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One-pot synthesis of in-situ carbon-coated Fe$_3$O$_4$ as a long-life lithium-ion battery anode

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Abstract

Fe$_3$O$_4$ has been regarded as a promising anode material for lithium-ion batteries (LIBs) due to its high theoretical capacity, low cost, and environmental friendliness. In this work, we present a one-pot reducing-composite-hydroxide-mediated (R-CHM) method to synthesize in situ carbon-coated Fe$_3$O$_4$ (Fe$_3$O$_4$@C) at 280 °C using Fe(NO$_3$)$_3$ • 9H$_2$O and PEG800 as raw materials and NaOH/KOH as the medium. The as-prepared Fe$_3$O$_4$ octahedron has an average size of 100 nm in diameter, covered by a carbon layer with a thickness of 3 nm, as revealed by FESEM and HRTEM images. When used as anode materials in LIBs, Fe$_3$O$_4$@C exhibited an outstanding rate capability (1006, 918, 825, 737, 622, 455 and 317 mAh g$^{-1}$ at 0.1, 0.2, 0.5, 0.8, 1.0, 1.5 and 2.0 A g$^{-1}$). Moreover, it presented an excellent cycling stability, with a retained capacity of 261 mAh g$^{-1}$ after 800 cycles under an extremely high specific current density of 2.0 A g$^{-1}$. Such results indicate that Fe$_3$O$_4$@C can provide a new route into the development of long-life electrodes for future rechargeable LIBs. Importantly, the R-CHM developed in our work can be extended for the synthesis of other carbon-coated electrodes for LIBs and functional nanostructures for broader applications.

Supplementary material for this article is available online

Keywords: carbon-coated Fe$_3$O$_4$, R-CHM method, long-life, anode

(Some figures may appear in colour only in the online journal)
charging/discharging, poor cycling stability is still a serious issue that needs to be overcome before Fe3O4 can be used as a commercial anode material in LIBs [31, 46].

To mitigate the above predicament, carbon coatings have been explored to improve the performance of Fe3O4 anodes [26, 39, 42]. Studies have shown that coating carbon can not only facilitate ion and electron transports, but also relieve mechanical stress during the Li-ion insertion/extraction process. Various carbon coated Fe3O4 spheres, nanosheets, nanocubes, nanorods, pomegranate and sheaf-like structures have been successfully synthesized and they were found to possess improved electrochemical performances compared to a bare Fe3O4 electrode [2, 6, 45]. Thus, combining nanostructured Fe3O4 and a carbon matrix could be a promising way to optimize the electrochemical performance of an Fe3O4-based electrode, improve its cycling stability and prolonging its service life in LIBs [43, 44]. Recently, Zhao et al proposed a method of pyrolysis of polydopamine capsulated carbonate crystals to synthesize an Fe3O4@C hybrid, which possesses a high reversible capacity of 770 mAh g\(^{-1}\) at 200 mAg\(^{-1}\) after 50 cycles. In this method, the Fe2CO3 precursor was synthesized first, then the Fe3O4@C hybrid was obtained after pyrolysis at 500 °C [51]. Han et al reported hierarchically structured Fe3O4@C nanotubes prepared by three steps, which delivered a reversible capacity of 840 mAh g\(^{-1}\) at 1000 mA g\(^{-1}\) after 300 cycles. Mo3O4 nanorods and FeOOH nanotubes were synthesized first and then calcined at 500 °C for 4 h to obtain Fe3O4@C nanotubes [10]. Ma et al prepared a sheaf-like hierarchical Fe3O4@C nanostructure by a facile solvothermal method, which exhibited a reversible capacity of 849 mAh g\(^{-1}\) at 500 mA g\(^{-1}\) over 200 cycles. In this process, Fe(NO3)3 \(\cdot\) 6H2O and glucose were heated at 220 °C first and then calcined at 350 °C for 3 h in N2 gas [33]. Zhang et al proposed microwave irradiation as a heat source and Fe2O3/graphene composites were synthesized by depositing Fe\(^{3+}\) in the interspaces of graphene sheets. To obtain Fe3O4/graphene composites, GO was prepared by a modified Hummers’ method, and then a mixture of GO, Fe(NO3)3 urea and ascorbic acid were refluxed under ambient conditions for 1 h and microwave heated, and finally, MGCs were obtained by treating the above products in an Ar atmosphere at 873 K for 8 h [48]. However, most of these methods used to synthesize the Fe3O4@C nanostructure have some disadvantages, including specific organic reagents, complicated experimental processes involving two or more steps, a high reaction temperature (mostly more than 280 °C) and poor reproducibility. Therefore, it is highly desirable to synthesize a carbon coated Fe3O4 nanostructure by a one step process.

