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V2O5/mesoporous carbon composite as a cathode material for lithium-ion batteries

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Abstract
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Keywords
ion, lithium, material, batteries, cathode, carbon, composite, mesoporous, v2o5

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V₂O₅/Mesoporous Carbon Composite as a Cathode Material for Lithium-ion Batteries

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ABSTRACT

V₂O₅/mesoporous carbon composite has been prepared by an ultrasonically assisted method followed by a sintering process. The as-prepared V₂O₅/mesoporous carbon material containing 90 wt% V₂O₅ shows better electrochemical performance, with capacity of 163 mA h g⁻¹ after 100 cycles at the current density of 500 mA g⁻¹, as well as better charge/discharge rate capability for lithium storage than V₂O₅ nanoparticles. The improved electrochemical performance indicates that the V₂O₅/mesoporous carbon composite could be used as a promising cathode material for lithium ion batteries.

Keywords: vanadium pentoxide; mesoporous carbon; cathode; lithium ion batteries

1. Introduction

Nowadays, rechargeable Li-ion batteries (LIBs) are extensively used in almost all types of
electronic devices, including cell phones, laptop computers, camcorders, and even electric and hybrid electric vehicles, due to their high energy and power density, high voltage, and long lifespan [1-3]. The worldwide market for lithium ion batteries is growing fast, especially for consumer products, and it will grow even more in the next decade. Frost & Sullivan, a business consulting firm, has reported that the global lithium-ion battery market in 2012 was worth $11.7 billion, mainly for consumer applications, and this is expected to be twice as great, around $22.5 billion, in 2016 [4].

Until now, LiCoO₂, which was first introduced by SONY, has been the most commonly used cathode material in LIBs. Due to the toxicity, high cost, and safety issues of LiCoO₂, however, many efforts have been made to develop other cathode materials, such as LiNi₁/₃Mn₁/₃Co₁/₃O₂, LiMn₂O₄, and LiFePO₄ [5-7]. These materials have shown significant improvements in their cycling stability and rate capability. Enhancement of their reversible lithium storage capacity has been limited, however, due to their intrinsic redox chemistry, which allows only one Li⁺ insertion/extraction per formula unit. Hence, new materials need to be developed as cathode candidates with enlarged theoretical capacity through multi-electron reactions per formula unit, in order to comply with the demand for LIBs with high capacity and fast charge capability.

Among the many potential cathode candidates, vanadium pentoxide (V₂O₅) is one of the most promising due to its high energy density, abundance, low cost, and easy to synthesize [8-12]. The high theoretical capacity of V₂O₅ is especially attractive, around 294 mA h g⁻¹ for the intercalation/deintercalation of two Li⁺ ions between 2.0 and 4.0 V, which is much better than those of conventional cathode materials, such as LiMn₂O₄ (148 mA h g⁻¹) and LiFePO₄ (176 mA h g⁻¹). In spite of these advantages, the electrochemical performance of V₂O₅ is limited by its poor electrical conductivity (10⁻³ to 10⁻² S cm⁻¹) and its sluggish diffusion of lithium ions (≈ 10⁻¹² cm² s⁻¹) [13-16]. Moreover, phase transitions of LiₓV₂O₅ during the charge/discharge process often
cause structural instability and can further degrade its cycling performance [17-19]. These
drawbacks have limited the practical application of this material in commercial LIBs. Several
approaches have been tried to solve these issues: fabricating nanostructures, changing the pore
size, and modifying the electrical conductivity with a carbon matrix [11-13, 15, 18, 20-45].

