A comparative investigation on the effects of nitrogen-doping into graphene on enhancing the electrochemical performance of SnO$_2$/graphene for sodium-ion batteries†

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SnO$_2$/nitrogen-doped graphene nanohybrids have been synthesized by an in situ hydrothermal method, during which the formation of SnO$_2$ nanocrystals and nitrogen doping of graphene occur simultaneously. The as-prepared SnO$_2$/nitrogen-doped graphene nanohybrids exhibit enhanced electrochemical performance for sodium-ion batteries compared to SnO$_2$/graphene nanocomposites. A systematic comparison between SnO$_2$/nitrogen-doped graphene nanohybrids and the SnO$_2$/graphene counterpart as anode materials for sodium-ion batteries has been conducted. The comparison is in a reasonable framework, where SnO$_2$/nitrogen-doped graphene nanohybrids and the SnO$_2$/graphene counterpart have the same SnO$_2$ ratio, similar SnO$_2$ crystallinity and particle size, close surface area and pore size. The results clearly manifest that the improved electron transfer efficiency of SnO$_2$/nitrogen-doped graphene due to nitrogen-doping plays a more important role than the increased electro-active sites within graphene network in enhancing the electro-activity of SnO$_2$/nitrogen-doped graphene nanohybrids compared to the SnO$_2$/graphene counterpart. In contrast to the previous reports which often ascribe the enhanced electro-activity of nitrogen-doped graphene based composites to two nitrogen-doping effects (improving the electron transfer efficiency and increasing electro-active sites within graphene networks) in one single declaration, this work is expected to provide more specific information for understanding the effects of nitrogen-doping into graphene on improving the electrochemical performance of graphene based composites.

Introduction

The global distribution of lithium and the future capital investment in lithium usage would make lithium-ion batteries (LIBs) costly for the large-scale applications. The rich sodium source makes sodium-ion batteries (SIBs) a sustainable and economically attractive electrochemical energy conversion and storage technique in the long term, which can be used as a near-term substitution for LIBs.1–7 To support the practical applications of SIBs, one critical issue is to develop electrode materials with the capability for fast and stable sodium ion storage.8,9

Carbon materials have been applied as scaffolds to support Na-ion host materials, such as phosphorous,10–12 Sn-based compounds,4,6,13–16 and Sb-based materials,17,18 in order to increase the electronic conductivity and buffer the volume change of electrode materials during charge/discharge processes. Graphene has been widely used as effective building blocks for these purposes, owing to its high electronic conductivity, two-dimensional structure with high surface area, and flexibility.14,15,19–26 In order to meet the demand of high energy storage, numerous efforts have been devoted to enhancing the electrochemical performance of the graphene-based composite materials based on rational material manipulations. Chemical substitution of graphene by heteroatoms, such as B, N, and S, could bring new physicochemical functionalities.27–30 It is rife that the doping of graphene

