High-performance nitrogen-doped titania nanowire decorated carbon cloth electrode for lithium-polysulfide batteries

Y.X. Ren, T.S. Zhao*, M. Liu, L. Wei, R.H. Zhang

HKUST Energy Institute, Department of Mechanical and Aerospace Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

**A R T I C L E   I N F O**

Article history:
Received 10 February 2017
Received in revised form 31 March 2017
Accepted 30 April 2017
Available online 4 May 2017

Keywords:
Li-S battery
carbon cloth
nanowire
adsorption precipitation

**A B S T R A C T**

A semi-liquid polysulfide cathode renders a higher sulfur loading for Li-S batteries. However, the aggravated polysulfide shuttle effect and the poor interaction between polysulfide and carbonaceous electrode lower the battery's cycling stability and performance. Here we report a freestanding N-TiO2 nanowire (NW) decorated carbon cloth electrode for a Li-polysulfide battery, where the nitrogen doping in the formed nanowires allows for a higher electrical conductivity and stronger polysulfide binding ability. Meanwhile, with the facile adsorption of $S^2_8$ and more active sites provided by the nanowire structure, Li$_2$S precipitation can be improved as well. With the rationally engineered nanostructured polysulfide binding electrode, the battery achieves a remarkably enhanced cycling stability and prolonged discharge capacity (1210 mAh g$^{-1}$, 0.2C and 600 mAh g$^{-1}$, 1C), in comparison with the pristine carbon cloth (890 mAh g$^{-1}$, 0.2C and 210 mAh g$^{-1}$, 1C). The facile strategy of fabricating conductive and polysulfide binding nanostructure in this work is thus expected to facilitate the design of high-energy sulfur cathode.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Beyond the horizon of Li-ion batteries, rechargeable lithium-sulfur (Li-S) batteries nowadays hold the promise of prolonging electric vehicles’ mileage. Predominantly, the Li-S cathode discharge electrochemistry is the lithiation of S$_8$ to form Li$_2$S at the cathode ($S_8 + 16Li^+ + 16e^- \rightarrow 8Li_2S$), with Li stripping occurring at the anode ($Li - e^- \rightarrow Li^+$) [1–9]. Though the high specific capacities of Li anode (3860 mAh g$^{-1}$) and sulfur cathode (1673 mAh g$^{-1}$) render a high theoretical specific energy for the Li-S battery, critical issues arise from the inherent multiple-step cathodic reactions ($S_8 \rightarrow S_2^- \rightarrow S_2^{2-} \rightarrow S_4^{2-} \rightarrow Li_2S$). One is the dissolution of reactive polysulfide anions (so called “shuttle effect”), which can irreversibly passivate the Li anode and shorten the battery’s cycle life. The other concerns for the insulating nature of Li$_2$S ($< 10^{-14}$ S cm$^{-1}$ RT) as the final discharge product, leading to the necessity to facilitate Li$_2$S precipitation in the conductive matrix [10–13].

A variety of sulfur cathodes has thus been designed to fulfill the roles of conductive host as well as polysulfide reservoir. The conductive matrix is usually carbon material with different pore scales. One approach is to encapsulate sulfur in the microporous or mesoporous carbon, which confines polysulfides and Li$_2$S within the pores and thus mitigates the polysulfide shuttle effect [11,14–20]. Though the battery's cycle life can be prolonged, such a confinement strategy meets the challenge of the inferior sulfur loading and requires the use of metallic current collector [5,14]. An alternative approach is to adopt porous current collectors, such as the carbon paper, carbon cloth, CNT paper and graphene sponge, which eliminates the use of metallic current collectors and allows for using energy dense polysulfides (Li$_2$S$_8$ or Li$_2$S$_6$) as the starting active material [21–35]. A higher areal sulfur loading can be usually attained owing to their more porous structure. However, there are usually loose bindings between non-polar carbon and polysulfides/ Li$_2$S, leading to (i) fast polysulfide dissolution and aggravated side reactions on the Li anode; (ii) the sluggish Li$_2$S precipitation reaction ($2Li^+ + S_2^{2-} + 2e^- \rightarrow Li_2S$), and thus a lower utilization of active material [22–24,36–38].