One approach to address these issues is modifying the V$_2$O$_5$ with ordered mesoporous
carbon. Mesoporous carbon, which has pore sizes between 2 and 50 nm, will facilitate electrolyte
diffusion into the bulk of the electrode material and hence provide fast transport channels for the
conductive ions (i.e. Li$^+$ ions). Carbon will also provide fast electronic transport, which may
enhance the overall performance of lithium ion batteries. The other properties of mesoporous
carbon, such as its high thermal stability, large surface area, uniform pore diameter, high pore
volume, and interconnected pore structure, also increase its potential value in lithium ion batteries
[46, 47]. Some metal oxide/mesoporous carbon composites have already been synthesized, such
as ones containing Sn/SnO$_2$, SnO$_2$, Cr$_2$O$_3$, and TiO$_2$, as electrode materials for lithium ion
batteries [18-22]. V$_2$O$_5$-mesoporous carbon composite as an electrode material for capacitors has
also been reported by Yu et al. [48]. In this work, we use mesoporous carbon to prepare V$_2$O$_5$-
mesoporous carbon composite as a cathode material for LIBs. The mesoporous structure of the
carbon helps the diffusion of electrolyte into the bulk of the electrode and, as a result, provides
fast transport channels for Li$^+$ ions.

2. **Experimental**

**Preparation of mesoporous carbon**

The mesoporous carbon was synthesized in a similar way to the procedure reported by C.
F. Xue et al. [49] with a slight modification. Firstly, a resol solution was prepared as the carbon
precursor. Phenol (61 g) was melted at 42 °C in a flask, and 20 mL 20 wt% NaOH solution was
then slowly added under stirring over a period of 20 minutes. After that, 100 mL formalin (37
wt%) was added to the solution, and the mixture was heat-treated at 70 °C for 1 h. The pH of the mixture was adjusted to 7.0 after cooling down to room temperature naturally. Water was then eliminated under vacuum at a temperature below 50 °C, and the obtained product (resol solution) was dissolved in ethanol (40 wt%).

The mesoporous-carbon-silica composite monoliths were prepared via evaporation-induced coating self-assembly (EISA). In a typical synthesis, 16 g F127 triblock copolymer was dissolved in a mixture of ethanol (82 mL) and 0.2 M HCl (10 mL), and stirred for 1 h at 40 °C. Then, the resol solution was slowly added to this solution under stirring for 10 min, followed by the addition of 20.8 g tetraethyl orthosilicate (TEOS), and stirring was continued for 2 h at ambient temperature. The obtained solution was poured onto polyurethane (PU) foam. The air bubbles inside the PU foam were eliminated by regularly squashing the foam with a glass rod during the infusion process. The infused PU foam was turned constantly for 5–8 h to vaporize the solvent. Then, the PU foam was heated at 100 °C for 20 h in an oven for further thermopolymerization. The calcination was carried out at 900 °C for 3 h under flowing N₂, with heating rates of 1 °C min⁻¹ below 600 °C and 5 °C min⁻¹ above 600 °C, so that a mesoporous composite was obtained. Then, the resultant composite was washed in boiled NaOH solution (2.5 M) to remove the silica in order to obtain mesoporous carbon. Surface modification of the mesoporous carbon was performed in the following way: 1 g mesoporous carbon was added into 100 mL HNO₃ (20 wt%) and stirred for 3 h at 80 °C. The resultant product was recovered by filtration and washed with deionized water until the filtrate pH was 7. Then, the product was added into 100 g of H₂O₂ 30 wt% solution and stirred at room temperature for 30 min, after which, the stirring was continued at 60 °C for 1 h. Finally, the product was obtained by filtration, washed thoroughly with water, and dried at 80 °C for 12 h.
Preparation of V$_2$O$_5$/mesoporous carbon

V$_2$O$_5$ was prepared by the sol method by stirring 0.5 g V$_2$O$_5$ powder into 50 mL H$_2$O$_2$ (30 wt%) for 24 h at room temperature [50]. Then, 0.2 g mesoporous carbon was dispersed into the V$_2$O$_5$ sol, and the mixture was stirred for 1 h. After that, the mixture was ultrasonicated for 3 h at room temperature. The precipitate was filtered and washed with distilled water and ethanol. Then, the solvent was removed by drying at 120 °C for 12 h. The resultant product (denoted as V$_2$O$_5$/mc before sintering) was divided into three portions: the first portion was reserved without further treatment, another portion was sintered at 550 °C in air atmosphere for 2 h with a 5 °C min$^{-1}$ heating rate to burn away the carbon to produce V$_2$O$_5$ nanoparticles (denoted as V$_2$O$_5$ np), and the third portion was sintered at 300 °C for 5 h in air atmosphere (denoted as V$_2$O$_5$/mc).

