Research Article

Tailoring Defects in Hard Carbon Anode towards Enhanced Na Storage Performance

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Hard carbon (HC) anodes show conspicuously commercialized potential for sodium-ion batteries (SIBs) due to their cost-effectiveness and satisfactory performance. However, the development of hard carbon anodes in SIBs is still hindered by low initial Coulombic efficiency (ICE) and insufficient cyclic stability, which are induced by inappropriate defects in the structure. Herein, we introduce a simple but effective method to tailor the defects in HC by the chemically preadsorbed K⁺. The soft X-ray absorption spectroscopy at the C K-edges reveals that K⁺ can anchor on the hard carbon via C-O-K bonds, occupying the irreversible reactive sites of Na⁺. Therefore, the irreversible capacity caused by some C-O bonds can be reduced. Moreover, the preadsorbed K⁺ can induce the rearrangement of carbon layers and lead to a high graphitization structure with fewer defects and large interlayer spacing, which not only improves the structural stability and electrical conductivity of the HC anode but also facilitates fast Na⁺ diffusion. Therefore, the as-obtained optimized anode demonstrates a higher ICE with better cyclic stability and superior rate capacities compared with the anode without preadsorbed K⁺. This work indicates that K⁺ preadsorbed into hard carbon is a practicable alternative to enhance the Na storage performances of HC anodes for SIBs.

1. Introduction

Lithium-ion batteries (LIBs) have been successfully utilized in various fields during the past several decades, thanks to their satisfactory overall performance [1–3]. However, the geographically constrained lithium resources and gradually rising cost make LIBs difficult to meet the demands for large-scale energy storage [4, 5]. Accordingly, multitudinous new energy storage systems such as sodium-ion, metal-sulfur, and metal-air batteries have been widely studied. In particular, SIBs are considered the most suitable candidate to replace LIBs due to the abundant natural stock of sodium with physicochemical properties similar to those of lithium [6–9].

Thanks to the SIBs possessing a similar operation mechanism to LIBs, the development of SIBs can be accelerated by the knowledge acquired from LIBs. On account of this logic, researchers have made rapid progress in cathode materials of SIBs, where polyanionic compounds and layered metal oxides exhibit gratifying results [10–12]. However, on the anode side, the commercial graphite anode for LIBs cannot form thermodynamic stable compounds in SIBs [13]. Thus, it is essential to find out a suitable anode material for SIBs. So far, many anode materials, including carbonaceous materials, metal oxide/sulfide, and alloys, have been widely investigated [14–23]. Among them, hard carbon materials have been studied extensively due to their higher capacity below 0.1 V (vs. Na/Na⁺) and abundant resource [24]. However, some obstacles hinder its commercialization, especially its low ICE, poor cyclic stability, and poor rate capability.

To enhance the rate performance of hard carbon, many studies focus on amorphous carbons with large specific surface area (SSA) or heteroatom-doped carbon materials with more defects, such as porous carbon [25–28], nanosized carbon [29], or heteroatom-doped carbon by anions (F, N, P,
and S) [30–35]. Unfortunately, both large SSA and excessive defects in the structure of carbon tend to induce the uncontrollable decomposition of electrolyte and the formation of an uneven and unstable solid electrolyte interphase film (SEI), resulting in an extremely low ICE, poor cyclic stability, and decreased sodium diffusivity [36]. Besides, the oxygen functional groups in HC would irreversibly react with Na⁺ during the first 10 cycles leading to rapid capacity decay [37]. Therefore, an effective modification strategy to shield the oxygen functional groups and excessive defects from the irreversible reactions, which can boost the rate performance without sacrificing ICE and cyclic stability, is urgently needed. Introducing heteroatoms is considered a simple but effective approach to change the microstructure and electronic properties of carbon materials. Thus, many carbon materials doped with anions with enhanced electronic conductivity or enlarged layer spacing have been studied. However, doping anions tends to introduce more defects in the structure of carbon, which always causes an extremely low ICE. To our knowledge, there are very few reports on the introduction of cations in hard carbon so far. Recently, Lin et al.’s group has reported that oxygen functional groups and defects in the RGO can adsorb metal cations and form electro-inert Al₂O₃ nanocluster coverage, leading to higher ICE and capacity retention [38]. Our group has synthesized a natural potassium-doped hard carbon with expanded interlayer spacing by directly carbonizing the high charged oxygen-containing functional groups with large ionization energy and can bind with negatively polarized K⁺ to boost the Na storage performance of hard carbon.