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†Electronic supplementary information (ESI) available: Schematic illustration for the preparation of SnO$_2$/NG nanocomposite, TGA curves of SnO$_2$/G and SnO$_2$/NG, N$_2$ sorption isotherms of SnO$_2$/G and SnO$_2$/NG composites, CV profiles of NG at a scan rate of 0.1 mV s$^{-1}$ between 0.01 and 3.0 V, charge–discharge curves of bare SnO$_2$ at a current density of 20 mA g$^{-1}$, galvanostatic charge–discharge profiles of the SnO$_2$/NG and SnO$_2$/G composites of the 50th cycle and 100th cycle at 20 mA g$^{-1}$, SEM images of SnO$_2$/NG electrode after 100 cycles, kinetic parameters of SnO$_2$/G and SnO$_2$/NG electrodes. See DOI: 10.1039/c4nr07054b
matrix by nitrogen heteroatoms can improve the electrochemical performance for Na⁺ storage. For example, Kang and co-workers have reported the enhanced electrochemical performance for SIBs in TiO₂/nitrogen-doped graphene nanocomposites with open pore channel compared to TiO₂/graphene counterparts. Qin et al. found nitrogen-dopants in graphene can restrict further structural growth and result in smaller size of TiO₂, which contributes to the improved capacity and rate capability of TiO₂/nitrogen-doped graphene compared to TiO₂/graphene for SIBs. However, to manifest the inherent nitrogen-doping effects for enhancing the sodium-ion storage performance, a logical comparison between nitrogen-doped graphene based nanocomposites and the nitrogen-free ones should be in a reasonable framework excluding: (1) the difference of the loading ratio of supported materials in the compared composites, (2) the possible morphology effects, such as the crystallinity and particle size of supported materials, the surface area of the composites determining the electrode/electrolyte contact. In this aspect, a rational and systematic comparison between nitrogen-doped graphene based nanocomposites and the nitrogen-free ones for Na⁺ storage has been still unavailable. On the other hand, the previous reports available in this area often attribute the enhanced electroactivity of the nitrogen-doped graphene (NG) based nanocomposites to the increased electro-active sites within graphene networks and the improvement of electron transfer efficiency of the overall electrode due to nitrogen-doping. Nevertheless, the contribution ratio of each effect to the overall capacity enhancement is still ambiguous.

Herein, we choose SnO₂ as a typical example to investigate the intrinsic nitrogen-doping effects for improving the sodium-ion storage in the graphene-based nanocomposites. An in situ hydrothermal route was used to prepare SnO₂/nitrogen-doped graphene (SnO₂/NG) nanohybrids as anode materials for SIBs. For comparison, SnO₂/graphene (SnO₂/G) nanohybrids with the same SnO₂ weight ratio were prepared by the similar procedure without nitrogen-doping agents. The results indicate that the particular characteristics in these two series of composites including the crystallinity, the particle size, and the morphology of SnO₂ are identical. Based on such a desirable system, a comparison between SnO₂/NG and SnO₂/G featuring analogous morphology as anode materials for SIBs has been conducted. The as-prepared SnO₂/NG electrode exhibits a higher sodium-ion storage capacity than the SnO₂/G counterpart. In particular, by controlled experiments using bare NG and graphene as anode materials for SIBs, we find that the improved electron transfer efficiency due to nitrogen-doping has an important contribution to the observed enhanced electrochemical performance; whereas the increased electro-active sites within graphene networks benefiting from nitrogen-doping has limited contribution to the overall electrochemical performance enhancement. This work could provide more specific information for understanding the effects of nitrogen-doping into graphene on improving the electrochemical performance of graphene based composites.

### Experimental

#### Materials

Graphene oxide (GO) nanosheets were synthesized from natural graphite powders by a modified Hummer’s method. SnO₂/G and SnO₂/NG composites were produced by a hydrothermal method. Typically, SnCl₄·5H₂O (40 mg, Sigma-Aldrich, ≥98%) was mixed with GO aqueous suspension (40 mL, 1 mg mL⁻¹) by ultrasonication using a Branson Digital Sonifier (S450D, 40% amplitude). After ultrasonication for 1 h, the mixture was divided into two parts (20 mL each). To prepare SnO₂/NG nanohybrids, urea (5 g) was added to one part and stirred for 30 min. Both solutions were then heated to 180 °C in a Teflon-lined autoclave (25 mL in capacity) and maintained at that temperature for 24 h. The precipitates were cooled to room temperature naturally, and then collected and washed with distilled water and ethanol several times. After drying at 60 °C in a vacuum oven overnight, the final products were obtained.