Characterisation

The specific surface area (determined by the Brunauer-Emmett-Teller (BET) method) and nitrogen adsorption-adsorption isotherms of samples of mesoporous carbon and V$_2$O$_5$/mc before sintering were measured in order to observe the effects of the insertion process on the properties of the mesoporous carbon. V$_2$O$_5$/mc before sintering was examined by transmission electron microscopy (TEM; JEOL 2010 and JEOL ARM-200F) in order to determine whether the insertion process of V$_2$O$_5$ into the mesoporous carbon was successful or not.

All the resultant products were characterised by X-ray diffraction (XRD; GBC MMA Diffractometer, Cu Kα radiation, $\lambda = 1.5406$ Å). The content of V$_2$O$_5$ in the V$_2$O$_5$/mc was investigated by thermogravimetric analysis (TGA; Mettler Toledo TGA/DSC1), which was taken into account in the battery testing. For electrochemical performance testing, working electrodes were prepared by mixing 85 wt% active material, 6 wt% conductive agent (carbon black, Super-P-Li), and 9 wt% polyvinylidene difluoride (PVDF) binder (Sigma-Aldrich) in N-methyl-2-pyrrolidinone (NMP) to form a homogeneous slurry. The slurry was uniformly pasted onto
aluminium foil and dried in a vacuum oven at 120 °C for 12 h. Electrochemical cells (CR2032 coin type) containing the working electrode and Li foil as the counter and reference electrode were assembled in an Ar-filled glove box (Mbraun, Unilab, USA). 1 M LiPF$_6$ in a 3:4:3 (v/v) mixture of ethylene carbonate (EC), dimethyl carbonate (DMC), and diethyl carbonate (DEC), with 5% fluoroethylene carbonate (FEC) additive was used as the electrolyte. The galvanostatic charge-discharge measurements were performed on a Land CT2001A battery tester.

3. Results and discussion

Fig. 1 presents the nitrogen adsorption–desorption isotherms and the pore size distribution curves of the mesoporous carbon (mc) and V$_2$O$_5$/mc composites before sintering. As can be seen in Figure 1(a), N$_2$ sorption isotherms of both samples show hysteresis and therefore represent type-IV behaviour, according to the IUPAC classification, indicating mesoporous structure. Fig. 1(b) reveals that the main pore size of the mesoporous carbon (mc) is about 3 nm, and the pore size decreases to 2-3 nm after insertion of V$_2$O$_5$. This is consistent with the BET surface area and total pore volume data for the mesoporous carbon and the V$_2$O$_5$/mc before sintering, as summarized in Table 1. The BET surface area ($S_{BET}$) of the V$_2$O$_5$/mc before sintering is decreased significantly compared to that of mesoporous carbon matrix alone, which are calculated to be 77.2 and 874 m$^2$ g$^{-1}$, respectively. This clearly indicates that the V$_2$O$_5$ nanoparticles have filled most of the pores in the mesoporous carbon. The total pore volumes of the mc and the V$_2$O$_5$/mc composite are 0.76 and 0.06 cm$^3$ g$^{-1}$, respectively which also demonstrates that the V$_2$O$_5$ nanoparticles block the pore channels.