Herein, we developed a reducing-composite-hydroxide-mediated (R-CHM) method to obtain the in situ carbon coated Fe3O4 (Fe3O4@C) using Fe(NO3)3 \(\cdot\) 9H2O and polyethylene glycol-800 (PEG800) as raw materials and NaOH/KOH (MOH) as a medium at 280 °C in one step. When used as an anode for LIBs, such Fe3O4@C possessed an exceptional capacity of 1006 mAh g\(^{-1}\) at a current density of 0.1 A g\(^{-1}\). Moreover, the reversible capacities of 268 mAh g\(^{-1}\) can still be retained after 800 cycles under a high current density of 2.0 A g\(^{-1}\).

### Experimental section

#### Chemicals

Fe(NO3)3 \(\cdot\) 9H2O, KOH, NaOH, and PEG800 were of analytical grade and were purchased from Sigma-Aldrich, with 99.9% purity. Deionized water was used in all the experimental processes.

#### Synthesis

Fe3O4@C was synthesized by the R-CHM method via the following steps. (1) First, 5.15 g of NaOH, 4.85 g of KOH and 1.2 g of Fe(NO3)3 \(\cdot\) 9H2O were mixed in a mortar and fully ground. (2) Then 0 or 5 g of PEG800 were added to the mixture, and were further ground. (3) Two mixtures were put into a 25 ml Teflon container, placed in an electric oven and heated at 280 °C for 48 h. (4) The Teflon container was taken out and cooled to room temperature naturally after reaching the specified time. (5) The precipitate formed in the container was washed with deionized water and ethanol until the pH value reached 7, and then dried in vacuum. The sample obtained with 0 g PEG800 was labelled as S1, while the other one was labelled S2.

#### Characterizations

X-ray diffraction (XRD) analysis was carried out using nickel filtered Cu Kα radiation on a Bruker D8 Advance diffractometer to identify the crystalline phase of the as-prepared samples. The morphology was characterized by an SU8010 field emission scanning electron microscope (FE-SEM) and D8-high resolution transmission electron microscopy (HR-TEM). The reaction mechanism in the R-CHM method was analyzed via a thermo-gravimetric differential scanning calorimeter (TG–DSC) (STA449C/3/G) with a heating rate of 10 °C min\(^{-1}\). Fourier transform infrared spectroscopy (FT-IR) was performed to analyze the surface characteristics of PEG800 and the intermediates in the reaction system by a SHIMAUZU-8400 system. The specimens were mixed with KBr pellets and then pressed into a pelletizer for FT-IR measurements. Magnetic measurements were performed by a Lake Shore 7410 vibrating sample magnetometer (VSM) operated at room temperature. The magnetic hysteresis loop was measured in the field range between ±10 kOe at room temperature.

#### Electrochemical measurements

For electrochemical analysis, coin-type half cells (CR 2025) were assembled in a glove box filled with high purity argon. The anode was prepared by mixing 80 wt% of the active material (e.g. Fe3O4@C), 10 wt% of Super P conductive carbon, and 10 wt% of polyvinylidene fluoride binder in N-methyl pyrrolidone solvent on copper foil. It was then put into
a vacuum oven and dried at 120 °C for 12 h. The copper foils coated with active materials were cut into circular sheets with a diameter of 1.33 cm and assembled in the glove box. Lithium (Li) metal was used as the cathode and the complex of ethyl methyl carbonate, 1 M LiPF6 in dimethyl carbonate and ethylene carbonate (1:1:1, v/v/v) was used as an electrolyte, and the Celgard 2400 as a separator. Cyclic voltammetry (CV) was carried out between 0.01 and 3.0 V versus Li/Li+ at scanning rates of 0.5 mV s⁻¹ using an electrochemical analyzer (Solartron, 1260/1287). The current density and cycle stability were performed on an Arbin battery tester (BT-2000, Arbin Instruments) between 0.01 and 3.0 V versus Li/Li+ at various charging rates of 0.1, 0.2, 0.5, 0.8, 1.0, 1.5 and 2.0 A g⁻¹. To validate the electrochemical kinetics of Fe₃O₄@C, electrochemical impedance spectroscopy (EIS) measurements were examined by a frequency response analyzer (Solartron, 1260/1287) in the frequency range from 0.1 Hz–100 kHz with an AC signal amplitude of 10.0 mV.