Identifying polysulfide binding material (PBM) is thus critical for improving the battery’s performance and has drawn increasing research efforts [11,13,39–47]. Polar metal oxides, such as Al$_2$O$_3$, TiO$_2$ and Ti$_6$O$_7$, have been identified to adsorb electron-donating polysulfides on their electron-accepting metal sites by forming Lewis acid-base bonds [48–52]. It is reported that exploring metal

* Corresponding author.
E-mail address: metzhao@ust.hk (T.S. Zhao).

http://dx.doi.org/10.1016/j.electacta.2017.04.171
0013-4686/© 2017 Elsevier Ltd. All rights reserved.
oxides with lithiation potential higher than the sulfur redox reactions, such as δ-MnO2 and V2O5, can facilitate the transformation of polysulfides to Li2S by generating thiosulfate/polysulphonate redox mediators [41,49,53]. In addition to controlling polysulfide shuttles, with facile adsorption of polysulfides, adding polysulfide binding material can also provide controllable amounts of Li2S nucleation sites, which shows a potential for accelerating Li2S precipitation kinetics [12,49,54–56]. Though promising, a constraining factor is that the majority of PBMs are nonconductive and the absorbed polysulfides need to diffuse to the conductive carbon to undergo further reactions [51]. Enabling conductive polysulfide binding nanostructure that balances surface adsorption and reactions is thus of a notable significance.

To address this issue, an efficient nanostructured carbon cloth electrode is proposed for Li-polysulfide batteries (sulfur loading 4.8 mg cm\(^{-2}\)) in this work. Specifically, we synthesized self-supported TiO2 nanowires onto the carbon fiber surface. We show that, with nitrogen doping, the electrical conductivity as well as the polysulfide binding ability of the formed nanowires can be enhanced spontaneously, which facilitates both polysulfide adsorption and Li2S precipitation. As a result, batteries assembled with N-TiO2 nanowire decorated carbon cloth (denoted as N-TiO2 NW @ CC) electrodes show a much more stable cycling performance and a remarkable increase in discharge capacity (1210 mAh g\(^{-1}\) at 0.2C and 600 mAh g\(^{-1}\) at 1C), much better than the control group with pristine carbon cloth (890 mAh g\(^{-1}\) at 0.2C and 210 mAh g\(^{-1}\) at 1C).

2. Experimental

2.1. Material preparation

The Li2Sx solution was prepared by dissolving a desired amount of stoichiometric S and Li2S in 1,3-dioxolane (DOL)/1,2-dimethoxyethane (DME) solution (1:1 in volume) with the addition of 1 M LiTFSI and LiNO3 additive (1 wt.%). For the typical preparation of 0.5 M Li2Sx solution, 0.560 g of S and 0.115 g of Li2S were added to 5 mL of DOL/DME (1:1) based electrolyte. The obtained suspension was stirred and heated at 80 °C overnight to yield red-brown Li2Sx solution.

2.2. Preparation of N-TiO2 NW @ carbon cloth

Free-standing TiO2 nanowires were grown directly on carbon cloth by a two-step process [57]. Carbon cloths (6.0 cm × 3.0 cm) were thoroughly rinsed with ethanol, and then dried at room temperature for 12 h. The cleaned carbon cloths were immersed into 0.2 M titanium(IV) chloride aqueous solution for 10 min and blow-dried with compressed air. The dried carbon cloths were further heated on a hotplate in air at 350 °C for 10 min, forming TiO2 nanoparticles on the carbon fiber surface (TiO2 nanoparticle seeded substrate). 18.75 mL of concentrated hydrochloric acid (35%) was diluted with 18.75 mL deionized (DI) water, and mixed with 0.56 mL titanium n-butoxide. This clear solution mixture together with the carbon cloth coated with TiO2 seeds were transferred to a Teflon-lined stainless steel autoclave (50 mL volume). The sealed autoclave was heated in an electric oven at 150 °C for 6 hours, and then cool down slowly at room temperature. A white TiO2 nanowire film was uniformly coated on the carbon cloth surface. The obtained carbon cloth was further annealed in air at 550 °C for 1 hour to stabilize the nanowire structure. The areal loading of TiO2 NW (1.60 ± 0.15 mg cm\(^{-2}\)) was determined by measuring the weights of carbon cloths before and after the hydrothermal synthesis.

To convert TiO2 to nitrogen doped-TiO2 (N-TiO2), the samples were respectively annealed under ammonia atmosphere at temperatures of 700 °C or 800 °C for 1.5h. The color of the nanowire film transformed from white to black subsequent to the annealing process.