The TEM images and energy dispersive spectroscopy (EDS) results confirm the dispersion of the V$_2$O$_5$ particles in the pores of the mesoporous carbon. Fig. 2(a) shows the highly ordered mesoporous carbon in the mesoporous carbon sample. Scanning transmission electron microscope
(STEM) images of V2O5/mc before sintering are presented in Fig. 2(b) and (c), which are in bright field (BF) and annular dark field (ADF) mapping mode, respectively. Amorphous structures of carbon and lattice fringes of V2O5 are observed in the BF mode figure. In the ADF mapping mode, the dark contrast is from the pores of carbon without any V2O5 particles, while the light contrast reflects the very fine particles of V2O5 in the occupied pores of mesoporous carbon. The EDS spectrum in Fig. 2(d) of the area in Fig. 2(b) and (c) confirms the presence of V2O5 in the sample.

We have applied two strategies to prevent the coating of V2O5 on the carbon. Firstly, the V2O5 was dissolved in H2O2 to form a V2O5 sol. Secondly, due to the capillary effect of the mesopores and the applied ultrasonication, the majority of V2O5 can be sucked into the pores of the mesoporous carbon. BET test results have confirmed the insertion of the V2O5 particles into the pores of the carbon. The TEM image in Figure 2(b) shows some light contrast representing pores in the carbon and some dark contrast representing V2O5 in the occupied pores, confirming that our strategies have been successful.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** (a) Nitrogen adsorption-desorption isotherms; (b) pore size distributions of mesoporous carbon (mc) and V2O5/mc before sintering.
Table 1. BET surface area and total pore volume per gram of the mesoporous carbon and the V₂O₅/mc before sintering.

<table>
<thead>
<tr>
<th>Sample</th>
<th>S_{BET} (m² g⁻¹)</th>
<th>V_{pore} (cm³ g⁻¹)</th>
</tr>
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<tbody>
<tr>
<td>Mesoporous carbon (mc)</td>
<td>874</td>
<td>0.76</td>
</tr>
<tr>
<td>V₂O₅/mc before sintering</td>
<td>77.2</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Figure 2. (a) TEM image of mesoporous carbon sample; (b) STEM image of V₂O₅/mc before sintering in BF mapping mode; (c) STEM image of V₂O₅/mc before sintering in ADF mapping mode (with dark contrast representing pores of carbon, light representing pores + V₂O₅ particles); (d) EDS spectrum of the area in (b) and (c) (with the Cu peak coming from the TEM sample holder).
The reactions of $\text{V}_2\text{O}_5$ powder and $\text{H}_2\text{O}_2$ in the order used to make $\text{V}_2\text{O}_5$ sol can be described by the following reactions [39]:

$$x\text{V}_2\text{O}_5 + 4x\text{H}_2\text{O}_2 + y\text{H}_2\text{O} \rightarrow 2x[\text{VO(O}_2\text{)}_2]^+ + 2x\text{H}^+ + (3x + y)\text{H}_2\text{O} \quad \text{…………………………}(1)$$

$$2x[\text{VO(O}_2\text{)}_2]^+ + 2x\text{H}^+ + (3x + y)\text{H}_2\text{O} \rightarrow (2x - a)[\text{VO(O}_2\text{)}_2]^+ + a[\text{VO(O}_2\text{)}]^+ + 2(x - a)\text{H}^+ + 0.5a\text{O}_2 \uparrow + (3x + y + a)\text{H}_2\text{O} \quad \text{…………………………}(2)$$

$$(2x - c - 10b)[\text{VO(O}_2\text{)}]^+ + b[\text{H}_n\text{V}_{10}\text{O}_{28}]^{(6-n)^-} + (x + 0.5c + 5b)\text{O}_2 \uparrow + (4x + y - 0.5nb)\text{H}_2\text{O} \quad \text{[n = (16b - 2x)/b]} \quad \text{…………………………}(3)$$