#### Structural and physical characterization

The crystal structure and phases of as-prepared materials were characterized by X-ray diffraction (XRD, Siemens D5000) using a Cu Kα radiation at a scanning step of 0.02° s⁻¹. The morphology was analyzed by field emission scanning electron microscopy (FESEM, Zeiss Supra 55VP). The crystal structure details were further characterized by transmission electron microscopy (TEM) and high-resolution transmission electron microscopy (HRTEM, JEOL JEM-2011). Simultaneous thermogravimetric analysis and differential thermal analysis (TGA/DTA) were performed with a 2960 SDT system to analyze the weight ratio of SnO₂ at a heating rate of 10 °C min⁻¹ in air from room temperature to 800 °C. The XPS spectra were carried out on an ESCALAB 250Xi XPS System with a monochromated Al Ka X-ray source (13 kV 150 W 500 μm with pass energy of 100 eV for survey scans, or 20 eV for region scans). All of the binding energies were calibrated by C 1s as the reference energy (C 1s = 284.6 eV). Raman spectra were collected using a Renishaw inVia Raman spectrometer system (Glouces tershire, UK) equipped with a Leica DMLB microscope (Wetzlar, Germany) and a Renishaw He–Ne laser source that produced 17 mW at λ = 633 nm. The N₂-sorption measurement was carried out at 77 K with a Micromeritics 3Flex Surface Characterization Analyser.

#### Cell assembly and electrochemical testing

The electrodes were prepared by dispersing the as-prepared material (80 wt%) and poly(Vinylidene fluoride) binder (PVDF, 20 wt%) in N-methyl-2-pyrrolidone (NMP) to form a slurry. The resultant slurry was pasted onto copper foil using a doctor blade and dried in a vacuum oven for 12 h, followed by pressing at 200 kg cm⁻². The loading weight of the electro-active material is around 1.1 mg cm⁻². Electrochemical measurements were carried out using two electrode coin cells with Na metal as counter and reference electrodes and the glass micro-
fiber (Whatman) as the separator. The CR2032-type coin cells were assembled in an argon-filled glove box (Unilab, Mbraun, Germany). The electrolyte solution was 1 M NaClO4 dissolved in a mixture of ethylene carbonate (EC) and propylene carbonate (PC) with a volume ratio of 1:1 with a 5 vol% addition of fluoroethylene carbonate (FEC). All the capacities were calculated based on the mass of the composites. Cyclic voltammetry (CV) was conducted on a CHI 660C instrument between 0.01 and 3 V vs. Na/Na\textsuperscript{+} at room temperature. For the electrochemical impedance spectroscopy (EIS) measurement, the excitation amplitude applied to the cells was 5 mV. The charge–discharge measurements were performed at ambient temperature at different current densities in the voltage range from 0.01 and 3 V vs. Na/Na\textsuperscript{+}.

**Results and discussion**

In the present study, a facile hydrothermal method has been developed to prepare SnO\textsubscript{2}/NG nanohybrids using urea as the nitrogen precursor (Fig. S1, ESI†). SnCl\textsubscript{4} was mixed with GO aqueous suspension first. Because of the electrostatic interaction between Sn\textsuperscript{4+} anions and negatively charged GO, Sn\textsuperscript{4+}/GO hybrids can be readily obtained in this step. The Sn\textsuperscript{4+}/GO hybrids, together with urea, were then subjected to hydrothermal treatment. During hydrothermal treatment, NH\textsubscript{3} can be released slowly from urea, which can be used as nitrogen-doping agent in the confined space.\textsuperscript{36} The low-temperature incorporation of nitrogen heteroatoms into graphene networks was achieved by the reason that the hydrothermal condition, i.e., 180 °C and autogenous pressure, promoted the reaction between basic NH\textsubscript{3} and oxygen functionalities (such as carboxylic acid and hydroxyl species) and finally enabled the \textit{in situ} doping of nitrogen.\textsuperscript{36} The oxygen-containing groups on GO, such as carboxyl, hydroxyl and epoxy groups, act as the nucleation and growth sites, and homogeneously dispersed SnO\textsubscript{2} nanocrystals formed consequently. The nitrogen dopants can also interact with the Sn\textsuperscript{4+}, providing additional active sites for SnO\textsubscript{2} formation, which results in a strong coupling between metal species and N-doped graphene.\textsuperscript{37,38} Our synthesis protocol avoids high-temperature nitridation of graphene. For comparison, we prepared SnO\textsubscript{2}/G using the same procedure without the addition of urea as a benchmark to investigate the nitrogen-doping effects of SnO\textsubscript{2}/NG nanocomposites as anode materials for SIBs. TGA curves in Fig. S2 (ESI†) suggest that SnO\textsubscript{2}/G has the same SnO\textsubscript{2} weight ratio as SnO\textsubscript{2}/NG (47.0%).