**Results and discussion**

Figure 1 shows the XRD patterns of S₁ and S₂. The lower standard XRD pattern confirmed that all the diffraction peaks of S₁ can be assigned to the hexagonal phase of α-Fe₂O₃ (JCPDS No.33-0664) [53]. Meanwhile, the diffraction peaks of S₂ at 2θ = 26.30°, 30.01°, 35.41°, 43.11°, 53.61°, 56.91° and 62.41° were indexed to (111), (220), (311), (400), (422), (511) and (440)—in good agreement with the pure face-centred cubic Fe₃O₄ (JCPDS No. 75-0449) [5, 29]. This suggests that the α-Fe₂O₃ had completely transformed into the Fe₃O₄ after being heated to 280 °C for 48 h together with PEG800. All the diffraction peaks of S₂ were sharp in width and strong in intensity, indicating that it has excellent crystallinity, while there was no diffraction peak corresponding to carbon observed in the XRD pattern. FT-IR spectra of bare PEG800 (figure S1(a) is available at stacks.iop.org/NANO/28/155603/mmedia) and PEG800 reacting in MOH at 280 °C (figure S1(b)) have been obtained. As shown in figure S1, compared to bare PEG800, the absorption peaks of –OH and –CH₂ almost disappeared after PEG800 was reacted in MOH for some time, suggesting that PEG800 could be converted into carbon after prolonging the reaction time. Therefore, combining the XRD and FT-IR results, we suggested that PEG800 has transformed into carbon in the process of the synthesis of Fe₃O₄, which was confirmed by the subsequent TEM image.

In order to characterize the microstructures, FE-SEM, HR-TEM and SAED images of S₂ (Fe₃O₄@C) were examined. The FE-SEM image revealed the detailed morphology of Fe₃O₄@C, which showed an octahedral shape and uniform size (figure 2(a)). From the enlarged image in figure 2(b), it was found that Fe₃O₄ crystals have an octahedral morphology with eight facets and have a lateral size of 100 nm. With reference to the FE-SEM analysis above, the TEM images gave a further view of the octahedral Fe₃O₄@C nanocrystalline structure. The same selected area was presented in bright and dark fields, and is shown in figures 2(c) and (d). From the bright-field TEM image in figure 2(c), it can be seen that Fe₃O₄ possesses regular geometrical morphology, and thus good crystallization. From the dark-field TEM image in figure 2(d), it was observed that some bright spots were covered by shallow grey flocculent matter, suggesting that the surface of the Fe₃O₄ octahedron was coated with a layer of amorphous material, believed to be carbon. From the higher-magnification TEM image in figure 2(e), it can be seen that the Fe₃O₄ nanocrystals exhibited a regular octahedral shape and the entire surface of the Fe₃O₄ octahedron was covered by a uniform carbon layer to form a composite structure of Fe₃O₄@C. After further magnification, the carbon coating wrapping the Fe₃O₄ octahedron was revealed, as shown in figure 2(f). The thickness of the carbon was measured to be around 3 nm, as marked by the blue dashed lines in figure 2(f). The homogeneous carbon coating structure could effectively improve the conductivity of the electrodes, limit the volume change of Fe₃O₄ octahedron materials and keep the Fe₃O₄ electrode stable during Li⁺ intercalation and deintercalation. Moreover, a small amount of lattice fringes can be observed in the local area. The lattice fringe pitch of 0.30 nm corresponds well with the d-spacing of the (220) reflections of Fe₃O₄ [17]. In addition, the relative SAED pattern (inset in figure 2(f)) disclosed rectangular bright diffraction spots, which can be indexed to the crystal planes (220) and (111) of Fe₃O₄, indicating the perfect single crystalline structure of the Fe₃O₄ nanocrystals [40]. At the same time, the morphology and structural characteristics of S₁ (α-Fe₂O₃) were examined by SEM and TEM as well, as shown in figure S2, revealing the as-synthesized α-Fe₂O₃ sample consisting of dispersed nanosheets that were hexagonal plates with an average diameter of 1 μm and a thickness of about 50 nm. The structures of Fe₃O₄@C and α-Fe₂O₃ were further supported by their magnetic properties measured using VSM.
at room temperature, as shown in figure S3, confirming their ferromagnetic characteristics. The saturation magnetization of 26.8 emu g$^{-1}$, the remanent magnetization of 5.2 emu g$^{-1}$, and the coercivity of 165.4 Oe measured in Fe$_3$O$_4$@C are smaller than values reported previously, which could be explained by the surface coating of the carbon layer on Fe$_3$O$_4$.