$$c[\text{VO}_2]^+ + (2x - c - 10b)[\text{VO(O}_2\text{)}]^+ + b[\text{H}_n\text{V}_{10}\text{O}_{28}]^{(6-n)^-} + (x + 0.5c + 5b)\text{O}_2 \uparrow + (4x + y - 0.5nb)\text{H}_2\text{O} \quad \text{[n = (16b - 2x)/b]} \rightarrow 2x - 10d[\text{VO}_2]^+ + d[\text{H}_n\text{V}_{10}\text{O}_{28}]^{(6-n)^-} + 2x\text{O}_2 \uparrow + (4x + y - 0.5nd)\text{H}_2\text{O} \quad \text{[n = (16d - 2x)/d]} \quad \text{…………………………}(4)$$

$$2x - 10d[\text{VO}_2]^+ + d[\text{H}_n\text{V}_{10}\text{O}_{28}]^{(6-n)^-} + 2x\text{O}_2 \uparrow + (4x + y - 0.5nd)\text{H}_2\text{O} \quad \text{[n = (16d - 2x)/d]} \rightarrow x\text{V}_2\text{O}_5\cdot[4 + (y/x)]\text{H}_2\text{O} + 2x\text{O}_2 \uparrow \quad \text{…………………………}(5)$$

$x\text{V}_2\text{O}_5\cdot[4 + (y/x)]\text{H}_2\text{O}$ represents the resulting vanadium pentoxide sol. In lithium ion battery tests, the resulting vanadium pentoxide sol sample will suffer from poor electrochemical performance due to the crystal water, and therefore, a sintering process at 300 °C for 5 h was applied to the $\text{V}_2\text{O}_5$/mc before sintering sample to further remove the crystal water. Fig. 3 (a) presents the XRD patterns of $\text{V}_2\text{O}_5$/mc, $\text{V}_2\text{O}_5$ np, and $\text{V}_2\text{O}_5$/mc before sintering. The XRD patterns of $\text{V}_2\text{O}_5$/mc and $\text{V}_2\text{O}_5$ np indicate that all the diffraction peaks are in good agreement with the standard pattern of orthorhombic $\text{V}_2\text{O}_5$ (space group: $\text{Pnmn (No. 59)}$, $a = 1.1516$ nm, $b = 0.3565$ nm, $c = 0.4372$ nm, JCPDS card No. 41-1426). In contrast, the pattern of $\text{V}_2\text{O}_5$/mc before sintering shows two diffraction peaks at 26.2° and 51.3°. The weakness and broadness of the peaks indicate the poor crystallization and small crystallite size of the vanadium pentoxide. It can be concluded that ultrasonic treatment inhibits the aggregation of vanadium pentoxide.

The content of $\text{V}_2\text{O}_5$ in the $\text{V}_2\text{O}_5$/mc sample (after sintering) was examined by thermogravimetric analysis (TGA) in air (Figure 3 (b)). As illustrated in the Figure, the weight loss before 150 °C can be assigned to the evaporation and removal of moisture. When the heating
was continued to 550 °C, the weight loss could be determined to be carbon removal. The content of V$_2$O$_5$ in the V$_2$O$_5$/mc sample after sintering is 90 wt%, which was taken into account in the battery testing.

The rate capabilities of V$_2$O$_5$/mc and V$_2$O$_5$ np were measured at various current densities between 2 and 4 V. Figure 4(a) presents the rate capability of V$_2$O$_5$/mc, which is better than that of V$_2$O$_5$ np. The V$_2$O$_5$/mc electrode displays better performance than the V$_2$O$_5$ np electrode at all current densities. The capacities of V$_2$O$_5$/mc are 291, 265, and 247 mA g$^{-1}$, at current densities of 100, 250, and 500 mA g$^{-1}$, respectively. In contrast, the capacity of V$_2$O$_5$ np rapidly decreases as the current density is increased. It shows the capacities of 275, 235, and 182 mA g$^{-1}$ at current densities of 100, 250, and 500 mA g$^{-1}$, respectively. After a deep cycling at 5 A g$^{-1}$, the V$_2$O$_5$/mc electrode can almost recover its initial capacity when the current density is returned to 100 mA g$^{-1}$. Evidently, the V$_2$O$_5$/mc sample demonstrates higher capacity at every current density. The V$_2$O$_5$/mc electrode also shows improved rate capability performance compared with those of V$_2$O$_5$/rGO [40], V$_2$O$_5$/PEDOT/MnO$_2$ nanowire [41], multiwalled CNT- V$_2$O$_5$ [39], V$_2$O$_5$ nanosheet /RGO [42], and graphene nanoribbon / V$_2$O$_5$ [43], as shown in Table 2.