The crystal structure of SnO\textsubscript{2}/NG and SnO\textsubscript{2}/G nanocomposites has been characterized by X-ray diffraction (XRD), as shown in Fig. 1(a). The XRD patterns show diffraction peaks at 26.6°, 33.7°, 37.9°, 51.8° and 65.3°, which can be well indexed to the pure tetragonal rutile phase of SnO\textsubscript{2} crystals with the space group of P4\textsubscript{2}mm (JCPDS card no. 41-1445). Because of the balance between the depletion of oxygen-containing groups and the introduction of nitrogen heteroatoms,\textsuperscript{36} there should be no big difference of the total sites for the growth of SnO\textsubscript{2} nucleus between NG and graphene, which can be reflected by the XRD results. As calculated by Scherrer equation, the crystalline size of SnO\textsubscript{2} in SnO\textsubscript{2}/NG (1.6 nm) is similar to that in SnO\textsubscript{2}/G (1.4 nm). The microstructure of NG has been investigated by Raman spectroscopy, as presented by Fig. 1(b). Two characteristic peaks at 1323 and 1589 cm\textsuperscript{−1} can be observed in the range of 800–2000 cm\textsuperscript{−1}, corresponding to the D and G band of NG, respectively. Compared to the SnO\textsubscript{2}/G counterpart, the as-synthesized SnO\textsubscript{2}/NG nanohybrids exhibit an upshift of the D band and G band (from 1321 cm\textsuperscript{−1} to 1323 cm\textsuperscript{−1} for D band and from 1587 cm\textsuperscript{−1} to 1589 cm\textsuperscript{−1} for G band). This may originate from structural distortion of graphene caused by the different bond distances of C–C and C–N.\textsuperscript{29} Moreover, SnO\textsubscript{2}/NG shows a higher \(I_D/I_G\) (intensity ratio between D band and G band) value (1.33) than that of SnO\textsubscript{2}/G composites (1.18), which suggests a more disordered structure for NG than graphene owing to the introduction of N heteroatoms in graphene networks. Both the shift of band positions and the larger \(I_D/I_G\) value indicate that nitrogen heteroatoms...
have been successfully inserted into graphene by the hydrothermal method.

TEM has been used to investigate the microstructures of the as-obtained \( \text{SnO}_2/\text{NG} \) and \( \text{SnO}_2/G \), as depicted in Fig. 2. The crumpling of NG layers, as observed in Fig. 2(a), is attributed to defective structures formed during the oxidation-reduction procedure for the synthesis of NG, which is in agreement with the Raman result. On the other hand, it can be clearly seen that ultrafine \( \text{SnO}_2 \) nanocrystals have been successfully loaded onto the surface of NG after hydrothermal treatment. A high-resolution TEM image of \( \text{SnO}_2/\text{NG} \) nanohybrids is shown in Fig. 2(c), from which it can be observed that the crystal plane distance is 0.33 and 0.26 nm, corresponding to the (110) and (101) face of tetragonal \( \text{SnO}_2 \), respectively. The particle size distribution of \( \text{SnO}_2 \) in the as-prepared \( \text{SnO}_2/\text{NG} \) nanohybrids is shown in Fig. 2(e). And the average particle size of \( \text{SnO}_2 \) is calculated to be 4.7 nm. The morphology of \( \text{SnO}_2/G \) composites (Fig. 2(b, d and f)) is similar to that of \( \text{SnO}_2/\text{NG} \), and the average particle size of \( \text{SnO}_2 \) in \( \text{SnO}_2/G \) composites is 4.0 nm. Fig. S3 (ESI†) shows the nitrogen sorption isotherms of \( \text{SnO}_2/\text{NG} \) and \( \text{SnO}_2/G \) composites at 77 K. Both the two adsorption–desorption curves can be classified as the typical type-IV isotherm with an \( \text{H}_1 \)-type loop hysteresis.\(^{39}\) It is calculated that the BET surface area of \( \text{SnO}_2/G \) and \( \text{SnO}_2/\text{NG} \) material is very close, which is 215 and 206 m\(^2\) g\(^{-1}\), respectively. It is calculated that the average pore diameter of \( \text{SnO}_2/\text{NG} \) nanocomposites is 3.0 nm, approximating to that of \( \text{SnO}_2/G \) nanocomposites (3.3 nm).

