High-performance lithium-selenium battery with Se/microporous carbon composite cathode and carbonate-based electrolyte

Chao Wu, Lixia Yuan*, Zhen Li, Ziqi Yi, Rui Zeng, Yanrong Li and Yunhui Huang*

Selenium attracts increasing attention as cathode material for rechargeable lithium batteries due to its high conductivity and comparable volumetric capacity with sulfur. Microporous carbon spheres (MiPCS) are synthesized via a hydrothermal-annealing route followed by activation with KOH. The MiPCS are used as matrix for Se loading to form Se/MiPCS composite. Such composite delivers a high specific capacity close to the theoretical value of Se. In carbonate-based electrolyte, the capacity is as high as 733 mAh g⁻¹ at a current density of 50 mA g⁻¹, and 353 mAh g⁻¹ at 5000 mA g⁻¹. At 0.5 C, the capacity retains up to 515 mAh g⁻¹ even after 100 cycles. Such outstanding electrochemical performance of the composite cathode in the carbonate electrolyte can be ascribed to the robust structure of MiPCS and to the “solid-solid” electrode process.

With the ever-increasing portable devices and electric vehicles (EVs), state-of-the-art lithium-ion battery based on intercalation mechanism is not sufficient to meet the market technical demand due to its inherent low energy density, which is mainly restricted by the low capacity of the intercalation cathode materials [1–4]. To address this issue, new electrode materials and advanced next-generation lithium battery systems that can provide higher energy density have been continuously explored. Among them, lithium-sulfur battery has been paid much attention due to high specific energy density, which may provide 2–5 times energy density of current commercial systems [5]. However, lithium-sulfur battery suffers from insulating nature of sulfur and high dissolubility of the intermediate polysulfides, resulting in low sulfur utilization and poor cycle life [6,7]. Lots of efforts have been devoted to overcoming the above problems and remarkable improvements have been achieved, such as confining sulfur into porous carbon matrices [8–13] or conductive polymers [14], surface coating [15–19], electrolyte optimization [20–22] and cell configuration redesign [23–28]. Some nano-architected sulfur composites have been reported to exhibit specific capacity

higher than 1000 mAh g⁻¹ (calculated based on elemental sulfur) and the cycle life over 500 times. However, for sulfur system, the contradiction always exists between the energy density and the electrochemical performance: the higher the sulfur utilization, the lower the sulfur content is; the better the cycle stability, the lower the sulfur content is. Low sulfur content greatly reduces the overall volumetric capacity and energy density of the cathode. Thus, the practical application of lithium-sulfur battery is still impeded by the intrinsic drawbacks of sulfur.

Selenium (Se), the congener of sulfur, has a similar (de)lithiation mechanism to sulfur, which can be described as [29]:

Based on the above reaction, the theoretical capacity of Se is 675 mAh g⁻¹. Although it is much lower than that of sulfur (1672 mAh g⁻¹, provided full reduction of sulfur to sulfide), the high density of Se (gray, 4.81 g cm⁻³), which is almost 2.4 times of sulfur (2.07 g cm⁻³), offsets this disadvantage and provides comparable volumetric capacity (3266 mAh cm⁻³) with sulfur (3461 mAh cm⁻³). Furthermore, the electronic conductivity of Se (1 × 10⁻³ S m⁻¹) is more than 20 orders of magnitude higher than that of sulfur (5 × 10⁻²⁸ S m⁻¹) [23], which means higher active material utilization and better rate performance. Pioneering work carried out by Abouimrane *et al.* [5] shows that bulk Se has moderate cycling stability, but only delivers a limited capacity, indicating a low Se utilization. However, if Se is confined in porous carbon matrix, a largely enhanced capacity and excellent cycle stability can be achieved [30–33]. Meanwhile, it is suggested that cyclic Se₈ is converted into chain-like Se_n after the first charge, and the chain structure maintains in the following cycles. Sustainable stability of the cathode may attribute to strong affinity between chain-like Se and carbon [30,32].

Up to now, porous carbon materials used in previous research are always complicated to synthesize and Se load-

State Key Laboratory of Material Processing and Die & Mould Technology, School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

* Corresponding authors (emails: huangyh@mail.hust.edu.cn (Huang Y); yuanlixia@hust.edu.cn (Yuan L))

ing is low. Furthermore, it is still not clear which kind of electrolyte is proper for such materials. In this work, we report a high-performance Se composite confined within microporous carbon spheres (Se/MiPCS) prepared by a facile method. The microporous carbon matrix can not only improve the Se utilization and rate capability because of the high conductivity, but also prevent the side reaction between the selenium anion and the electrolyte due to the microporous structure.

