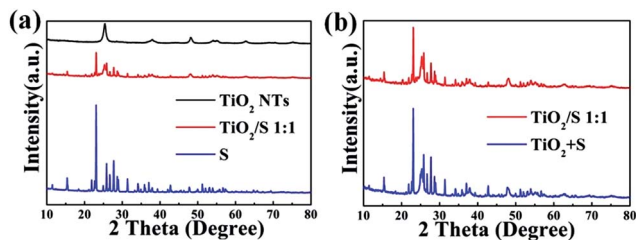


Fig. 2 XRD patterns of (a) TiO<sub>2</sub> nanotubes, TiO<sub>2</sub>/S composites, elemental sulfur and (b) TiO<sub>2</sub>/S composites, the mixture of TiO<sub>2</sub> nanotubes and elemental sulfur.

and oxygen based on the area shown in Fig. 3c. The element mappings for sulfur and titanium display a very similar intensity distribution, further indicating that element sulfur are uniformly distributed in the TiO<sub>2</sub>/S composites. This result can also be verified from the following TEM image and corresponding element mapping (Fig. 4).

Nitrogen adsorption-desorption isotherms and pore size distribution curves of the prepared TiO<sub>2</sub> derived from BET measurements are depicted in Fig. 5. The nanotube structure of TiO<sub>2</sub> nanotube gives rise to a relatively high BET surface area of 134.85 m<sup>2</sup> g<sup>-1</sup> and a pore volume of 0.69 cm<sup>3</sup> g<sup>-1</sup>. The nitrogen adsorption-desorption isotherms of the TiO<sub>2</sub>/S composites with a mass ratio of 1 : 1 and 1 : 2 were also shown in Fig. 5. It's clear that the adsorption volumes become lower. The BET surface area of TiO<sub>2</sub>/S composites (1 : 1 and 1 : 2) dramatically decreases to 40.70 m<sup>2</sup> g<sup>-1</sup> and 11.52 m<sup>2</sup> g<sup>-1</sup>, respectively. In addition, with the increasing of the sulphur loading, the pore size distribution plot in Fig. 5b shows that there is a significant decrease of small mesopores from 2 to 4 nm, while the large mesopores are also slight reduced. The BET results indicate that

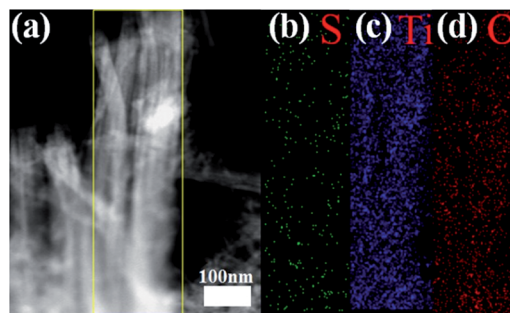


Fig. 4 TEM image of (a) TiO<sub>2</sub>/S composites and the corresponding element mapping of (b) S, (c) Ti and (d) O.

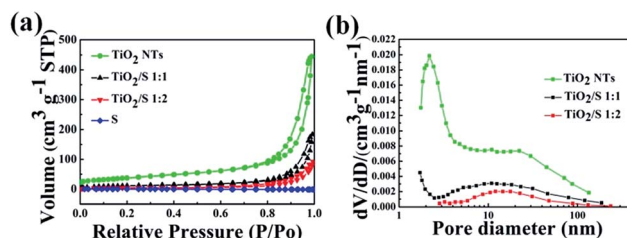


Fig. 5 (a) Nitrogen adsorption-desorption isotherms of TiO<sub>2</sub> nanotubes, TiO<sub>2</sub>/S composites (1 : 1, 1 : 2), element sulfur and (b) corresponding pore-size-distribution.

the loaded sulfur in TiO<sub>2</sub>/S composites mainly occupies the mesopores of TiO<sub>2</sub> nanotubes.

The thermal decomposition characteristic of the TiO<sub>2</sub>/S composites (the mass ratios of TiO<sub>2</sub> nanotubes and S are 1 : 1 and 1 : 2) was investigated under an air atmosphere by means of TGA (Fig. 6). Both TGA curves of TiO<sub>2</sub>/S composites show one weight loss stage from around 200 to 300 °C, which corresponds to the evaporation of sublimed sulfur. The corresponding weight loss of TiO<sub>2</sub>/S composites is approximately up to 50 wt% and 65 wt%, respectively, which is consistent with the proportions of the added amount.

