Chromium (III) Oxide Carbon Nanocomposites Lithium-ion Battery Anodes with Enhanced Energy Conversion Performance

Ya Fu,¹ Hongbo Gu,³ Xingru Yan,² Jiurong Liu^{1,*}, Yiran Wang,² Jiangnan Huang,² Xiaoyu Li,¹
Hailong Lv,¹ Xinzhen Wang,¹ Jiang Guo,² Guixia Lu,¹ Song Qiu¹, Zhanhu Guo^{2*}

¹Key Laboratory for Liquid–Solid Structural Evolution and Processing of Materials, Ministry of Education and School of Materials Science and Engineering, Shandong University, Jinan, Shandong 250061, China

² Integrated Composites Laboratory (ICL),
Department of Chemical and Biomolecular Engineering,
University of Tennessee, Knoxville, TN 37996 USA

³Department of Chemistry,
Tongji University, Shanghai, 200092, People's Republic of China

*Corresponding authors.

E-mail addresses: jrliu@sdu.edu.cn (J. L.);
zguo10@utk.edu (Z. G.)

Abstract

The chromium (III) oxide (Cr_2O_3) nanoparticles embedded in the carbon sheets are fabricated by combining a sol-gel approach with an efficient carbonization process using glycine as carbon precursor. These Cr_2O_3 /carbon nanocomposites serving as anode materials for lithium-ion batteries (LIBs) have been tested, exhibiting higher cycling (reversible capacity of 465.5 mAh g^{-1} after 150 cycles at a current density of 100 mA g^{-1}) and rate performances (the discharge capacities of 448.7 , 287.2 , and 144.8 mAh g^{-1} at a current density of 200 , 400 , and 800 mA g^{-1} , respectively) than pure Cr_2O_3 (reversible capacity of 71.2 mAh g^{-1} after 150 cycles at a current density of 100 mA g^{-1} and the discharge capacities of 174.4 , 60.5 , 29.5 , and 13.6 mAh g^{-1} at a current density of 100 , 200 , 400 , and 800 mA g^{-1} , respectively) due to the presence of carbon sheets, which efficiently buffer the volume change during the lithiation/delithiation and improve the electrical conductivity between Cr_2O_3 nanoparticles.

Keywords: chromium (III) oxide; anode materials; carbon; lithium-ion battery.

1. Introduction

Lithium-ion batteries (LIBs) have become sustainable and renewable power sources for various portable electronic devices due to their high voltage, high energy density and long lifespan [1-3]. Transition-metal oxides, such as cobalt (II,III) oxide (Co_3O_4) [4, 5], manganese (II) oxide (MnO) [6], magnetite (Fe_3O_4) [7], copper (II) oxide (CuO) [8], etc., have been considered as potential anode materials for LIBs because they possess a theoretical specific capacity far larger than the commercial graphite material (372 mAh g^{-1}) [9]. For example, chromium (III) oxide (Cr_2O_3) has also been reported as anode materials for LIBs with a theoretical capacity of 1058 mAh g^{-1} and relatively low electromotive force (EMF) value of 1.085 V [10]. Cr_2O_3 follows a similar mechanism to that of other transition metal oxides, i.e., $6\text{Li}^+ + \text{Cr}_2\text{O}_3 + 6\text{e}^- \rightleftharpoons 3\text{Li}_2\text{O} + 2\text{Cr}$. However, similar to other pure metal oxide anodes, Cr_2O_3 still has challenges or disadvantages including fast capacity fading and low rate performance due to its drastic volume expansion/contraction, and severe structural destruction during discharge/charge processes [11].