2.3. Cell assembly and test

One piece of lithium foil (16 mm diameter) was placed onto the bottom Cu cell body. One piece of Celgard (2500) separator (18 diameter) was placed onto the lithium foil, following by the addition of 12 μL DOL/DME electrolyte (1 M LiTFSI and LiNO3 additive (1 wt.%)). Subsequently, a piece of hydrophilic carbon cloth (10 mm, 0.79 cm\(^{-2}\)) was exploited as the cathode and 30 μL 0.5 M Li2Sx catholyte was uniformly dropped onto the carbon cloth cathode, with a theoretical areal sulfur loading around 4.8 mg cm\(^{-2}\) (S→Li2S). The galvanostatic discharge and charge tests were conducted on a battery cycling system (Neware, CT-3008W) at room temperature (298 K).

2.4. Material characterization

The discharged cathodes after cycling were soaked in pure DME for 10 minutes and then dried before SEM observation. JSM-6700F field emission SEM instruments were used for micrograph observation at an acceleration voltage of 5.0 kV. Transmission electron-microscopy (TEM) images of N-TiO2 nanowires were measured by a high-resolution JEOL 1010F TEM system with a LaB6 lamp at 200 kV. The samples were dispersed in ethanol, sonicated and dripped onto the regular carbon-coated Cu grids. The crystal phase and composition of the nanowires were analyzed by a Philips high-resolution X-ray diffraction system (XRD, model PW 1825) using a Cu-Ka source operating at 40 kV and a Micro-Raman spectrophotometer (Renishaw RM 3000) at an excitation wavelength of 514 nm.

2.5. Soaking experiment and surface analysis

20 mM Li2Sx solution was also prepared by dissolving a desired amount of stoichiometric S and Li2S in 1,3-dioxolane (DOL)/1,2-dimethoxyethane (DME) solution (1:1 in volume) electrolyte. Commercial TiO2 and TiN powders with similar particle sizes (~30 nm) were obtained from Sigma-Aldrich. To convert TiO2 to nitrogen doped-TiO2 (N-TiO2), the samples were respectively annealed under ammonia atmosphere at temperatures of 700, 800 °C for 1.5h. 20 mg sample material [#1-4] were added into 1 mL 20 mM Li2Sx in DOL/DME respectively and the obtained suspensions were rigorously sonicated for 1 h before observation. To prepare the samples for XPS surface analysis, the sample material impregnated with Li2Sx were filtered, dripped in the glove box and transferred to the XPS setup in a sealed box to exclude the effects of moisture and oxygen. The X-ray photoelectron spectroscopy (XPS) was performed using a Physical Electronics PHI 5600 multi-technique system equipped with an Al monochromatic X-ray source at a power of 350 W. The binding energy values were all calibrated using the C 1s peak at 285.0 eV.

3. Results and discussion

The carbon cloth (Fig. 1a) was exploited as the current collector in Li-polysulfide batteries, as it renders an excellent liquid absorbence for the semi-liquid cathode and accommodates the volume change induced by the charge/discharge product formation over repeated cycles owing to its robust interweave structure [22,23,30,58,59]. TiO2, as one of the earliest recognized polysulfide binding material was selected [14,25,32–34]. In the latter section, we demonstrate that by growing one-dimensional TiO2 nanowire on the carbon fiber surface and improving TiO2’s surface properties (nitrogen doping) (Fig. 1b), an enlarged electrode/electrolyte...
interface, a stronger polysulfide binding ability as well as an excellent electronic conductivity can be spontaneously rendered for the electrode surface (Fig. 1c, d) [60].

As shown in Fig. 2a, the pristine carbon fiber is usually highly graphitized and possesses a smooth morphology [60]. To prepare the N-TiO2 @ CC electrode, a dense TiO2 nanowire coverage was firstly obtained by hydrothermal synthesis followed by thermal treatment in air. These stabilized nanowires adhere to the surface of the carbon fiber without any binder, which is beneficial for exposing larger active surface to the electrolyte. On the other hand, surface properties of TiO2 can be improved by reducing Ti4+ and creating oxygen vacancies. Previous studies have reported that hydrogen-reduced TiO2 (TiO2−x) can function as an efficient sulfur host [49,61,62]. However, it is usually demanding to construct freestanding TiO2−x structure as the hydrogen reduction of TiO2 requires a higher annealing temperature (usually above 1000 °C) and can usually destroy the nanostructured electrode [63]. In addition to hydrogen reduction, we realize that a facile and effective route to reduce Ti4+ is nitrogen doping. The abundant Ti-N bonds render the N-TiO2 a narrow band gap and thus facilitate charge transfer [57,64]. Also, the electron-accepting oxygen vacancies formed by the Ti-N bonds allow for a more facile binding with the electron-donating polysulfides [65–67]. Therefore, nitrogen doping in the formed nanowires can contribute to improve the electronic conductivity and polysulfide binding ability spontaneously.