### Electrochemical properties of the TiO<sub>2</sub>/S composites electrode

CV curves of pristine sulfur electrode and the TiO<sub>2</sub>/S composite cathodes (1 : 1, 1 : 2) at a scan rate of 0.1 mV s<sup>-1</sup> are shown in Fig. 7. Fig. 7a shows a typical CV curve of pure sulfur electrode. The peak at 2.30 V associates with the conversion of elemental

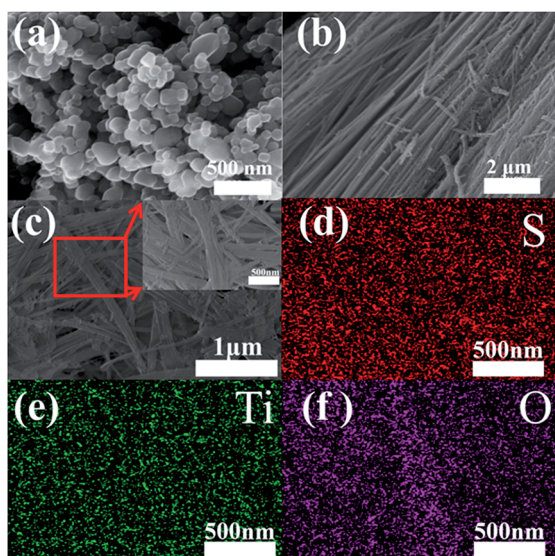


Fig. 3 SEM images of (a) commercial TiO<sub>2</sub> particles and (b) TiO<sub>2</sub> nanotubes; (c) FESEM image of TiO<sub>2</sub>/S composites; inset: high resolution FESEM image of the TiO<sub>2</sub>/S composites, and the corresponding element mapping of (d) S, (e) Ti and (f) O.

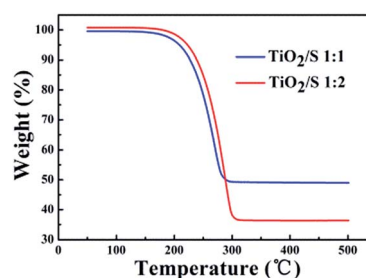


Fig. 6 TGA curves of TiO<sub>2</sub>/S composites.





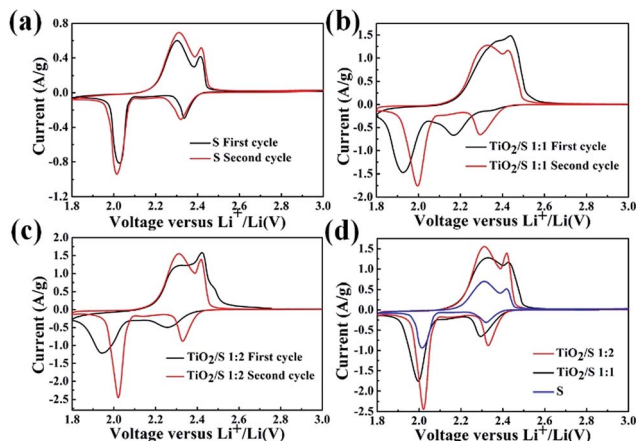
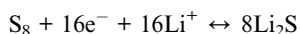


Fig. 7 Typical CV curves at  $0.1 \text{ mV s}^{-1}$  of (a) element sulfur cathode and  $\text{TiO}_2/\text{S}$  composites cathode (b) (1 : 1), (c) (1 : 2); CV curves of the second cycle of the three electrode mentioned above (d).

sulfur to soluble lithium polysulfide ( $\text{Li}_2\text{S}_n$ ,  $4 \leq n \leq 8$ ), and the peak at 2.05 V is related to the reduction of lithium polysulfides to insoluble  $\text{Li}_2\text{S}_2$  and  $\text{Li}_2\text{S}$ .<sup>32–34</sup> In the anodic scan, two oxidation peaks are observed at the potentials of 2.36 V and 2.45 V, which correspond to the conversion of  $\text{Li}_2\text{S}$  into high-order soluble polysulfides.<sup>35,36</sup> Therefore, according to the CV curves, the “integration” reaction of elemental sulfur is the mainly electrochemical reaction process of the  $\text{TiO}_2/\text{S}$  composites cathode, as denoted in equation below.



When compared with the CV curve of the element sulfur cathode (Fig. 7a), obvious differences could be observed from the CV curves of  $\text{TiO}_2/\text{S}$  composites (Fig. 7b and c). The curves of the initial cycle are quite different from that of pure sulfur electrode, which is possibly owing to the redistribution of sulfur in the cathode through the electrochemical reactions at first cycle.