Various strategies have been used to improve the cycling and rate performance of Cr_2O_3 , such as downsizing particles [12], constructing porous nanostructures [13], and preparing composites [14, 15]. Among these methods, carbon composites have been widely investigated since carbon can not only cushion the stress from volume expansion of active materials and maintain the structural integrity of electrode during cycling, but also prevent the agglomeration of metal oxide particles. Therefore, the addition of carbon has brought an evident effect on the improvement of cycling stability [16, 17]. For example, carbon-coated graphene- Cr_2O_3

composites, which were synthesized using a hydrothermal method followed by a subsequent thermal treatment, exhibit a reversible capacity of more than 550 mAh g⁻¹ after 100 cycles [14]. The carbon coating formed simultaneously with Cr₂O₃ particles could separate the particles and limit their growth, which resulted in the enhancement of electrochemical performances [14]. However, this approach suffers from high cost and complicated operation, which limit its practical application. Jiang et al [18]. reported that the Cr₂O₃-C hierarchical core/shell nanospheres exhibit better cycling performance (600 mAh g⁻¹ after 35 cycles) than pure mesoporous Cr₂O₃ spheres (320 mAh g⁻¹ after 35 cycles), while the Cr₂O₃-C hierarchical core/shell nanospheres still showed poor cycling stability and the capacity decreased successively with cycling.

In this work, a facile approach to prepare the Cr₂O₃/carbon nanocomposites by directly carbonizing glycine-CrCl₃ gel precursor is reported for the first time. The crystalline structure of the Cr₂O₃/carbon and pure Cr₂O₃ samples is investigated by XRD. TGA and DSC tests have been carried out to evaluate the carbon content in the synthesized Cr₂O₃/carbon sample. Scanning electron microscope (SEM) and transmission electron microscopy (TEM) are used to characterize the structures and morphologies of the prepared Cr₂O₃/carbon nanocomposites. The electrochemical performances of prepared Cr₂O₃/carbon nanocomposites as anode materials for LIBs are evaluated by cyclic voltammogram (CV), galvanostatic charge-discharge and electrochemical impedance spectroscopy (EIS) measurement techniques.

2. Experimental

2.1 Materials

Chromic chloride ($\text{CrCl}_3 \cdot 6\text{H}_2\text{O}$), glycine ($\text{NH}_2\text{CH}_2\text{COOH}$), ammonium hydroxide ($\text{NH}_3 \cdot \text{H}_2\text{O}$), polyvinylidene fluoride (PVDF) and N-Methyl-2-pyrrolidone (NMP) were purchased from Sinopharm Chemical Reagent Co., Ltd. Carbon black, Li foil and Celgard 2300 were purchased from Hefei Kejing Material Technology Co., Ltd, China. LiPF_6 (dissolved in ethylene carbonate, dimethyl carbonate, and ethylene methyl carbonate with a volume ratio of 1: 1: 1) was purchased from Shenzhen Biyuan Technology Co., Ltd, China. All the chemicals were analytical grade and used as received without any further purification.

2.2 Preparation of Cr_2O_3 /carbon nanocomposites and pure Cr_2O_3 nanoparticles

The Cr_2O_3 nanoparticles embedded in the carbon sheets were fabricated by combining a sol-gel approach with an efficient carbonization process using glycine as carbon precursor. Briefly, 0.1 mol $\text{CrCl}_3 \cdot 6\text{H}_2\text{O}$ and 0.08 mol glycine were dissolved in 30 mL deionized water under magnetic stirring, and then the solution was transferred into a vessel. The gel precursor was obtained after the solution was aged and dried in air for two weeks. Then the gel precursor was carbonized at 550°C for 5 h in a tube furnace under nitrogen flux to prepare Cr_2O_3 /carbon nanocomposites. The preparation procedure of the Cr_2O_3 /carbon nanocomposites is shown in Scheme 1. Pure carbon (C) was prepared in the same way except the addition of $\text{CrCl}_3 \cdot 6\text{H}_2\text{O}$. Pure Cr_2O_3 nanoparticles were also prepared for comparison. Briefly, 0.1 mol $\text{CrCl}_3 \cdot 6\text{H}_2\text{O}$ was dissolved in 30 mL deionized water. Then 13 mL ammonium hydroxide (25 wt%) was added into the above solution dropwise under magnetic stirring for 30 min. The $\text{Cr}(\text{OH})_3$ precipitate was centrifuged, washed using deionized water for several times, and dried at 50°C in an oven

overnight. Cr_2O_3 was obtained by sintering $\text{Cr}(\text{OH})_3$ at $550\text{ }^\circ\text{C}$ for 5 h in a furnace.