The experimental process (see Supplementary information) is illustrated in Fig. 1. The microporous carbon spheres (MiPCS) were synthesized by a hydrothermal-annealing approach, followed by activation with KOH [34]. Selenium was infiltrated into pores of MiPCS via a two-step heating method. Fig. 2a shows the scanning electron microscopy (SEM) image of MiPCS. It can be seen that

Figure 1 Schematic illustration for the preparation process of Se/MiPCS.

Figure 2 SEM images of (a) MiPCS and (b) Se/MiPCS composite. (c) TEM image of microporous carbon spheres. Elemental mappings of (d) C and Se, (e) C and (f) Se. (g) Particle size distribution of MiPCS. (h) Nitrogen adsorption and desorption isotherms and pore size distribution (inset).

the carbon particles are highly monodispersed with average size around 740 nm (Fig. 2g). The micropores can be clearly identified from transmission electron microscopy (TEM) image (Fig. 2c), and further characterized by type I nitrogen adsorption/desorption isothermals (Fig. 2h) [8]. The pore size distribution is mainly around 0.54 nm (inset of Fig. 2h). With selenium infiltrated into carbon pores, the morphology of the carbon spheres maintains and the surface still keeps smooth, indicating that all Se particles are well confined within the pores. The elemental mappings of C and Se (Figs 2e and f) also confirm that Se distributes in carbon matrix homogeneously after heat treatment. The calculated Brunauer-Emmett-Teller (BET) equivalent surface area and adsorption total pore volume are $1211.8 \text{ m}^2 \text{ g}^{-1}$ and $0.53 \text{ cm}^3 \text{ g}^{-1}$, respectively. Thus, the largest theoretical loading of Se is 72% calculated according to the density of Se (4.81 g cm^{-3}). The actual Se content in Se/MiPCS is 62% determined by thermogravimetric (TG) analysis (Fig. 3c). The free space can help to tolerate the volume expansion during cycles so that the structure collapse can be alleviated. Fig. 3a shows the X-ray diffraction (XRD) patterns of Se, MiPCS and Se/MiPCS. For MiPCS, two characteristic peaks of carbon appear at around 24° and 43° . All diffraction peaks of Se disappear after being infused into the pores of MiPCS, indicating good dispersion of Se in MiPCS. Raman spectra (Fig. 3b) of Se show three peaks at 142, 236 and 460 cm^{-1} . The peaks at 142 and 460 cm^{-1} are identified as the ring structure of Se, while the peak at 236 cm^{-1} represents the chain structure [33]. No peak is found in the Raman spectra for Se/MiPCS, which also indicates that all Se particles are well diffused into pores of carbon after the two-step heat process.

The electrochemical properties of Se/MiPCS were investigated in two different electrolytes: carbonate-based electrolyte with 1 M LiPF_6 in a mixture of ethylene carbonate (EC), ethyl methyl carbonate (EMC) and dimethyl carbonate (DMC) (1/1/1, v/v/v), and ether-based electrolyte composed of 1 M lithium bis(trifluoromethane sulfonyl) imide (LiTFSI) in a mixture of 1, 3-dioxolane (DOL) and 1,

2-dimethoxymethane (DME) (1/1, v/v) with 0.2 M LiNO_3 as additive. The redox behavior of Se/MiPCS in the ether-based electrolyte is very similar to sulfur cathode, which shows two reductive peaks and one oxidative peak in the cyclic voltammogram (CV) curves (Fig. 4a). The two reduction peaks at 2.15 and 1.95 V correspond to the reduction from Se molecule to polyselenides and then to the final reductive product Li_2Se . The oxidation peak at 2.3 V can be attributed to the conversion from Li_2Se to Se [35–37]. In the carbonate-based electrolyte, only one pair of redox peaks can be observed (Fig. 4c), indicating the single phase transition of Se: the reduction peak at 1.75 V corresponds to the direct transform from Se to Li_2Se ; the oxidation peak at 2.2 V is attributed to the recovery of Se. Since the polyselenides are insoluble in the carbonate electrolyte [38], the transition between Se and Li_2Se is carried out by a solid-solid process. Figs 4b and d show discharge/charge profiles of Se/MiPCS in ether-based and carbonate-based electrolyte within the voltage ranging from 3 to 1 V. The profiles agree well with the corresponding CV curves. Se/MiPCS displays two discharge plateaus in ether electrolyte and one single discharge plateau in carbonate electrolyte. It can also be seen that the discharge voltage remains stable at about 1.9 V in the carbonate electrolyte during the cycles (Fig. 4d), whereas the plateau in the ether electrolyte decreases from 1.95 V in the 1st cycle to 1.7 V after 20 cycles and continuously drops in the subsequent cycles (Fig. 4b). It is interesting that the same Se/MiPCS cathode exhibits different electrochemical behaviors in different electrolytes, which should be ascribed to the different electrode process. The electrode reaction is carried out via a solid-liquid-solid mechanism in the ether electrolyte, while it undergoes a solid-solid phase transition in the carbonate electrolyte [5, 30]. The different charge-discharge mechanism can also be visually proved by checking the disassembled cells after 100 cycles (the insets of Figs 4b and d). The inside of the cell became dark brown in the ether electrolyte, but no color change was observed in the carbonate electrolyte. The Se/MiPCS cathode with carbonate electrolyte maintains a ca-