Conversion of TiO2 to N-TiO2 was realized by annealing the samples under NH3 atmosphere at 800 °C to avoid heat distortion on the nanowire morphology. The crystal structure of the obtained

Fig. 1. (a) SEM image of the pristine carbon cloth; (b) photography of the carbon cloths at different synthesis steps; (c, d) the schematics of the electrode surfaces of the pristine carbon cloth (c) and the conductive polysulfide binding nanowire decorated carbon cloth (d).

Fig. 2. SEM image of (a) pristine carbon cloth; (b) HRTEM image of one typical N-TiO2 nanowire (nitridated at 800 °C); (c) crystal structure of the N-TiO2 nanowire and corresponding fast Fourier transform (FFT) pattern; (d, e) SEM image of N-TiO2 NW @ carbon cloth. (f) XRD spectra of TiO2 NW @ CC and N-TiO2 NW @ CC electrodes (The blue and red dashed lines highlight peaks corresponding to rutile TiO2 and cubic phase TiN, respectively). (g) Raman spectra of TiO2 NW @ CC and N-TiO2 NW @ CC electrodes.
N-TiO₂ nanowires was analyzed by high-resolution transmission electron microscopy (HRTEM) as shown in Fig. 2(b, c). The images reveal that the deposited nanowire possesses a high degree of crystallinity with an interfringe distance of about 2.48 Å, which can be indexed to the (111) plane of the face-centered cubic-structured TiN. Moreover, as shown in Fig. 2d and e, a dense layer of nanowire coverage on the carbon fiber was successfully obtained.

XRD measurement was further conceived to confirm the structure transformation after nitrogen doping as can be seen in Fig. 2f. The original TiO₂ sample shows intense peaks of rutile TiO₂ (JCPDS #21-1276). After nitridation at 800 °C, the obtained samples exhibit diffraction peaks at 36.7°, 42.6°, 61.8°, corresponding to the (111), (200) and (220) planes of the cubic TiN phase (JCPDS #65-0714) [68]. Such conversion can be further verified with the Raman spectra in Fig. 2g. The TiO₂ sample displays four characteristic peaks at around 145, 236, 445 and 609 cm⁻¹, while after nitridation the TiN phase shows other three peaks at around 201, 323 and 552 cm⁻¹. The cubic TiN phase has thus been successfully obtained after nitridation, in well consistence with the XRD measurement.

The as-prepared nanowire structured electrode is expected to exhibit polysulfide binding ability. Here, we probe the role of nitrogen doping in the chemisorption function of TiO₂ material, exploiting soaking experiment as well as surface analysis (the details can be found in experimental section). Four samples were impregnated with polysulfides, including rutile TiO₂ (#1), rutile TiO₂ annealed under NH₃ atmosphere at 700 °C for 1.5 h (#2), at 800 °C for 1.5 h (#3) and commercial TiN (#4). As shown in the optical image in Fig. 3a, it is found that with the increase of nitrogen doping, the color of Li₂S₄ solution becomes increasingly clearer, indicating that the polysulfide adsorption on N-TiO₂ should be thermodynamically favorable compared with pure TiO₂. Such a message is further verified by the X-ray photoelectron spectroscopy (XPS) surface analysis. As shown in the N 1s spectrum in Fig. 3b, with the increase of nitrogen doping, the peak related to Ti-N at 396.6 eV becomes more intense, in comparison with the peaks related to LiTFSI at 399.3 and 401.7 eV, a satellite peak is found to emerge besides the Ti-N bond, which could be attributed to the lowered Ti-N binding energy induced by the formation of Ti-S bonds. Such a message can be further verified in the Ti 2p spectrum in Fig. 3(c-e). Besides the peaks representing for Ti-O, there emerge more intense shoulder peaks for Ti-N and Ti-N-O at a higher nitrogen content [57]. As the nitrogen doping lowers the binding energy of Ti⁴⁺, the peak representing Ti-S bond is found to be remarkably promoted. Notably, N-TiO₂ sample annealed under NH₃ atmosphere at 800 °C exhibits very similar nitrogen content and adsorption performance with the commercial TiN powders, indicating that the annealing is sufficient for the nitridation of the formed nanowires.