The X-ray photoelectron spectroscopy (XPS) experiments provide further evidences of the chemical configuration of nitrogen species and the interaction between \( \text{SnO}_2 \) nanocrystals and the NG matrix. From the survey XPS scan in Fig. 3(a), it can be identified that the as-obtained \( \text{SnO}_2 \) composites are composed of C, N, O and Sn elements. No other signals can be found, which implies the purity of the as-synthesized samples. The high resolution C 1s spectrum is shown in Fig. 3(b), which can be fitted into five peaks at 284.6 eV (graphitic carbon), 285.4 eV (N–C\(_{sp2}\)), 286.7 eV (N–C\(_{sp3}\)), 288.7 eV (C\(_{vO}\)) and 291.0 eV (shake-up satellite peak due to \( \pi-\pi^* \) transitions in aromatic systems).\(^{40}\) The overwhelming percentage of graphitic carbon suggests the graphitized nature of the NG in \( \text{SnO}_2/\text{NG} \) composites. The nitrogen bonding configuration can be obtained from the high resolution N 1s spectrum, as shown in Fig. 3(c). The result from the curve fitting indicates the presence of four different types of nitrogen species bonded to carbon in the composite: pyridinic N (398.3 eV), pyrrolic N (399.8 eV), graphitic N (400.9 eV) and oxidic N of pyridinic-N.
Fig. 4 CV profiles of the SnO2/NG composites at a scan rate of 0.1 mV s⁻¹ between 0.01 and 3.0 V.
20, 40, 80, 160, 320, 640 mA g$^{-1}$ and 320, 160, 80, 40, 20 mA g$^{-1}$. As depicted in Fig. 6(b), the SnO$_2$/NG nanocomposite electrode shows an excellent high rate performance. At a current density of 640 mA g$^{-1}$, SnO$_2$/NG can still deliver a capacity of 170 mA h g$^{-1}$, which is preferable for high power density devices. When the current density reversed to the lower value (20 mA g$^{-1}$), the electrode recovered substantial capacities without obvious capacity decay.

We experimentally observe that SnO$_2$/NG exhibits enhanced electrochemical performance for sodium-ion storage compared to the SnO$_2$/G counterpart. The TGA results, TEM analysis, and BET results clearly demonstrate that the electrochemical performance enhancement does not originate from either the loading ratio difference of SnO$_2$ or the morphology effect. Consequently, it is reasonable to conclude that the nitrogen dopants in the graphene structure contribute to the improved capacity of SnO$_2$/NG compared to the SnO$_2$/G counterpart for Na$^+$ storage. Firstly, it is theoretically and experimentally well known that N substitution can enhance Li$^+$ storage in pristine graphene by inducing surface defects and introducing heteroatomic N into the graphene structure, which can provide additional sites for Li$^+$ adsorption.