Figure 3 (a) XRD patterns and (b) Raman spectra of Se, MiPCS and Se/MiPCS. (c) TGA curve of Se/MiPCS composite.

Figure 4 (a) CV curves at scanning rate of 0.1 mV s⁻¹ and (b) discharge/charge curves at 1 C for Se/MiPCS cathode with ether electrolyte. (c) CV curves at 0.1 mV s⁻¹ and (d) discharge/charge curves in different cycles at 0.5 C for Se/MiPCS cathode with carbonate electrolyte. The insets of (b) and (d) show the disassembled cell after 100 cycles in ether- and carbonate-based electrolyte, respectively.

capacity of 515 mAh g⁻¹ at 0.5 C even after 100 cycles and a capacity retention of 72.8%, which are much higher than those with ether electrolyte (151 mAh g⁻¹, 23.4%). Obviously, the solid-solid electrode process promises better cycle stability. The fast capacity decay in the ether electrolyte is mainly ascribed to the formation of polyselenides that can be dissolved into the electrolyte, leading to a serious loss of active material.

Fig. 5a shows detailed cycle performance for the Se/MiPCS cathode in the carbonate electrolyte at 0.5 C. The cathode delivers an initial reversible capacity of 707 mAh g⁻¹, which is slightly higher than the theoretical capacity of elemental Se. The excessive capacity may come from MiPCS. To verify this, the electrochemical performance of pristine MiPCS was tested. As shown in Fig. 5d, the pristine MiPCS delivers an irreversible capacity of ca. 60 mAh g⁻¹ at the first cycle and the capacity keeps at 50–20 mAh g⁻¹ in the following 4 cycles. Therefore, it can be inferred that all Se molecules confined in MiPCS are almost fully reduced to Li₂Se, and the active material utilization reaches 100%, much higher than the sulfur system. After 100 cycles, a reversible capacity of 515 mAh g⁻¹ is retained

with coulombic efficiency always approaching 100%.

Besides outstanding cycle stability, the Se/MiPCS cathode also shows excellent rate capability. As shown in Fig. 5b, Se/MiPCS delivers reversible capacity of 733, 713, 661, 584, 522, 453 and 353 mAh g⁻¹ at 50 (0.12 C), 100 (0.24 C), 200 (0.48 C), 500 (1.2 C), 1000 (2.4 C), 2000 (4.8 C) and 5000 mA g⁻¹ (12 C), respectively. When the current is tuned back to 50 mA g⁻¹ after running at various rates, a reversible capacity as high as 646 mAh g⁻¹ is regained, suggesting excellent cycling stability. Noticeably, a capacity of 353 mAh g⁻¹ can be obtained even at a high current density of 5000 mA g⁻¹, which means that more than half of theoretical capacity can be recharged within 5 min. This superior rate capability is of great advantage for practical application for the Li-Se batteries. Electrochemical impedance spectroscopy (EIS) was further employed to demonstrate the stable performance of the Se/MiPCS electrode. Fig. 5e shows the EIS spectra of the Se/MiPCS cathode before cycling and after 1, 5 and 10 cycles. Two semicircles in the high and middle frequency region, and a sloping line in the low frequency region are identified from the fresh cathode. After the first discharge/charge cycle, the semicircles in the

Figure 5 (a) Cycling performance of Se/MiPCS cathode at 0.5 C and (b) rate capability at current densities from 50 mA/g (0.12 C) to 5000 mA g⁻¹ (12 C). (c) Specific capacity as a function of current density for Se/MiPCS. (d) Charge/discharge curves at 0.5 C for pristine MiPCS. (e) Nyquist plots at charged state in various cycles (fresh, 1st, 5th, 10th) at 1 C for the Se/MiPCS cell.

high and middle frequency are merged into a single semi-circle. Although the interpretation on the EIS curves for the Se/C cathode is still uncertain, the impedance curves after initial several cycles overlap with each other, indicating that the electrode is very stable during the cycles.