Hence, in this work, we prepared K⁺-preadsorbed hard carbon through a facile hydrothermal treatment using sucrose and KCl as a carbon source and a potassium source, respectively. The oxygen functional groups such as carbonyls and hydroxyls and some defect sites on carbon can work as anchoring sites for cations [40–42]. Thus, the K⁺ is chemically adsorbed on the oxygen functional groups by forming C-O-K bonds and occupying some defect sites which is revealed using sXAS at the C K-edges and O K-edges [39]. However, the mechanism of the interaction between carbon and potassium is not clear. Inspired by these findings, K⁺ was selected to be preadsorbed on oxygen functional groups and some defects in hard carbon to deactivate these active sites which generally react with Na⁺ irreversibly leading to low ICE and poor cycle stability. In addition, compared with other alkali metal ions, potassium has low ionization energy and can bind with negatively charged oxygen-containing functional groups with large electrostatic attraction, forming a stable structure. Therefore, we choose K⁺ to boost the Na storage performance of hard carbon.

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2. Experimental Section

2.1. Synthesis of Hard Carbon Spheres. In a simple procedure, 6.8 g sucrose was dissolved in 80 mL of KCl aqueous solution with different KCl contents (0 mg mL⁻¹, 5 mg mL⁻¹, 10 mg mL⁻¹, and 15 mg mL⁻¹) and stirred for 0.5 h. Subsequently, the solution was placed in an autoclave (100 mL) and heated at 180°C for 8 h to get brown (without KCl) or black powder [43]. After the reaction, the obtained powder was collected and cleaned many times using deionized water and dried under vacuum for 12 h. The dried precursors were annealed at 1200°C for 2 h in a tube furnace under Ar. The final obtained samples were named as HC, HCK-5, HCK-10, and HCK-15, respectively.

2.2. Material Characterization. A scanning electron microscope (SEM, ZEISS-SUPRA55) was used to observe the material morphology. Transmission electron microscopy (TEM, TECNAI G2 F30 S-TWIN) equipped with an energy-dispersive X-ray mapping (EDX) system was used to obtain the structure and element distribution of hard carbon. X-ray diffraction (XRD, Rigaku DMAX2400) stimulated by Cu Ka radiation was applied to characterize the material structure. Raman spectra were obtained on a LabRAM HR Evolution, and X-ray photoelectron spectra (XPS) were acquired on a PHI QUANTERA-II SXM analysis system. The microporous structure was characterized by the carbon dioxide adsorption-desorption measurement system (ASAP 2020, Micromeritics) at 273 K. The C K-edge and O K-edge soft X-ray absorption spectroscopy (sXAS) was recorded in Beamline 8.0.1 of the Advanced Light Source (ALS) in Lawrence Berkeley National Laboratory (LBNL).

2.3. Electrochemical Measurements. The electrodes were fabricated by mixing the hard carbon power, super P, and poly (vinylidene fluoride) (PVDF) in N-methylpyrrolidone solvent with a mass ratio of 8:1:1 and casting the mixture slurry onto a Cu foil. After being dried at 100°C under vacuum for 24 h, the electrodes were cut into discs with a diameter of 11 mm. The mass loading of each electrode was about 1 mg cm⁻². The press density applied on the current collector is 5 MPa. Half cells (CR2025) were assembled in an argon-filled glove box using sodium foil (99.8%, Acros, America) as the counter/reference electrode, a glass-fiber separator (Whatman GF/C), and 1 M NaClO₄ in propylene carbonate (PC) with 5 vol% fluoroethylene carbonate as an electrolyte (Duoduo Chemical Technology Co. Ltd., China). Galvanostatic charge-discharge (GCD) tests were carried out on a battery test system (Wuhan LAND electronics) over a voltage range of 0.001-2.5 V at a current density of 50 mA g⁻¹. Cyclic voltammetry (CV) measurements at a scan rate of 0.1 mV s⁻¹ and electrochemical impedance spectroscopy (EIS) measurements in a frequency range of 0.01 to 100 kHz were both carried out on a CHI660E electrochemical workstation. Galvanostatic intermittent titration technique (GITT) tests were employed by alternant current pulse of 50 mA g⁻¹ for 5 min with an interval time for 10 min. The HCK-10–Na₂/3Ni₁/2Mn₂/3O₂ full cell was
assembled with a N/P ratio of about 1:2. Here, the cathode part was prepared by mixing Na2/3Ni1/3Mn2/3O2 with Super P and PVDF in the same mass ratio 8:1:1, then spreading the paste onto the Al foil.