In addition to enhancing polysulfide binding ability, the electrical conductivity in the formed TiO₂ nanowires is remarkably improved with nitrogen doping. Using the first principle calculation, the density of state (DOS) of pristine and N-doped TiO₂ has been calculated to analyze the electronic properties [69–72]. For example, Yang et al. investigated the effect of nitrogen concentration on the electrical conductivity of TiO₂. They found that as the nitrogen concentration increased from 0 to 1.39%, and then to 4.17%, TiO₂ gradually transformed to metallic states (the nitrogen atomic concentration of N-TiO₂ is 4.21 in this study) [73]. Experimentally, using the 4-point probe measurement method, it is also found that N-TiO₂ offers a high electrical conductivity of 46 S cm⁻¹ at 200 psi, comparable with carbonaceous material [42,70].

With above results, it can be deduced that the N-TiO₂ NW @ CC electrode can perform a remarkable role in adsorbing polysulfide species and transferring electrons. In the following section, we proceed to see whether the nitrogen doping in the formed nanowires leads to the performance enhancement.

Comparison of the electrochemical performance was conceived among the pristine carbon cloth (CC), TiO₂ NW @ CC and N-TiO₂ NW @ CC electrodes. Li-polysulfide batteries with an areal sulfur loading around 4.8 mg cm⁻² were assembled. It is found that the batteries assembled with the as-prepared functionalized carbon cloth demonstrates dramatically improved rate performances as shown in Fig. 4a. The corresponding voltage profiles are displayed.
in Fig. 4(b–d). For the battery with the pristine carbon cloth cathode, the cell voltage declines rapidly at the precipitation region even at an intermediate discharge rate of 0.4C, as can be seen in Fig. 4b. On the contrary, as shown in Fig. 4c and d, both TiO$_2$ NW @ CC and N-TiO$_2$ NW @ CC maintain the typical two-plateau voltage profiles at discharge rates ranging from 0.2 to 1C, while N-TiO$_2$ NW @ CC demonstrates a prolonged discharge capacity, owing to its enlarged electrode/electrolyte interphase as well as its stronger polysulfide binding ability. Also, as can be seen in Fig. 4e, in terms of the cycling performance, for the battery with the pristine carbon cloth electrode, the discharge capacity decayed dramatically after the initial 20 cycles for the reason that the graphitized carbon surface cannot well immobilize the polysulfide species. In comparison, for the battery with the TiO$_2$ NW @ CC electrode, the average decay rate is lowered to 0.36% for 120 cycles, indicating that polysulfide shuttles have been effectively reduced by the adsorption of TiO$_2$ nanowires. However, the utilization ratio of active material can be lowered due to the semi-conducting nature of TiO$_2$ and the residual polysulfides in the electrolyte can keep passivating the Li anode over cycling. Therefore, reasonably, with both enhanced polysulfide binding ability and electrical conductivity, the battery with the N-TiO$_2$ NW @ CC electrode performs...
better in maintaining its capacity, with an average decay rate of 0.19% for 200 cycles. The corresponding voltage profiles can be also found in Fig. 4f.

Specifically, in this work, we intend to characterize the role of polysulfide binding nanowire structured electrode’s role in improving the battery’s performance. The stabilized cycling of the battery was achieved without additional anode protection strategies. Here we list recent papers related with titania based polysulfide binding material and carbon cloth electrode in Table S1. It is seen that the use of porous carbon current collectors renders a higher areal sulfur loading than those composite electrodes, which are usually below 2 mg cm⁻² [67,69]. Also, we show that with the rational integration of polysulfide binding material, the carbon cloth electrode can achieve an improved cyclability in comparison with those bare porous carbon current collectors such as carbon paper and carbon cloth [59,74]. Compared with the carbon nanostructured CC electrode, the polysulfide binding nanowire structured CC electrode also achieves more superior performance, further confirming the rationality of this design [30].