The reaction process of Fe(NO$_3$)$_3$·9H$_2$O and PEG800 in the MOH medium can be understood from the TG–DSC curves in figure 3. According to the DSC results, there were five endothermic peaks at 66 °C, 91 °C, 105 °C, 132 °C, and 261 °C, and one exothermic peak at 114 °C. The endothermic peak at 66 °C occurs with hardly any weight change, which was believed to correspond to Fe(NO$_3$)$_3$·9H$_2$O changed to Fe(OH)$_3$. The endothermic peaks at 91 °C and 105 °C were associated with a 1.2% weight loss, which was ascribed to the amount of adsorbed water that was lost from the heating process. At 114 °C, a sharp exothermic peak occurred with obvious weight loss, corresponding to the start of the PEG800
decomposition. An endothermic peak appears at 132 °C, which was attributed to Fe(OH)₃ decomposition. Finally, an endothermic peak occurred at 262 °C corresponding to the carbon thermal reduction of Fe₂O₃ into Fe₃O₄. It should be pointed out that, during the process from 114 °C–300 °C, the weight loss was about 22.5%—much larger than the theoretical value of 3.8% for the weight loss associated with the decomposition of Fe(NO₃)₃·9H₂O into Fe₂O₃. This difference was likely caused by the weight loss associated with the gradual carbonization of PEG800. Combined with the XRD results above, it was thus concluded that PEG800 provided a reducing agent to transform Fe³⁺ into Fe²⁺ and thus form Fe₃O₄.

The detailed reaction mechanism during the R-CHM synthesis of Fe₃O₄@C is summarized by the following equations:

\[
\begin{align*}
50 \degree C \sim 100 \degree C: & \quad \text{Fe}^{3+} + 3\text{OH}^- \rightarrow \text{Fe(OH)}_3 \\
100 \degree C \sim 250 \degree C: & \quad \text{PEG}800 \rightarrow \text{C} + \text{O}_2 + \text{H}_2\text{O} \\
120 \degree C \sim 200 \degree C: & \quad \text{Fe(OH)}_3 \rightarrow \text{Fe}_2\text{O}_3 + \text{H}_2\text{O} \\
200 \degree C \sim 300 \degree C: & \quad \text{Fe}_2\text{O}_3 + \text{C} \rightarrow \text{Fe}_3\text{O}_4 + \text{CO}_2
\end{align*}
\]

According to the above results of XRD, FESEM and TG–DSC, the formation mechanism of Fe₃O₄@C can be inferred. As illustrated in scheme 1, the Fe₃O₄@C was obtained by a simple one-pot method, as follows: (a) the raw mixture consisted of Fe(NO₃)₃·9H₂O, PEG800, MOH that were mixed uniformly with full grinding; (b) after heating at 132 °C, the introduced PEG800 formed a carbon–oxygen skeleton by partial dehydration in the MOH medium, and Fe(OH)₃ decomposed to α-Fe₂O₃. The carbon–oxygen skeleton was then adsorbed on the surface of the obtained α-Fe₂O₃ nanosheets by a large number of hydroxyl groups; (c) when the temperature increased to 262 °C, the carbon–oxygen skeleton transformed to carbon molecules and the α-Fe₂O₃ was reduced to Fe₃O₄ by carbon molecules; the remaining carbon–oxygen skeleton was coated on the surface of octahedral Fe₃O₄; (d) as the reaction time progressed, the remaining carbon–oxygen skeleton transformed to carbon molecules and was coated on the surface of the Fe₃O₄ octahedron. As a result, a carbon coated octahedral Fe₃O₄
nanostructure was obtained. The phase transition can be demonstrated by XRD, the morphological description can be obtained according to the FESEM images, and the reaction temperature is confirmed by the TG–DSC results from (a) to (d).