3. Results and Discussion

The amount of K+ in each HC sample with K+ preadsorbed was determined using inductively coupled plasma atomic emission spectroscopy (ICP-AES), and the results show that the K+ content of each sample is 1618 mg kg⁻¹ (HCK-5), 2508 mg kg⁻¹ (HCK-10), and 3412 mg kg⁻¹ (HCK-15). The interaction between K⁺ and carbon framework in the HCK-10 is investigated by comparing the C K-edge sXAS spectra of the HC and the HCK-10 (Figure 1(a)). The C K-edge sXAS spectra show two main peaks at around 286 and 292 eV, corresponding to the C-C π* and the C-C σ* bond, respectively. Additionally, a broad peak located at 288.2 eV corresponding to the C-O bond is greatly enhanced in the HCK-10 compared with HC, indicating that the C-O bond is combined with other components [44–46]. Thus, the spectroscopic evidence strongly proves the formation of the covalent bond between K⁺ and the carbon framework in HCK-10, which is likely to be in the form of C-O-K bond.

The formation of the C-O-K bond also causes a change in the electronic structure of C 2p orbital in HCK-10. As can be seen, the C-C π* peak of HCK-10 shifts to negative energy; the offset is approximately 0.24 eV, leading to an elevated electronic conductivity of HCK-10, due to the increase in electrons near the conduction band, as reported by the previous literature [47]. Besides, the formation of the C-O-K bond is further demonstrated by the O K-edge sXAS study (Figure 1(b)). The O K-edge sXAS spectra detect the unoccupied O 2p projection state, which can bond with carbon or K⁺. The HC shows two broad peaks at 532 eV and 542 eV, corresponding to the π* and σ* of the C-O bond, respectively [48]. Interestingly, the C-O σ* peak of HCK-10 shifts to lower energy after introducing K⁺ ions, indicating a loosely bonded O compared to that of HC. In fact, the covalent characteristic of the K-O bond is weaker than that of the C-O bond; thus, this again proves the formation of the C-O-K bond.

To reveal the variation in crystal structure after preadsorbing K⁺, all HC samples were characterized by XRD and are shown in Figure 1(c). As can be seen, each HC sample exhibits two broad diffraction peaks around 22 and 43°, corresponding to the (002, 101) plane diffraction of HC, respectively. It is noticeable that the (002) peak slightly moves to the lower angle with the increase in KCl in samples until reaching 10 mg mL⁻¹ (HCK-10), corresponding to a gradually enlarged tendency of the d_(002)-spacing. The calculated values based on the Bragg equation can be seen from Table S1. The d_(002)-spacing increases from 0.399 to 0.413 nm, thus facilitating the Na⁺ diffusion and storage effectively. Interestingly, when the content of KCl is up to 15 mg mL⁻¹ (HCK-15), the (002) peak slightly moves back to a higher angle, signifying a diminished d_(002)-spacing of HCK-15 and the reason will be discussed later. Raman spectra reflect the effect of preadsorbed K⁺ on defects of hard carbon. In Figure 1(d), two characteristic peaks at 1336 cm⁻¹ (D-band) and 1569 cm⁻¹ (G-band) correspond to defective or disordered carbon and crystalline carbon, respectively. Generally, the defect concentration of hard carbon can be evaluated by the intensity ratio of I_D/I_G. As can be seen, the I_D/I_G ratio of HC is 1.09, apparently higher than that of all those other samples. The decrease in the I_D/I_G ratio can be attributed to the inactivation of defective sites by preadsorbed K⁺. In addition, the G-bands of the samples preadsorbed with K⁺ show a significant red shift, which indicates that defects such as vacancies, holes, and edges are gradually disappearing as reported in previous studies [49, 50]. The CO₂ adsorption-desorption tests were implemented to study the microstructure of all HC samples. Figures 1(e) and 1(f) show the CO₂ adsorption isotherms and the micropore size distributions of each HC sample, respectively. The relatively lower specific surface areas of 382.35 m² g⁻¹ (532.46 m² g⁻¹ for HC) with pore volumes of 0.123 cm³ g⁻¹ (0.160 cm³ g⁻¹ for HC) were measured for the HCK-10 sample as shown in Table S1 (Supplementary). Generally, a relatively low specific surface area can decrease the active surface area and reduce the formation of SEI, resulting in a high ICE.