The cycling performances of V$_2$O$_5$/mc and V$_2$O$_5$ np samples at a current density of 500 mA g$^{-1}$ are shown in Figure 4(b). The capacity retention of V$_2$O$_5$/mc is considerably higher than that of V$_2$O$_5$ np. A better reversible capacity of 163 mAh g$^{-1}$ is maintained after 100 cycles, which represents a capacity loss of 40 %, while the capacity of V$_2$O$_5$ np electrode declines to around 50 % after 100 cycles. V$_2$O$_5$/mc with capacity of 198 mAh g$^{-1}$ after 50 cycles also shows comparable or better performance in comparison with several V$_2$O$_5$/carbon composites from recently published works (Table 2), for example, V$_2$O$_5$/rGO (105 mAh g$^{-1}$ at 5700 mA g$^{-1}$) [40], V$_2$O$_5$/PEDOT/MnO$_2$ nanowire (166 mAh g$^{-1}$after 40 cycles at 50 mA g$^{-1}$) [41], multiwalled CNT-V$_2$O$_5$ (199 mAh g$^{-1}$ at 100 mA g$^{-1}$) [39], V$_2$O$_5$ nanosheet /RGO (150 mAh g$^{-1}$ at 600 mA g$^{-1}$) [42], and graphene nanoribbon / V$_2$O$_5$ (230 mAh g$^{-1}$ at 30 mA g$^{-1}$) [43].
Figure 3. (a) XRD patterns of V$_2$O$_5$ nanoparticles (V$_2$O$_5$ np) and of V$_2$O$_5$/mesoporous carbon (V$_2$O$_5$/mc) before and after sintering; (b) TGA curve of V$_2$O$_5$/mesoporous carbon (V$_2$O$_5$/mc) after sintering
We have also synthesized a composite of V$_2$O$_5$ nanoparticles and mesoporous carbon made by simple mixing (denoted as V$_2$O$_5$/mc sm) for comparison. Its rate capability and cycling performance, as shown in Figure 4(a) and (b), are not as good as those of V$_2$O$_5$/mc produced by the ultrasonication technique. The lower rate capability and cycling performance indicate that the mesoporous structure plays an important role in Li$^+$ ion transport that the performance will be improved much more by the insertion of V$_2$O$_5$ particles into the pores.

Figure 4. (a) Rate capability of V$_2$O$_5$/mc, V$_2$O$_5$ n, and V$_2$O$_5$/mc sm at various current densities; (b) cycling performance of V$_2$O$_5$/mc, V$_2$O$_5$ np, and V$_2$O$_5$/mc sm in the voltage range of 2.0–4.0 V at the current density of 500 mA g$^{-1}$; (c) charge/discharge voltage profiles of V$_2$O$_5$/mc at the current density of 100 m g$^{-1}$ for the selected cycles indicated; (d) electrochemical impedance spectra of V$_2$O$_5$/mc and V$_2$O$_5$ np electrodes after 5 charge/discharge cycles and the equivalent circuit used to fit the impedance data (inset).
Table 2. Comparison of our and recently published works on V$_2$O$_5$/Carbon composites for lithium ion batteries.