The electrochemical properties of the Fe₃O₄@C were examined by CV and galvanostatic charge/discharge tests. The typical cyclic voltammograms of the Fe₃O₄@C anode in the initial three cycles between 0.01 V and 3.0 V at a scanning rate of 0.5 mVs⁻¹ are shown in figure 4(a). In the first cathodic process, the major peaks located around 0.85 V could be attributed to the formation of Li₂O and solid electrolyte interface (SEI) film [11, 20]. Further, the anodic peak at 1.72 V demonstrated the extraction of Li from the electrode material. In the subsequent cycles, it could be seen that the cathodic peak at 0.85 V shifted to 0.90 V, which might be considered to enhance the physical buffering affect and increase the polarization of the electrode material after being coated with a layer of amorphous carbon. The peak at 1.72 V shifting to 1.79 V might be ascribed to the increased oxidation of Fe⁰ to Fe³⁺ due to the formation of the carbon layer.

Figure 4. (a) Cyclic voltammograms of Fe₃O₄@C at a scan rate of 0.5 mVs⁻¹ between 0.01 and 3.0 V; (b) discharge/charge profiles of Fe₃O₄@C for the initial 100 cycles at a specific current of 0.1 A g⁻¹; (c) the rate capabilities of Fe₃O₄@C at different specific currents between 0.1 and 2.0 A g⁻¹; (d) Nyquist plots of Fe₃O₄@C electrodes before electrochemical cycling by applying an AC voltage of 10 mV over the frequency range from 0.1 Hz–100 kHz.

Figure 5. Cycling performance of Fe₃O₄@C at a specific current of 2.0 A g⁻¹.
Table 1. Comparison of the electrochemical performance for the iron oxides as anode materials of LIBs in the recently reported literature.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Synthesized steps</th>
<th>Current density</th>
<th>Charge capacity after cycling</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>commercial Fe3O4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Fe3O4@C</td>
<td>one step</td>
<td>0.1 C</td>
<td>70 mAh g⁻¹ after 50 cycles</td>
<td>[48]</td>
</tr>
<tr>
<td>Fe3O4@C</td>
<td>one step</td>
<td>0.2 C</td>
<td>350 mAh g⁻¹ after 100 cycles</td>
<td>[49]</td>
</tr>
<tr>
<td>MoO2–GO</td>
<td>two steps</td>
<td>500 mA g⁻¹</td>
<td>310 mAh g⁻¹ after 30 cycles</td>
<td>[12]</td>
</tr>
<tr>
<td>MnO2/carbon</td>
<td>three steps</td>
<td>2000 mA g⁻¹</td>
<td>525 mAh g⁻¹ after 1000 cycles</td>
<td>[16]</td>
</tr>
<tr>
<td>Fe3O4@C</td>
<td>three steps</td>
<td>0.2 C</td>
<td>543 mAh g⁻¹ after 2000 cycles</td>
<td>[23]</td>
</tr>
<tr>
<td>Fe3O4@C</td>
<td>three steps</td>
<td>0.2 C</td>
<td>254 mAh g⁻¹ after 100 cycles</td>
<td>[28]</td>
</tr>
<tr>
<td>Fe3O4@C</td>
<td>one step</td>
<td>2000 mA g⁻¹</td>
<td>268 mAh g⁻¹ after 800 cycles</td>
<td>this work</td>
</tr>
</tbody>
</table>

Figure 4(b) reveals the galvanostatic charge/discharge curves of the Fe3O4@C at 0.1 A g⁻¹. At 1.0 V, there was a distinct voltage plateau in the discharge curve that corresponds to Li⁺ insertion into Fe3O4 and the formation of the SEI films after electrolyte decomposition [3, 10, 41]. A reversible conversion from Fe to Fe3O4 at a sloping plateau around 1.7 V was observed in the charge curve. The capacities during the first two cycles were measured to be 1297 mAh g⁻¹ and 950 mAh g⁻¹. Furthermore, it was noted that a high reversible capacity of 630 mAh g⁻¹ was achieved after 50 cycles. After 100 cycles, it still maintained a reversible capacity of 505 mAh g⁻¹. These results suggest that the integrity of Fe3O4@C could be retained during long-life cycles.