The SEM images of all samples were obtained to illustrate the effect of the preadsorbed K⁺ on the morphology. As shown in Figure S1 (Supplementary), all samples exhibit typically spherical shape with smooth surfaces and a uniform particle size. The diameter of HC is about 1 μm; after preadsorbing K⁺, the diameter is increased to approximately 5 μm. Clearly, the presence of KCl on hydrothermal carbonization can drastically accelerate the carbonization process, which is similar to the function of NaCl [51]. To further disclose the structure difference of all samples and reveal the influence of preadsorbed K⁺, HRTEM was conducted. The comparative results can be seen from Figure 2. The d-spacing of local graphitic structure ranges from 0.387 to 0.412 nm for HC. After K⁺ preadsorbed, the d-spacing gradually expanded to around 0.415 nm for HCK-5 and 0.43 nm for HCK-10, consistent with the XRD results. Noticeably, the highly disordered structure of the hard carbons gradually evolves into a graphite-like state after preadsorbing K⁺; in particular, HCK-15 (Figure 2(d)) shows amorphous microcrystallites with much clearer carbon lattice stripes. In order to clarify the reason for the increase in the degree of graphitization of hard carbon with preadsorbed K⁺, elemental analysis was used to detect the content of C and O in the precursor and the hard carbon samples (Supplementary Tables S2 and S3). The percentage of C gradually increases and the percentage of O gradually decreases with the increase in the mass of KCl, indicating that KCl can promote the dehydration reaction of sucrose in the hydrothermal process. Furthermore, the increase in C content contributes to the development of graphitization in the carbonization process, resulting in the highest C content of HCK-15. The increased graphitization extent leads to the enhancement of van der Waals forces between graphite-like layers; hence, the HCK-15 exhibits diminished d_(002)-spacing. To
investigate the distribution of the K⁺ in the HCK-10, the EDX elemental mapping was carried out. As shown in Figure 2(h), the distribution of K⁺ is uniform on the spherical particle, which is critical to effectively occupying the irreversible adsorption sites of Na⁺ by preadsorbed K⁺.

High-resolution C 1s XPS spectra of all HC samples are carefully analyzed to clearly reveal the different components of the carbon skeleton, as shown in Figure 3. For all samples, the fitted C 1s spectra can be divided into three peaks. The main peak at 284.6 eV belongs to the C-C bond. Besides, two other peaks at 285.2 and 287.6 eV are related to the C-O bond and O−C=O bond, respectively. Comparatively, the HC sample owns the lowest ratio of the C-C bond. After preadsorbing K⁺, the percentage of the C-C bond is significantly increased, whereas both the C-O bond and O−C=O bond are greatly decreased. It is indicated that after preadsorbing K⁺ in the precursors, the carbon composition has been tailored to a more reasonable state and the graphite structure becomes more stable. These results are consistent with sXAS, Raman, and HRTEM. In addition, the survey spectrum of HCK-10 was also collected, as shown in Figure S2 (Supplementary); K 2s and K 2p peaks can be obviously seen besides C1s and O 1s, indicating that the preadsorbed K⁺ is able to enter the carbon framework.

To investigate the effect of the preadsorbed K⁺ on the Na storage behavior of HC, GCD tests at a current density of 5.0 mA g⁻¹ were carried out. As shown in Table 1, the HCK samples exhibit superior Na storage performance compared to the HC sample. After preadsorbing K⁺, the capacity of the HCK-10 sample is increased by 65.4%, and the rate capability is improved. These results are consistent with the EDX elemental mapping and XPS analysis, indicating that the preadsorbed K⁺ is able to enhance the Na storage performance of HC.

Figure 1: (a, b) C K-edge and O K-edge sXAS spectra of HC, HCK-10, and KCl standard sample. (c) Raman spectra of all samples, (d) XRD patterns of all samples, (e) CO₂ adsorption-desorption isotherms, and (f) pore size distributions of all samples.