2.3 Characterizations

X-ray diffraction (XRD) analysis was carried out on a Rigaku D/Max-RC X-ray diffractometer with Ni filtered Cu $K\alpha$ radiation ($\lambda = 0.1542\text{ nm}$, $V = 40\text{ kV}$, $I = 40\text{ mA}$) in the range of $10 \sim 80^\circ$ at a scanning rate of 4° min^{-1} . Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) were performed from ambient temperature to $800\text{ }^\circ\text{C}$ in air at a heating rate of $10\text{ }^\circ\text{C min}^{-1}$ using a SDT thermal-microbalance apparatus. Raman spectra were obtained by a Renishaw confocal Raman microspectroscopy (Renishaw Co. Ltd., Gloucestershire, U.K.) with a laser excitation wave length of 780 nm . Fourier transform infrared spectroscopy (FTIR) was recorded on a VERTEX-70FT-IR spectrometer. X-ray photoelectron spectroscopy (XPS) was conducted on a Kratos Analytical spectrometer, using Al $K\alpha = 1486.6\text{ eV}$ radiation as the excitation source, under a condition of anode voltage of 12 kV and an emission current of 10 mA . The microstructure of the sample was observed on a JSM-6700F field emission scanning electron microscope (SEM), and a JEOL JEM-2100 transmission electron microscopy (TEM). The N_2 adsorption-desorption isotherms of hollow porous cobalt structures were measured at 77 K on a Quadrasorb-SI instrument. The specific surface area (SBET) was calculated with the Brunauer-Emmett-Teller (BET) model and the pore size distribution was calculated by the density functional theory (DFT) method.

The working electrode was prepared as follows. The active anode composite material, carbon black, and PVDF with a weight ratio of 8: 1: 1 were mixed in NMP to form a homogenous slurry. The slurry was coated on a copper foil substrate and dried in a vacuum oven

at 120 °C for 12 h. The CR2025-type cells were assembled using Li foil as counter electrode, Celgard 2300 as separator, and 1.0 M LiPF₆ as electrolyte in a glovebox filled with argon atmosphere. The charge-discharge experiments were performed on a LAND CT2001A battery test system over a voltage of 0.02 ~ 3 V at various current densities. The cyclic voltammetry (CV) experiment was performed on a IviumStat electrochemistry workstation with a scanning rate of 0.1 mV s⁻¹ and the potential vs. Li/Li⁺ ranging from 0.01 to 3 V. The electrochemical impedance spectroscopy (EIS) was tested on the same instrument with AC signal amplitude of 10 mV in the frequency range from 100 kHz to 0.01 Hz.

3. Results and discussion

Fig. 1A shows the XRD patterns of the as-prepared nanocomposites and pure Cr₂O₃ nanoparticles. All the peaks can be indexed as Cr₂O₃ with the lattice parameters of $a = 4.959$, $b = 4.959$ and $c = 13.594$ nm (JCPDS No.38-1479). There is no peak of any other phases, indicating that Cr₂O₃ has been obtained for the Cr₂O₃/carbon nanocomposites after high-temperature treatment in the presence of carbon. According to the Scherrer's formula [19, 20]: $\beta = k\lambda / L \cos \theta$, where λ is the X-ray wavelength ($\lambda = 0.154$ nm), L is the average crystallite size, k is the shape factor and $k = 0.89$, β is the full width at half maximum, and θ is Bragg angle in degree, the average crystalline size of Cr₂O₃ for the Cr₂O₃/carbon sample composites is calculated to be about 30 nm, based on the (1 0 4) peak at $2\theta = 33.4^\circ$.

Fig. 1B shows the FT-IR spectra of the gel precursor consisted CrCl₃ with glycine and Cr₂O₃/carbon nanocomposites. In the FT-IR spectrum of the gel precursor, Fig. 1B-a, two peaks