<table>
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<th>Specific Capacity after 50 cycles</th>
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<tr>
<td>V$_2$O$_5$/rGO</td>
<td>220 mAh g$^{-1}$ at 190 mA g$^{-1}$</td>
<td>105 mAh g$^{-1}$ at 5700 mA g$^{-1}$</td>
<td>[40]</td>
</tr>
<tr>
<td></td>
<td>180 mAh g$^{-1}$ at 950 mA g$^{-1}$</td>
<td></td>
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</tr>
<tr>
<td>V$_2$O$_5$/PEDOT &amp; MnO$_2$ nanowire</td>
<td>164 mAh g$^{-1}$ at 100 mA g$^{-1}$</td>
<td>166 mAh g$^{-1}$ after 40 cycles at 50 mA g$^{-1}$</td>
<td>[41]</td>
</tr>
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<td></td>
<td>48 mAh g$^{-1}$ at 500 mA g$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiwalled CNT-V$_2$O$_5$</td>
<td>250 mAh g$^{-1}$ at 200 mA g$^{-1}$</td>
<td>199 mAh g$^{-1}$ at 100 mA g$^{-1}$</td>
<td>[39]</td>
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</tr>
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<td>V$_2$O$_5$ nanosheet/RGO</td>
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<td>150 mAh g$^{-1}$ at 600 mA g$^{-1}$</td>
<td>[42]</td>
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<td>138 mAh g$^{-1}$ at 3000 mA g$^{-1}$</td>
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<tr>
<td>Graphene nanoribbon/ V$_2$O$_5$</td>
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<td>230 mAh g$^{-1}$ at 30 mA g$^{-1}$</td>
<td>[43]</td>
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<tr>
<td></td>
<td>165 mAh g$^{-1}$ at 600 mA g$^{-1}$</td>
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</tbody>
</table>

Figure 4(c) presents charge/discharge profiles of V$_2$O$_5$/mc at a current density of 500 mA g$^{-1}$ in the voltage window of 2.0–4.0 V. There are three plateaus at about 3.3, 3.1, and 2.2 V in the first cycle, which can be attributed to the phase transitions during Li$^+$ ion intercalation from α-Li$_x$V$_2$O$_5$ ($x < 0.01$) to ε-Li$_x$V$_2$O$_5$ ($0.35 < x < 0.7$), from ε-Li$_x$V$_2$O$_5$ to δ-Li$_x$V$_2$O$_5$ ($x < 1$), and from δ-Li$_x$V$_2$O$_5$ to γ-Li$_x$V$_2$O$_5$ ($x > 1$), respectively [39]. Three plateaus corresponding to the Li$^+$ ion deintercalation processes are also occurred on the charge curve. Figure 4(d) shows the Nyquist plots of V$_2$O$_5$/mc and V$_2$O$_5$ np after five cycles. In the equivalent circuit (inset), $R_\Omega$ and $R_{ct}$ reflect the ohmic resistance and the charge transfer resistance, respectively. CPE is the constant phase-angle element, involving double layer capacitance; and $W$ is the Warburg impedance, representing the solid-state diffusion of Li$^+$ ions into the bulk of the active material. The charge transfer resistance, $R_{ct}$, for V$_2$O$_5$/mc (397 $\Omega$ cm$^2$) is less than that for V$_2$O$_5$-np (604 $\Omega$ cm$^2$), indicating
improved charge transfer in the $V_2O_5/mc$ electrode. The reason for the better performance of $V_2O_5/mc$ is likely to be because the $V_2O_5$ is in a composite with mesoporous carbon, which can provide fast transport channels for lithium ions.

4. Conclusions

We have successfully fabricated a $V_2O_5$/mesoporous carbon composite by using an ultrasound assisted method followed by sintering. The mesoporous structure of the carbon facilitates the electrolyte diffusion into the bulk of the electrode material and hence provides fast transport channels for $Li^+$ ions. As a cathode material for LIBs, $V_2O_5$/mesoporous carbon shows better performance than $V_2O_5$ nanoparticles, suggesting that $V_2O_5$/mesoporous carbon composite could be used as a promising cathode material for lithium ion batteries.

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