Figure 2: (a–d) HRTEM images of HC, HCK-5, HCK-10, and HCK-15. (e) TEM image of HCK-10. (f–h) EDX elemental distribution mapping of HCK-10 based on (e).
50 mA g\(^{-1}\) and CV tests at 0.1 mV s\(^{-1}\) were conducted. The first three cycles of GCD curves of all samples are shown in Figure 4(a). All the samples display the typical GCD profiles of HC, which contain a sloping region above 0.1 V resulting from the Na\(^+\) adsorption/desorption on defects or other active sites and a plateau region under 0.1 V originating from Na\(^+\) insertion/extraction into the interlayer of graphite-like layers. In the first discharge process, two small reduction processes at around 1.2 and 0.6 V result from the electrolyte decomposition and the formation of a SEI film on the electrode surface, respectively [52]. The correlation between the reversible capacities derived from the slope and plateau region and the preadsorbed K\(^+\) content in HCs is plotted in Figure S3 and shown in Table S4 (Supplementary). Interestingly, the plateau capacity up to 198 mAh g\(^{-1}\) of HCK-10 was compared with 138 mAh g\(^{-1}\) of HC, 163 mAh g\(^{-1}\) of HCK-5, and 179 mAh g\(^{-1}\) of HCK-15, respectively. Meanwhile, the sloping capacity presents a negligible evolution with preadsorbed K\(^+\) ions. To further explore the relationship between capacity change and structural evolution, the (002) diffraction peak of each sample is divided into two peaks, corresponding to highly disordered region \((d_{002}) \approx 0.4 \text{ nm}\) and pseudo-graphitic region \((d_{002}) \approx 0.37 \text{ nm}\), respectively, as shown in Figure 4(c). In addition, highly disordered region can adsorb Na\(^+\) through the “pseudo-adsorption” mechanism, offering sloping capacities. The pseudo-graphitic region can capture Na\(^+\) through the “interlayer insertion” mechanism, contributing plateau capacities [53]. As can be seen in Figure S1 and Table S4 (Supplementary), after preadsorbing K\(^+\), the interlayer spacing of both two regions increases gradually except the HCK-15, thus facilitating the storage of Na\(^+\) through the “pseudo-adsorption” and “interlayer insertion” mechanism. Although the preadsorption of K\(^+\) reduces defects in HC, the \(d_{002}\) of the highly disordered region is enlarged to 0.4225 nm for HCK-5, 0.4309 nm for HCK-10, and 0.4245 nm for HCK-15, by the preadsorption of K\(^+\), as shown in Table S4 (Supplementary). The larger
interlayer spacing can offer more Na$^+$ adsorption sites, resulting in more slope capacities. In addition, the ratio of the pseudo-graphitic region also increases gradually after preadsorbing K$^+$; as a result, the ratio of plateau capacity also increased. This indicates that the larger interlayer $d$-spacing is conducive to Na$^+$ storage. Further, the CV

![Figure 4: (a) Galvanostatic charge-discharge profiles of the first three cycles for all samples at a current density of 50 mA g$^{-1}$. (b) CV curves of the first three cycles at a scan rate of 0.1 mV s$^{-1}$. (c) Peak fitted of the (002) peaks based on the XRD patterns.](image-url)
Curves of all samples in Figure 4(b) reveal a regular evolution, which are consistent with the GCD curves. As evident, two irreversible cathodic peaks at around 1.2 and 0.6 V also can be seen in the first reduction process. In addition, the pair sharp peaks at ~0.05 V and the weak humps in the wide potential range of 0.2-1.5 V are also observed, which are in accord with the plateau region and sloping region in the GCD curves, respectively. With the increasing content of K⁺, the sharp peaks near 0.05 V become sharper, which is in good accordance with the GCD curves.