are observed between 2500 and 3600 cm^{-1} . The peak at 3123 cm^{-1} is attributed to the C-H bonds of glycine, and the shoulder peak at 3386 cm^{-1} is assigned to the O-H stretching vibration arising from water molecules remained in the gel precursor and the hydroxyl groups of glycine [21]. The peaks at 1665, 1469 and 1345 cm^{-1} are related to the stretching vibration of C-O, N-H and C-C bonds, respectively. These vibration modes are known to be the signatures of amino acids [22, 23]. For the Cr_2O_3 /carbon nanocomposites, the absorption peaks at 3426, 1395 and 1621 cm^{-1} (Fig. 1B-b) are assigned to the stretching vibrations of O-H, C-C and C-O groups [24], respectively, while the peaks of C-H (3123 cm^{-1}) and N-H (1469 cm^{-1}) (Fig. 1B-a) are disappeared after carbonization. The bands at 570 and 625 cm^{-1} are associated with the vibration mode of O-Cr-O bonds, confirming the formation of Cr_2O_3 phase [25]. The FT-IR results indicate that glycine in gel precursor has been transformed into carbon structure and Cr_2O_3 has been generated during the carbonization process, which is consistent with the XRD analysis.

TGA and DSC tests have been carried out to evaluate the carbon content in the synthesized Cr_2O_3 /carbon sample. The results are shown in Fig. 1C. The weight losses can be distinguished into two stages in the TGA profiles. In the first stage from room temperature to 200 $^{\circ}\text{C}$, the weight loss of about 3.0% is due to the evaporation of water absorbed on the surface of Cr_2O_3 /carbon sample. The second stage around 200 ~ 400 $^{\circ}\text{C}$ with about 14.2% weight loss, corresponding to the exothermic peak in the DSC curve, is attributed to the oxidation process of carbon to form volatile species such as CO and CO_2 . After 400 $^{\circ}\text{C}$, there are no apparent exothermal peak and weight loss observed, suggesting the complete oxidation of carbon. Thus, Cr_2O_3 accounts for 82.8% of the total weight in the formed carbon nanocomposites. The Raman

spectra of Cr₂O₃/carbon nanocomposites are shown in Fig. 1D. The broad peaks located at about 1356 and 1596 cm⁻¹ are assigned to the D band (disordered carbon) and G band (graphitic carbon) of carbon materials, respectively [26, 27]. The intensity ratio of the two peaks (I_D/I_G) could be used to evaluate the disordered degree of carbon materials. The ratio of ca. 1.0 indicates the low graphitization degree of carbon sheets, which is consistent with the result of XRD.

The chemical composition of the Cr₂O₃/carbon nanocomposites is investigated by XPS and the results are shown in Fig. 2. In the survey scan XPS spectrum of the Cr₂O₃/carbon nanocomposites, Fig. 2a, the peaks of Cr 2p, O 1s, C 1s and N 1s are observed, indicating the existence of Cr, O, C and N elements in the prepared Cr₂O₃/carbon nanocomposites. The deconvoluted C 1s peaks at 284.7 and 286.2 eV (Fig. 2b) correspond to the C-C and C-O components, respectively [24]. The deconvoluted peaks around 398 and 400 eV (Fig. 2c) in the N 1s XPS spectrum demonstrate the formation of -N= (398.0 eV) and -NH- (400.2 eV) in the carbon sheets [28]. Our previous work has confirmed that the N-doped carbon nanocomposites were favorable to the enhancement of electrochemical performances [29]. As shown in Fig. 2d, the peaks at 576.9 and 586.4 eV are assigned to Cr 2p_{3/2} and Cr 2p_{1/2}, respectively [30, 31].

Fig. 3a&b show the SEM images of pure Cr₂O₃ and Cr₂O₃/carbon nanocomposites, respectively. The observed sheets in Fig. 3b are carbon according to the TGA test. In Fig. 3b, it's clear that the synthesized Cr₂O₃/carbon nanocomposites are composed of Cr₂O₃ particles and carbon sheets. A close inspection from TEM image (Fig. 3c) reveals that Cr₂O₃ nanoparticles are embedded in the carbon sheet matrix. As shown in Fig. 3c, the Cr₂O₃ nanoparticles have a size