In order to gain insight into the capacity decay mechanism, the Se/MiPCS cathode was investigated by SEM and energy dispersive X-ray spectroscopy (EDX) before cycling and after 500 cycles, as shown in Fig. 6. The cathode was cycled at a high current density of 4 C, which meant a fast volume expansion/shrinkage during discharge/charge. The calculated volume expansion is about 180% according to the theoretical densities of Se (4.81 g cm⁻³) and Li₂Se (2.0 g cm⁻³). We can see that some MiPCS particles are cracked after cycling due to the continuous large volume change, and the smooth carbon sphere surfaces become contaminated, where marked in red. The EDX results show large increase of “O” peak, a new peak of “F” and decrease of “Se” peak. The SEM and EDX results may imply some information for the solid electrolyte interface (SEI), which is formed through the reaction between selenide and carbonyl groups in the carbonate solvent [5,32,39,40]. Nevertheless, no significant change or collapse can be found in the morphology of the cycled cathode, indicative of a robust structure of MiPCS, which is mainly responsible for the stability of the Se/MiPCS cathode.

In summary, we have synthesized MiPCS through a facile route and used it as a matrix for Se loading. A high Se

Figure 6 SEM images of the Se/MiPCS cathode (a) before cycling and (b) after 500 cycles at 4 C. Corresponding EDX spectra of Se/MiPCS (c) before cycling and (d) after cycled.

content of 62.2% is attained in the Se/MiPCS composite. In the carbonate electrolyte, the composite delivers a high reversible capacity that reaches the theoretical one of Se, showing 100% utilization of the active material. The composite also exhibits high cycle stability and excellent rate capability. Interestingly, different electrolytes achieve different electrochemical behaviors for the Se/MiPCS cathode, demonstrating that their electrode mechanisms are

different. Our work indicates that with microporous carbon matrix and proper electrolyte, Li-Se batteries are also hopeful to achieve superior performance, which provides an alternative option for practical application of high energy storage.

Received 7 January 2015; accepted 28 January 2015
published online 10 February 2015