Cycle stability and rate performance of all samples were tested to confirm the favorable influence of preadsorbed K⁺. The cycle stability of all samples at 50 mA g⁻¹ is shown in Figure 5(a). The HCK-10 sample displays the highest reversible capacity of 331.9 mAh g⁻¹ (HC: 261.1 mAh g⁻¹, HCK-5: 292.9 mAh g⁻¹, and HCK-15: 305 mAh g⁻¹) and ICE of 68% (HC: 57%, HCK-5: 62%, and HCK-15: 65%). After 200 cycles, the HCK-10 exhibits an astonishing capacity retention of 95.2% (HC: 85.6%, HCK-5: 97.6%, and HCK-15: 94.3%). The increased capacity retention after preadsorbing
K⁺ can be attributed to the more C-C bonds in the framework leading to enhanced structural integrity. As shown in Figure 5(b), HCK-10 also displays a superior rate capability. The reversible capacity of HCK-10 is up to 71.6 mAh g⁻¹ at 2 A g⁻¹. Moreover, the capacity of HCK-10 can completely recover when the current density goes back to 0.05 A g⁻¹. In contrast, the HC electrode only delivers a low capacity of 39.6 mAh g⁻¹ at 2 A g⁻¹. It is because the largest d-spacing of the HCK-10 ensures the fastest Na⁺ diffusion dynamics. Meanwhile, the higher graphitization extent guarantees higher conductivity. Thus, preadsorbed K⁺ does contribute to boosting the rate performance. To further disclose the influences of preadsorbed K⁺ on kinetic properties, EIS measurements and GITT tests were conducted. The gained Nyquist plots are shown in Figure 5(c). The semicircle parts in the high-frequency region represent the charge transfer resistances, and the corresponding values are 950, 650, 300, and 150 Ω for HC, HCK-5, HCK-10, and HCK-15, respectively. The gradually reduced charge transfer resistances after preadsorbing K⁺ could be attributed to the improved structure order degree [54]. Significantly, the elevated ion conductivity can synergistically boost the rate performance. GITT tests were performed to acquire the sodium diffusion coefficients (D_{Na⁺}), and it shows that the average D_{Na⁺} of HCK-10 is obviously higher than that of HC (Figure 5(d)), which confirms that the preadsorbed K⁺ can effectively accelerate Na diffusion kinetics of hard carbon. To evaluate the availability of HCK-10 in full cells, we assembled a Na-ion full cell with the HCK-10 anode and P2-Na_{2/3}Ni_{1/3}Mn_{2/3}O₂ cathode. When cycled at 100 mA g⁻¹ between 1.0 and 3.9 V, the full cell exhibits a high discharge capacity of 297.1 mAh g⁻¹ (based on the anode), accompanied by an average operating voltage of about 3.4 V as shown in Figure 5(e). After 50 cycles, a reversible capacity of 223.5 mAh g⁻¹ can be remained. Furthermore, the full cell can successfully light the LED lamp (Figure 5(f)).

*Figure 6: Scheme of the affection of the preadsorbed K⁺ on the reaction reversibility.*

We conclude that the rationally designed K⁺-preadsorbed method can effectively tailor the defects of the hard carbon anode and can significantly enhance Na storage performance (Figure 6). First, K⁺ can anchor on the hard carbon via C-O-K bonds, occupying the irreversible reactive sites of Na⁺, thus reducing the irreversible capacity caused by some C-O bonds. Additionally, transfer kinetics are also improved due to the high graphitization structure with fewer defects and large interlayer spacing, which can directly improve the electrical conductivity and lower Na⁺ diffusion energy barrier, thus facilitating fast Na⁺ storage. Therefore, the rate performance of HCK-10 is much better than that of HC. Lastly, high graphitization structure with fewer defects can enhance the structure stability, which is beneficial to cyclic stability.

4. Conclusions

In summary, K⁺-preadsorbed hard carbon was successfully fabricated as an anode for SIBs. Meanwhile, its structural properties were also demonstrated by the XAS, XRD, Raman, XPS, and HRTEM. We found that the preadsorbed K⁺ into HC can form C-O-K bonds and inactivate the redundant defects which are the irreversible reactive sites of Na⁺, thus leading to a higher ICE and superior cycling stability. In addition, the preadsorbed K⁺ leads to a high graphitization structure with large d(002)-spacing, thus facilitating the fast diffusion and reversible storage of Na⁺. Thanks to these structural changes, the HCK-10 displays excellent comprehensive performances, including higher ICE, superior cycling stability, and better rate performance. Furthermore, this work put forward a novel, efficient, and low-cost way to improve the electrochemical performances of hard carbon. Such method is suitable for large-scale production, thus promoting the commercial application of hard carbon for SIBs.
Data Availability

The authors declare that the main data supporting the findings in this study are available within the article and its supplementary information. Additional data are available from the corresponding authors upon reasonable request.

Conflicts of Interest

The authors declare no competing interests.

Authors’ Contributions

Y.B. and C.W. proposed the research idea. R.Q.D., Y.B., and C.W. designed the experiments. R.Q.D. synthesized and characterized the materials. H.Q.L. and X.Q.Y. performed the sXAS analysis. F.W., Q.N., and Y.L. were involved in the scientific discussions and provided technical support. Y.B., F.W., and C.W. supervised the research work. R.Q.D., Y.B., and C.W. wrote the manuscript. All authors discussed the results and commented on the manuscript.

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Supplementary Materials

Figure S1: SEM images of (a) HC, (b) HCK-5, (c) HCK-10, and (d) HCK-15. Figure S2: overall X-ray photoelectron spectrum of HCK-10. Figure S3: charge capacities of hard carbons and their capacities from the plateau region and slope region. Table S1: structural properties of all samples. Table S2: the mass fraction of C and O in the precursor (%). Table S3: the mass fraction of C and O in hard carbon (%). Table S4: XRD parameters and capacities of all samples. (Supplementary Materials)

References