distribution ranging from 20 to 40 nm. In the high resolution TEM (HR-TEM) image (Fig. 3d), the typical lattice fringe spacing is measured to be 0.227 nm, corresponding to the (0 0 6) crystal plane of rhombohedral eskolaite Cr_2O_3 , which is consisted with the XRD result. The elemental mapping of the selected area obtained on SEM is displayed in Fig. 3e, f&g, clearly demonstrating a uniform distribution of Cr, O and C elements. The nitrogen absorption-desorption isotherms and the corresponding pore size distribution of Cr_2O_3 /carbon nanocomposites are shown in Fig. 4. The isotherms can be ascribed to type IV with a hysteresis loop, indicating the presence of mesopores [32]. From the pore size distribution curve (inset in Fig. 4), the pore size is observed nonuniform ranging from several to 70 nm. The BET specific surface area and the pore volume of Cr_2O_3 /carbon nanocomposites were $39.5 \text{ m}^2 \text{ g}^{-1}$ and $0.049 \text{ cm}^3 \text{ g}^{-1}$, respectively.

The discharge/charge curves of Cr_2O_3 and Cr_2O_3 /carbon samples are shown in Fig. 5. The first discharge curve of Cr_2O_3 /carbon shows a voltage slope from 1.3 to 0.22 V with ca. 230 mAh g^{-1} capacity loss (Fig. 5a), corresponding to the decomposition of electrolyte and the formation of solid electrolyte interphase (SEI) films, which are common phenomena to the most anode materials [18, 33-37]. As the voltage decreases to 0.02 V, the cell exhibits an initial specific capacity of 812.6 mAh g^{-1} . A specific capacity of 449.1 mAh g^{-1} is obtained as the first charging is finished with the initial columbic efficiency (the ratio of charge capacity to discharge capacity) is 55%. The capacity of Cr_2O_3 /carbon nanocomposites remains around 465.5 mAh g^{-1} after 150 cycles. In comparison, the first discharge curve of pure Cr_2O_3 (Fig. 5b) shows a voltage drop to

0.02 V and the initial specific capacity is 635.4 mAh g⁻¹. The capacity of pure Cr₂O₃ rapidly decreases to 71.2 mAh g⁻¹ after 150 cycles, arising from the volume change and aggregation of Cr₂O₃ during discharge/charge processes [38, 39]. A better capacity retention of the Cr₂O₃/carbon nanocomposites can be assigned to the fact that the carbon sheets can accommodate the volume change and reduce the aggregation of Cr₂O₃ particles during discharge/charge processes, leading to a higher lithium activity. Meanwhile, the presence of carbon sheets can also improve the electrical conductivity.

Fig. 5c shows the CV curves for the Cr₂O₃/carbon electrode in the initial three cycles. The cathodic peaks around 0.70 V are ascribed to the electrolyte decomposition and concomitant SEI formation [40], which are mainly observed during the first cycle and almost disappeared in the following cycles. The peak at 0.01 V corresponds to the reduction reaction of Cr₂O₃ with Li⁺ [41]. One broad oxidation peak observed between 0.54 and 1.76 V in the anodic scan is attributed to the oxidation of Cr⁰ to Cr³⁺ and the decomposition of Li₂O [42]. In the CV curves of pure carbon electrode (Fig. 5d), two cathodic peaks at 0.01 and 1.21 V are observed corresponding to the Li⁺ ions insertion into carbon [43]. The cathodic peak ascribed to the reduction of Cr³⁺ to Cr⁰ also appears at 0.01 V (Fig. 5c). After the second cycle, the CV curves tend to overlap, suggesting that the electrode exhibits the gradually enhanced cycling stability.

Fig. 5e shows the cycling performances of Cr₂O₃/carbon nanocomposites evaluated at a constant current density of 100 mA g⁻¹. It's found that the Cr₂O₃/carbon nanocomposites deliver a stable reversible capacity of 465.5 mAh g⁻¹ after 150 cycles. The coulombic efficiency of the Cr₂O₃/carbon nanocomposites quickly reaches 98.6 % in the second cycle, and even remains