- Ji XL, Nazar LF. Advances in Li-S batteries. *J Mater Chem*, 2010, 20: 9821–9826
- Yang Y, Zheng GY, Cui Y. Nanostructured sulfur cathodes. *Chem Soc Rev*, 2013, 42: 3018–3032
- Song MK, Cairns EJ, Zhang YG. Lithium/sulfur batteries with high specific energy: old challenges and new opportunities. *Nanoscale*, 2013, 5: 2186–2204
- Moon S, Jung YH, Jung WK, *et al.* Encapsulated monoclinic sulfur for stable cycling of Li-S rechargeable batteries. *Adv Mater*, 2013, 25: 6547–6553
- Abouimrane A, Dambournet D, Chapman KW, *et al.* A new class of lithium and sodium rechargeable batteries based on selenium and selenium-sulfur as a positive electrode. *J Am Chem Soc*, 2012, 134: 4505–4508
- Li Z, Yuan LX, Yi ZQ, *et al.* A dual coaxial nanocable sulfur composite for high-rate lithium-sulfur batteries. *Nanoscale*, 2014, 6: 1653–1660
- Nelson J, Misra S, Yang Y, *et al.* In operando X-ray diffraction and transmission X-ray microscopy of lithium sulfur batteries. *J Am Chem Soc*, 2012, 134: 6337–6343
- Li Z, Yuan LX, Yi ZQ, *et al.* Insight into the electrode mechanism in lithium-sulfur batteries with ordered microporous carbon confined sulfur as the cathode. *Adv Energy Mater*, 2014, 4: 1301473
- Zhang B, Qin X, Li GR, *et al.* Enhancement of long stability of sulfur cathode by encapsulating sulfur into micropores of carbon spheres. *Energy Environ Sci*, 2010, 3: 1531–1537
- Xin S, Gu L, Zhao NH, *et al.* Smaller sulfur molecules promise better lithium-sulfur batteries. *J Am Chem Soc*, 2012, 134: 18510–18513
- Ye H, Yin YX, Xin S, *et al.* Tuning the porous structure of carbon hosts for loading sulfur toward long lifespan cathode materials for Li-S batteries. *J Mater Chem A*, 2013, 1: 6602–6608
- Jayaprakash N, Shen J, Moganty SS, *et al.* Porous hollow carbon@ sulfur composites for high-power lithium-sulfur batteries. *Angew Chem*, 2011, 50: 6026–6030
- Ji XL, Lee KT, Nazar LF. A highly ordered nanostructured carbon-sulfur cathode for lithium-sulfur batteries. *Nat Mater*, 2009, 8: 500–506
- Xiao LF, Cao YL, Xiao J, *et al.* A soft approach to encapsulate sulfur: polyaniline nanotubes for lithium-sulfur batteries with long cycle life. *Adv Mater*, 2012, 24: 1176–1181
- Zhou WD, Yu YC, Chen H, *et al.* Yolk-shell structure of polyaniline-coated sulfur for lithium-sulfur batteries. *J Am Chem Soc*, 2013, 135: 16736–16743
- Wang C, Wan W, Chen JT, *et al.* Dual core-shell structured sulfur cathode composite synthesized by a one-pot route for lithium sulfur batteries. *J Mater Chem A*, 2013, 1: 1716–1723
- Li WY, Zhang QF, Zheng GY, *et al.* Understanding the role of different conductive polymers in improving the nanostructured sulfur cathode performance. *Nano Lett*, 2013, 13: 5534–5540
- Seh ZW, Li WY, Cha JJ, *et al.* Sulfur-TiO₂ yolk-shell nanoarchitecture with internal void space for long-cycle lithium-sulfur batteries. *Nat Commun*, 2013, 4: 1331–1336
- Li WY, Zheng GY, Yang Y, *et al.* High-performance hollow sulfur nanostructured battery cathode through a scalable, room temperature, one-step, bottom-up approach. *PNAS*, 2013, 110: 7148–7153
- Lee JT, Zhao Y, Thieme S, *et al.* Sulfur-infiltrated micro- and mesoporous silicon carbide-derived carbon cathode for high-performance lithium sulfur batteries. *Adv Mater*, 2013, 25: 4573–4579
- Lin Z, Liu ZC, Fu WJ, *et al.* Phosphorous pentasulfide as a novel additive for high-performance lithium-sulfur batteries. *Adv Funct Mater*, 2013, 23: 1064–1069
- Zhang SS. Role of LiNO₃ in rechargeable lithium/sulfur battery. *Electrochim Acta*, 2012, 70: 344–348
- Yang Y, Zheng GY, Cui Y. A membrane-free lithium/polysulfide semi-liquid battery for large-scale energy storage. *Energy Environ Sci*, 2013, 6: 1552
- Fu YZ, Su YS, Manthiram A. Li₂S-carbon sandwiched electrodes with superior performance for lithium-sulfur batteries. *Adv Energy Mater*, 2014, 4: 1300655
- Chung SH, Manthiram A. A hierarchical carbonized paper with controllable thickness as a modulable interlayer system for high performance Li-S batteries. *Chem Commun*, 2014, 50: 4184–4187
- Su YS, Manthiram A. A new approach to improve cycle performance of rechargeable lithium-sulfur batteries by inserting a free-standing MWCNT interlayer. *Chem Commun*, 2012, 48: 8817–8819
- Huang C, Xiao J, Shao YY, *et al.* Manipulating surface reactions in lithium-sulfur batteries using hybrid anode structures. *Nat Commun*, 2014, 5: 3015–3021
- Su YS, Manthiram A. Lithium-sulfur batteries with a microporous carbon paper as a bifunctional interlayer. *Nat Commun*, 2012, 3: 1166–1171
- Liu LL, Hou YY, Wu XW, *et al.* Nanoporous selenium as a cathode material for rechargeable lithium-selenium batteries. *Chem Commun*, 2013, 49: 11515–11517
- Yang CP, Xin S, Yin YX, *et al.* An advanced selenium-carbon cathode for rechargeable lithium-selenium batteries. *Angew Chem Int Ed*, 2013, 52: 8363–8367
- Ye H, Yin YX, Zhang SF, *et al.* Advanced Se-C nanocomposites: a bifunctional electrode material for both Li-Se and Li-ion batteries. *J Mater Chem A*, 2014, 2: 13293–13299
- Li Z, Yuan LX, Yi ZQ, *et al.* Confined selenium within porous carbon nanospheres as cathode for advanced Li-Se batteries. *Nano Energy*, 2014, 9: 229–236
- Luo C, Xu YH, Zhu Y, *et al.* Selenium@mesoporous carbon composite with superior lithium and sodium storage capacity. *ACS Nano*, 2013, 7: 8003–8010
- Qie L, Chen WM, Xu HH, *et al.* Synthesis of functionalized 3D hierarchical porous carbon for high-performance supercapacitors. *Energy Environ Sci*, 2013, 6: 2497–2504
- Lai YQ, Gan YQ, Zhang ZA, *et al.* Metal-organic frameworks-derived mesoporous carbon for high performance lithium-selenium battery. *Electrochimica Acta*, 2014, 146: 134–141
- Liu L, Wei Y, Zhang C, *et al.* Enhanced electrochemical performances of mesoporous carbon microsphere/selenium composites by controlling the pore structure and nitrogen doping. *Electrochimica Acta*, 2015, 153: 140–148
- Jiang SF, Zhang Z, Lai YQ, *et al.* Selenium encapsulated into 3D interconnected hierarchical porous carbon aerogels for lithium-selenium batteries with high rate performance and cycling stability. *J Power Sources*, 2014, 267: 394–404
- Cui Y, Abouimrane A, Sun CJ, *et al.* Li-Se battery: absence of lithium polyselenides in carbonate based electrolyte. *Chem Commun (Camb)*, 2014, 50: 5576–5579
- Luo C, Zhu YJ, Wen Y, *et al.* Carbonized polyacrylonitrile-stabilized SeS_x cathodes for long cycle life and high power density lithium ion batteries. *Adv Funct Mater*, 2014, 24: 4082–4089
- Cui YJ, Abouimrane A, Lu J, *et al.* (De)lithiation mechanism of Li/SeS_x (x = 0–7) batteries determined by *in situ* synchrotron X-ray diffraction and X-ray absorption spectroscopy. *J Am Chem Soc*, 2013, 135: 8047–8056