Cycling performance and rate capability of the  $\text{TiO}_2/\text{S}$  composite cathodes (1 : 1, 1 : 2) and the element sulfur cathode are presented in Fig. 8. All capacity values in this study were calculated based on sulfur mass. Fig. 8a displays the cycling performance of the  $\text{TiO}_2/\text{S}$  composite cathodes (1 : 1, 1 : 2) and the element sulfur cathode at a current rate of 0.2C (1C =  $1675 \text{ mA g}^{-1}$ ). The initial specific discharge capacity of the

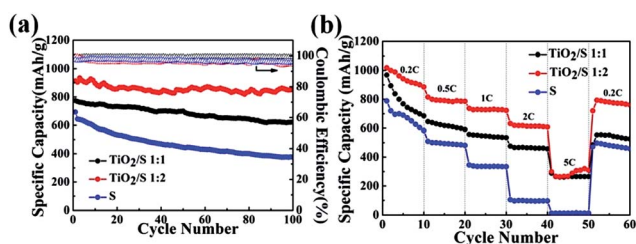


Fig. 8 (a) Cycling performances and (b) rate capability of the  $\text{TiO}_2/\text{S}$  composites cathode and the element sulfur cathode.

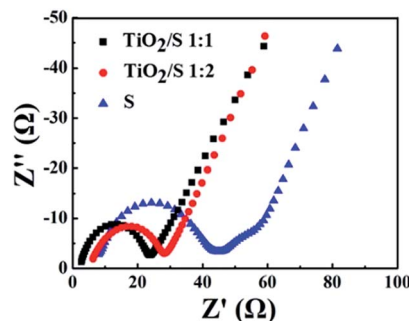


Fig. 9 Impedance plots for the element sulfur cathode and the  $\text{TiO}_2/\text{S}$  composite cathodes after 100 cycles. The insets show the corresponding EIS spectra at the high frequency domain.

$\text{TiO}_2/\text{S}$  composite cathodes (1 : 1, 1 : 2) is about  $795 \text{ mA h g}^{-1}$  and  $913 \text{ mA h g}^{-1}$ , respectively. After 100 cycles, the specific discharge capacity of the  $\text{TiO}_2/\text{S}$  composite cathodes (1 : 1, 1 : 2) still retains  $618 \text{ mA h g}^{-1}$  and  $851 \text{ mA h g}^{-1}$ , respectively. The excellent cyclic stability can be attributed to the good dispersion of sulfur in the  $\text{TiO}_2$  nanotube hosts. More importantly, chemical bond interaction between the titania and sulfur could permit fixed confinement of sulfur, which is critical to restrain the polysulfides and minimize the “shuttle effect”.<sup>13,21,30,37</sup> Moreover, Fig. 8b obviously demonstrates that the rate performance of the  $\text{TiO}_2/\text{S}$  composite cathodes (1 : 1, 1 : 2) is better than that of element sulfur cathode. The former can deliver a specific discharge capacity of  $295 \text{ mA h g}^{-1}$  and  $302 \text{ mA h g}^{-1}$ , respectively, at a current rate of 5C, however, the element sulfur cathode could not deliver any discharge capacity at the same current density.

To further clarify the roles of  $\text{TiO}_2$  nanotubes played in the  $\text{TiO}_2/\text{S}$  composite cathode, the EIS spectra of the  $\text{TiO}_2/\text{S}$  composite cathodes (1 : 1, 1 : 2) and element sulfur cathode after 100 cycles were also measured. As shown in Fig. 9, all the EIS spectra were composed of a semicircle at high frequency and a nearly straight line at low frequency. The depressed semicircle in the high frequency region is assigned to the charge-transfer resistance ( $R_{ct}$ ), while the inclined line in the low frequency region represents the Warburg impedance ( $W$ ), which is related to solid-state diffusion of lithium ions into the electrode material.<sup>38–41</sup> It can be seen that the charge-transfer resistances of the two  $\text{TiO}_2/\text{S}$  composites cathodes are much lower than that of element sulfur cathode. It could be attributed to the better conductivity of  $\text{TiO}_2$ , which is a semiconductor, compared to sulfur, which is an insulator, and the nanotube-structure of the  $\text{TiO}_2/\text{S}$  composite cathodes, which is helpful to absorb lithium polysulfides and reduce the negative impact of insulating precipitation on the cathode.<sup>32,42</sup>

## Conclusions

In summary, a novel  $\text{TiO}_2/\text{S}$  cathode, consisted of  $\text{TiO}_2$  nanotubes and homogeneously distributed sulfur, has been successfully prepared by a typical melt-diffusion strategy. The  $\text{TiO}_2/\text{S}$  composite shows high specific capacities and good



cycling stabilities as well as rate capability, due to the crucial role  $\text{TiO}_2$  nanotube plays in the  $\text{TiO}_2/\text{S}$  composite cathode during the electrochemical reaction. The specific capacity of  $\text{TiO}_2/\text{S}$  composite reaches as high as  $913 \text{ mA h g}^{-1}$  in the initial cycle and remains above 93% after 100 cycles when the loaded weight of sulfur in the  $\text{TiO}_2/\text{S}$  composite is 65 wt%. This result indicates that the  $\text{TiO}_2$  nanotube hosts could prevent the polysulfides from dissolving in the electrolyte and minimize the “shuttle effect” efficiently and successfully.

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