more than 97 % from the third to the 150th cycle. The capacity of the Cr₂O₃/carbon nanocomposites in the first cycle is 812.6 mAh g⁻¹, lower than the theoretical capacity of Cr₂O₃ (1058 mAh g⁻¹) due to the addition of carbon with low capacity (372 mAh g⁻¹ for graphite). From the cycling test, pure carbon only delivers a stable reversible capacity of 235.4 mAh g⁻¹ after 43 cycles (Fig. 5e). As a comparison, the cycling performance of Cr₂O₃ at a current density of 100 mA g⁻¹ is also shown in Fig. 5e. The capacity for Cr₂O₃ decreases successively with cycling (71.2 mAh g⁻¹ after 150 cycles). Thus, the Cr₂O₃/carbon nanocomposites have a better cycling stability and higher specific capacity retention than Cr₂O₃. These results suggest that the carbon sheets in the nanocomposites are beneficial to the cycling stability. The as-prepared Cr₂O₃/carbon nanocomposites show a better cycling stability (518.5 mAh g⁻¹ after 20 cycles) than C-Cr₂O₃ composites (460 mAh g⁻¹ after 20 cycles) prepared by ball-milling commercial Cr₂O₃ with sugar and pyrolyzed in a tube-furnace at 600 °C for 12 hrs under argon atmosphere [44], in which the capacities were decreased successively during 20 cycles.

The cells were cycled at various current densities for every ten cycles to investigate the rate performance of the Cr₂O₃/carbon nanocomposites. As shown in Fig. 5f, the Cr₂O₃/carbon nanocomposites deliver a reversible capacity of 580.6, 448.7, 287.2, and 144.8 mAh g⁻¹ at a current density of 100, 200, 400, and 800 mA g⁻¹, respectively. As the current density returns to 100 mA g⁻¹ after the rate performance test, the discharge capacity is 479.2 mAh g⁻¹. In contrast, the Cr₂O₃ anode only delivers a reversible capacity of 174.4, 60.5, 29.5, and 13.6 mAh g⁻¹ at a current density of 100, 200, 400, and 800 mA g⁻¹, respectively. Apparently, the Cr₂O₃/carbon anode exhibits better rate capability than pure Cr₂O₃. It is believed that the carbon sheets in the

Cr₂O₃/carbon nanocomposites are favorable to increase the electrical conductivity between Cr₂O₃ nanoparticles as proved in EIS analysis and finally improve the cycling and rate performances.

Fig. 6 shows the Nyquist plots, which exhibit a depressed semicircle in the high and medium frequency and a sloped straight line in the low frequency. Generally, the diameter of the semicircle is related to the charge-transfer process occurring at the electrode/electrolyte interface, and is in direct proportion to the impedance including electrolyte resistance (R_e), surface film resistance (R_{sf}), and charge transfer resistance (R_{ct}) [40, 45, 46]. The inclined line in the low frequency range corresponds to the Warburg impedance associated with the lithium ion diffusion process inside the electrode, and the slope of the straight line is in inverse proportion to the Warburg impedance [29]. As shown in the inset of Fig. 6, the diameter of the semicircle for the Cr₂O₃/carbon nanocomposites is smaller than that of pure Cr₂O₃, indicating that the carbon sheets improve the electrical conductivity and charge transfer at the interface of Cr₂O₃ nanoparticles. In addition, the Cr₂O₃/carbon nanocomposites show larger slope than pure Cr₂O₃ in the low frequency region (Fig. 6), suggesting a better lithium ion diffusion ability of nanocomposites. It's concluded that the Cr₂O₃/carbon nanocomposites exhibit lower impedances (including R_e , R_{sf} , R_{ct} and Warburg impedance) at the electrode/electrolyte interface and inside the electrode. This illustrates that the prepared Cr₂O₃/carbon nanocomposites have higher charge transfer and lithium ion diffusion rate than pure Cr₂O₃, which finally result in the enhanced capacity retention and rate performance [29, 47]. The carbon sheets in the nanocomposites not only play as a buffer to cushion the volume change, but also prevent the aggregation of Cr₂O₃ during discharge/charge processes. This is beneficial to maintaining the structural integrity of

electrode and prolonging the cycling life of LIBs.