Similarly, NG matrix in SnO$_2$/NG nanocomposites could be more active for Na$^+$ storage than the graphene matrix in SnO$_2$/G nanoalloys. As evidenced by Fig. 7(a), bare NG exhibits an enhanced capacity compared to graphene. In the first cycle, NG delivers a reversible capacity of 163 mA h g$^{-1}$, this value is 29 mA h g$^{-1}$ higher than that of graphene. On the other hand, nitrogen-doping can enhance the electron transport properties of the SnO$_2$/NG electrode, as demonstrated by the Nyquist plots in Fig. 7(b). Both Nyquist plots are composed of a depressed semicircle in the moderate frequency region and a straight line in the low frequency region. Normally, the depressed semicircle is attributed to the charge transfer process. Apparently, the semicircle of SnO$_2$/NG is smaller than that of the SnO$_2$/G material, indicating that SnO$_2$/NG composites possess higher electron transfer efficiency. On the other hand, the low-frequency slope angle is 49° for SnO$_2$/NG negative electrode, whereas SnO$_2$/G has a slope angle of 38°. The much steeper straight line in the low frequency region suggests that a better Na$^+$ kinetics in SnO$_2$/NG electrode than in SnO$_2$/G electrode. The improved Na$^+$ kinetics could be due to the higher electronegativity of NG than that of graphene. The ac impedance spectra can be modeled by the modified Randles equivalent circuit presented in the inset in Fig. 7(b). $R_e$ is the electrolyte resistance, CPE represents constant phase element, $R_I$ is the resistance of the passivation film formed on the surface of the electrode, $R_{ct}$ is the charge-transfer resistance, and $Z_w$ is the Warburg impedance related...
due to nitrogen-doping make SnO$_2$/NG favorable for electrochemical Na$^+$ storage compared to SnO$_2$/G. However, taking account of the NG weight ratio in the as-prepared SnO$_2$/NG nanohybrids, the increased electro-active sites within graphene matrix due to nitrogen-doping only have a contribution of 14 mA h g$^{-1}$ (29 mA h g$^{-1} \times W_{NG} = 14$ mA h g$^{-1}$, where $W_{NG}$ is the weight ratio of NG in the composite), which accounts for 12.3% of the overall capacity enhancement of the SnO$_2$/NG electrode compared to the SnO$_2$/G counterpart (114 mA h g$^{-1}$), as depicted in Fig. 7(c). Consequently, the important role of nitrogen-doping should lie in improving the electron transfer efficiency within the SnO$_2$/NG electrode during sodiation/de-sodiation processes.

We carried out post-mortem SEM analysis on the SnO$_2$/NG electrode to check the integrity of the electrode. Fig. S7† shows the SEM images of the SnO$_2$/NG composite electrode after 100 cycles. Neither pulverization nor peeling off of SnO$_2$ can be observed due to the small size of SnO$_2$ nanoparticles and the mechanical resilience of NG nanosheets, which can effectively buffer the big volume expansion during repeated charge/discharge processes. As a result, SnO$_2$/NG composites show good cycling stability as anode materials for SIBs.

Conclusions

In summary, SnO$_2$/NG nanohybrids have been successfully prepared by a facile hydrothermal method using urea as nitrogen-doping agents. The as-synthesized SnO$_2$/NG material contains ultrathin SnO$_2$ nanocrystals with an average particle size of 4.7 nm. When applied as anode material for sodium-ion batteries, the as-prepared SnO$_2$/NG nanohybrids exhibit an enhanced electrochemical performance for SIBs compared to the SnO$_2$/G counterpart. A comparison between SnO$_2$/NG nanohybrids and the SnO$_2$/G counterpart has been conducted in a reasonable framework to manifest the inherent nitrogen-doping effects for the enhancement of sodium-ion storage performance. It is found that although nitrogen-doping can improve the Na$^+$ storage capacity within the graphene networks by increasing electro-active sites, its contribution to the overall electrochemical performance enhancement of the SnO$_2$/NG compared to the SnO$_2$/G counterpart is limited. While the improvement of the electron transfer efficiency within the electrode due to nitrogen-doping plays the major role for the enhancement of the electro-activity of SnO$_2$/NG. This work highlights that nitrogen-dopants in graphene networks can effectively mediate the electron transfer between SnO$_2$ and NG, thereby offering fundamental concepts to rationally design graphene-based electrode materials with higher performance for SIBs.

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Notes and references