Acknowledgements This work was supported by the National Natural Science Foundation of China (51002057, 21271078 and 21273087), and the Program for Changjiang Scholars and Innovative Research Team in University. The authors acknowledge the Analytical and Testing Center of HUST for XRD, Raman, FESEM, FETEM, EDX measurements, and the State Key Laboratory of Material Processing and Die & Mould Technology of HUST for TG, BET.

Author contribution Huang Y and Yuan L initiated and guided the

work. Wu C, Li Z, Yi Z designed the experiments. Wu C, Li Y conducted the experiments. All authors contribute to analysis of the data and advice for the paper writing.

Conflict of interest The authors declare that they have no conflict of interest.

Supplementary information Experimental details are available in the online version of the paper.

Chao Wu received his BSc degree from Huazhong University of Science and Technology (HUST). He then worked with BYD for a year as an engineer. He is now an MSc candidate at HUST, and focuses on Li-S and Li-Se batteries.

Lixia Yuan received her PhD at Wuhan University in 2007. She worked as a post-doctoral researcher in Tsinghua University from 2007 to 2009. She is now an associate professor at HUST. Her research interests mainly focus on lithium rechargeable batteries.

Yunhui Huang received his BSc, MSc and PhD from Peking University. In 2000, he worked as a postdoctoral researcher in Peking University. From 2002 to 2004, he worked as an associate professor in Fudan University and a JSPS fellow at Tokyo Institute of Technology, Japan. He then worked in the University of Texas at Austin for more than three years. In 2008, he became a chair professor of materials science in Huazhong University of Science and Technology. He is now the dean of the School of Materials Science and Engineering. His research group works on batteries of energy storage and conversion. For details please see the lab website: <http://www.sysdoing.com.cn>.

中文摘要 因为硒的高电子电导, 以及和硫相近的体积能量密度, 锂硒电池继锂硫电池之后受到越来越多的关注. 本论文使用蔗糖作为碳源, 通过水热方法合成碳球, 经KOH造孔, 从而得到了具有微孔结构的多孔碳球. 进一步和单质硒进行热复合制备了Se/C复合材料作为锂硒电池的正极材料, 该复合材料在碳酸酯的电解液中表现出高的活性物质利用率、稳定的循环性能和良好的倍率性能. 其优异的电化学性能主要得益于Se/C复合材料的电子导电能力的改善, 以及硒在碳酸酯电解液中的“固-固”电极过程. 本工作关于碳酸酯电解液和醚类电解液用于锂硒电池的系统研究对今后锂硒电池电解液的选择有一定的参考意义.