The performance improvement was further verified using cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS). Corresponding to the charge/discharge curves, the higher peak at ~2.0 V representing the precipitation of the lower polysulfide species (Li₂Sₙ, n < 2) from Li₂S₄. With the use of N-TiO₂ NW @ CC electrode, as shown in Fig. 5(a, b), it is found that both peaks are promoted, while the ratio between the lower and higher peaks is significantly increased, indicating the polysulfide crossover is mitigated and the precipitation kinetics is improved. The enhanced rate performance can be also confirmed by electrochemical impedance spectroscopy (EIS). As shown in Fig. 5(c, d), the EIS results for the three electrodes are composed of depressed semicircles in the high-frequency region, corresponding to the charge-transfer processes (usually the semicircle at a higher frequency represents the anodic charge transfer while the lower one represents the cathodic charge transfer), and a sloping straight line in the low-frequency region corresponding to a semi-infinite Warburg diffusion process [75]. It is found that the carbon cloth cathode functionalized by N-TiO₂ NW, which is of a higher electrical conductivity and polysulfide binding ability, shows a remarkably lower charge transfer resistance than other two cathodes (pristine carbon cloth and TiO₂ NW @ CC). With the Li₂S deposition spatially controlled by the unique nanowire structure, there is a closer contact between Li₂S precipitates and the electrode, leading to the lower charge transfer resistance for N-TiO₂ NW @ CC electrode, explaining the excellent rate performance.

In the last section, we discuss the roles of the unique nanowire structured electrode in improving the battery’s precipitation kinetics, which is critically essential for the battery’s rate performance. As shown in the SEM image in Fig. 6a, on the pristine carbon cloth surface, since the conductivity of Li₂S is known to be as low as 10⁻¹⁰ S cm⁻¹, the Li₂S precipitates on the carbon fiber surface are found to be discrete thin flakes. In contrast, when the electrode surface is decorated with conductive polysulfide binding nanowires, more polysulfides can be adsorbed onto the electrode, which facilitates the transport of polysulfides to the precipitation sites on the conductive carbon surface [51]. In addition, more electron transport pathway can be provided, which allows for the precipitation of Li₂S along the nanowire [76]. As shown in the SEM image and corresponding EDX mapping of the discharge electrode in Fig. 6b and c, the carbon fibers decorated with functional nanowires are found to be uniformly impregnated with film-like Li₂S. Such a morphology can be linked to the lowered interfacial energy barrier to adsorb polysulfide anions, leading to the accelerated formation of nucleation sites as well as film-like precipitates [49].

![Fig. 5.](image-url) (a) Cyclic voltammetry (CV) of the battery with the pristine carbon cloth electrode; (b) CV of the battery with the N-TiO₂ NW @ CC electrode. (c) electrochemical impedance spectroscopy (EIS) after discharge for the batteries with different electrodes (the 5th cycle); (d) the equivalent circuit model and the fitted results.
4. Concluding remarks

To conclude, via facile and rational electrode engineering, the N-doped TiO$_2$ nanowire functionalized carbon cloth was fabricated as the open structure electrode for use in Li-polysulfide batteries. With soaking experiment and surface analysis, the polar surface of N-TiO$_2$ was found to demonstrate an enhanced polysulfide binding ability than rutile TiO$_2$. Combining the electrochemical performances and SEM characterization, it is found that the battery's rate performance corresponding to Li$_2$S precipitation can be considerably improved, which can be attributed to the enlarged electrode/electrolyte interface, excellent electronic conductivity as well as desirable adsorption properties provided by N-TiO$_2$ nanowire structured electrode. The achieved results suggest that rational integration of polysulfide binding material provide promising opportunities for enhancing Li-S batteries' performance.

Acknowledgements

The work described in this paper was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. 16213414).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.electacta.2017.04.171.

References


Z. Li, Y. Jiang, L. Yuan, Z. Yi, C. Wu, L. Liu, P. Strasser, Y. Huang, A highly ordered meso@microporous carbon-supported sulfur@smaller sulfur core-shell structured cathode for Li-S batteries, ACS Nano 8 (2014) 9295–9303.


Z. Liu, S. Bertolini, P.B. Balbuena, P.P. Mukherjee, Li2S Film Formation on Lithium Anode Surface of Li–S batteries, ACS applied materials & interfaces 8 (2016) 6760–6768.