To further investigate the effect of carbon sheets in the Cr_2O_3 /carbon nanocomposite electrode on the LIBs, the morphology of Cr_2O_3 and Cr_2O_3 /carbon nanocomposites is observed by SEM after 150 cycles at a current density of 100 mA g^{-1} and the results are shown in Fig. 7. In pure Cr_2O_3 electrode, it is clearly seen that the original Cr_2O_3 particles have been pulverized due to the large volume change and the particle size decreased from ca. 70 to 20 nm (Fig. 3a & Fig. 7a). The pulverized particles were aggregated to form more compact structure. However, there are no obvious variations on the morphology and particle size of Cr_2O_3 for the Cr_2O_3 /carbon nanocomposite electrode before and after 150 cycles (Fig. 3b & Fig. 7b), illustrating that the carbon sheets can alleviate the volume change and prevent the aggregation of Cr_2O_3 particles during the discharge/charge processes. After 150 cycles, the elemental mapping (Fig. 7c, d&e) reveals the uniform distribution of Cr, O and C elements, suggesting that the charge/discharge processes did little to break down the integrity of the electrode.

4. Conclusion

In this work, the nanocomposites with in-situ synthesized Cr_2O_3 nanoparticles embedded in carbon sheets were prepared by combining a sol-gel approach with an efficient carbonization process using glycine as carbon source. As anode materials for LIBs, the Cr_2O_3 /carbon nanocomposites exhibit superior cycling performance and rate performances compared with pure Cr_2O_3 nanoparticles. The carbon sheets play an important role on improving the electrical

conductivity of Cr_2O_3 as well as acting as a favorable buffer to the volume change during the lithiation/delithiation, leading to an enhanced electrochemical performance.

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Scheme 1. Schematic preparation procedure of $\text{Cr}_2\text{O}_3/\text{carbon}$ nanocomposites.

Figures and Figure Captions:

Fig. 1 (A) XRD patterns of $\text{Cr}_2\text{O}_3/\text{carbon}$ nanocomposites and pure Cr_2O_3 ; (B) FT-IR spectra of (a) gel precursor consisted CrCl_3 with glycine and (b) $\text{Cr}_2\text{O}_3/\text{carbon}$ nanocomposites; (C) TGA/DSC curves of $\text{Cr}_2\text{O}_3/\text{carbon}$ nanocomposites at a heating rate of $10\text{ }^{\circ}\text{C min}^{-1}$ under air condition; (D) Raman spectra of $\text{Cr}_2\text{O}_3/\text{carbon}$ nanocomposites.

Fig. 2 XPS spectra of $\text{Cr}_2\text{O}_3/\text{carbon}$ nanocomposites: Survey scan (a) and high resolution spectra of (b) C1s, (c) N1s, and (d) Cr2p.

Fig. 3 SEM images of (a) Cr_2O_3 and (b) $\text{Cr}_2\text{O}_3/\text{carbon}$ nanocomposites; (c) TEM (d) HRTEM images of $\text{Cr}_2\text{O}_3/\text{carbon}$ nanocomposites and (e, f, g) EDX mapping image (Cr, O, C) of $\text{Cr}_2\text{O}_3/\text{carbon}$ nanocomposites.

Fig..4 The nitrogen adsorption-desorption isotherms of $\text{Cr}_2\text{O}_3/\text{carbon}$ nanocomposites. Inset is the pore size distribution.

Fig. 5 Galvanostatic discharge/charge curves of the 1st, 2nd, 5th, and 150th cycles for (a) $\text{Cr}_2\text{O}_3/\text{carbon}$ nanocomposites and (b) Cr_2O_3 ; CV curves of (c) $\text{Cr}_2\text{O}_3/\text{carbon}$ nanocomposites and (d) C; (e) Cycling performance of $\text{Cr}_2\text{O}_3/\text{carbon}$ nanocomposites and Cr_2O_3 at the current density of 100 mA g^{-1} ; and (f) rate capabilities.

Fig. 6 Nyquist plots of $\text{Cr}_2\text{O}_3/\text{carbon}$ nanocomposites and Cr_2O_3 . Inset is the impedance spectrum in the high and medium frequency.

Fig. 7 SEM images of (a) Cr_2O_3 , (b) Cr_2O_3 /carbon nanocomposites after 150 cycles at the current density of 100 mA g^{-1} and (c, d, e) EDX mapping image (Cr, O, C) of Cr_2O_3 /carbon nanocomposites.

Graphical Abstract

The Cr_2O_3 /carbon nanocomposites synthesized by directly carbonizing glycine- CrCl_3 gel precursor exhibit superior cycling and rate performances as lithium-ion battery anode materials.