The rate capability of the as-prepared Fe3O4@C was tested at various current densities ranging from 0.1–2.0 A g⁻¹. As shown in figure 4(c), at 0.1 A g⁻¹, the stable capacity of Fe3O4@C was around 1006 mAh g⁻¹. When the specific current increased to 0.5 A g⁻¹, a stable high capacity of 825 mAh g⁻¹ could be achieved. At a high specific current of 1.0 A g⁻¹, the Fe3O4@C could possess a stable capacity of 622 mAh g⁻¹ (figure 4(c)). At an even higher specific current of 2.0 A g⁻¹, it presented a reversible capacity of 317 mAh g⁻¹. Remarkably, when the specific current was reduced back to 0.1 mA g⁻¹ after 35 cycles, a stable high capacity of 1006 mAh g⁻¹ could be recovered (figure 4(c)). Such enhanced electrode kinetics could be further examined by EIS measurements. The charge transport properties of the Fe3O4@C samples were measured by EIS at an open-circuit voltage of 2.85 V. As shown in figure 4(d), it was observed that from 10⁻² Hz–10⁵ Hz, the Nyquist plots displayed a depressed semicircle and from 0.1 Hz–10² Hz displayed a sloped line, which correspond to the charge transfer resistance (Rct) and Warburg impedance (Wa), respectively [1, 42]. The value of the charge transfer resistance (Rct) was 52 Ω for Fe3O4@C, indicating the significantly improved charge transport properties of the Fe3O4@C electrode due to the presence of the carbon layer on its surface.

To verify the long-term cycling stability and high rate capability of Fe3O4@C as an anode material for LIBs, it was tested at an extremely high specific current of 2.0 A g⁻¹ for 800 cycles, as shown in figure 5. It can be seen that the reversible capacity was stabilized around 300 mAh g⁻¹ at the 50th cycle and the capacity decay ratio was about 58%. After 800 cycles, the Fe3O4@C anode remained at a reversible capacity of 268 mAh g⁻¹ and the capacity decay ratio was about 52%. It is noted that the capacity decreased at the start of the 50 cycles. This phenomenon has also been observed in previous researches [15, 32, 52]. The possible reason is that when the current density is too large, the anode is prone to polarization which causes Li ion reduction by deposition. So the capacity decreased in the initial stage [32]. The excellent cycling stability and rate performance of Fe3O4@C may be attributed to the synergic effects of each component in the composite [18]. Firstly, the nanosize octahedral Fe3O4 can significantly increase the electrode/electrolyte contact area and shorten the electron and Li ion diffusion distances; secondly, the carbon coating can effectively improve the structural stability of the electrode by suppressing the aggregation of the Fe3O4 octahedron and accommodating its volume expansion during the process of charge/discharge [9, 47]. Moreover, to verify the long-term cycling stability, the performance of other similar materials reported in the literature are summarized in table 1. It can be seen that the Fe3O4@C exhibited a long-term cycling stability when synthesized by the R-CHM method. All the above characteristics proved Fe3O4@C to be a promising anode material for high performance LIBs.

Conclusion

A novel one-pot R-CHM strategy was developed for the synthesis of an octahedral Fe3O4@C nanostructure at 280 °C. Such Fe3O4@C delivered reversible capacities of 1006–317 mAh g⁻¹ over a wide range of specific currents of 0.1–2.0 A g⁻¹. Importantly, it maintained a reversible capacity of 268 mAh g⁻¹ after 800 cycles at 2.0 A g⁻¹. These excellent electrochemical properties are attributed to the uniform-sized octahedral Fe3O4 and in situ carbon coating. The carbon layer on the surface of the octahedral Fe3O4 could effectively improve the electrode conductivity, avoid direct exposure of the Fe3O4 octahedral to the electrolyte and help to reduce the mechanical stress during the Li-ion insertion/extraction process. Therefore, this R-CHM method is an ideal one-step technique to obtain an in situ carbon coating structure at lower temperatures. Thanks to its facility and versatility, the R-CHM method invented in our work can be extended to the synthesis of other functional nanostructures for various applications.
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