V$_2$O$_5$-SiO$_2$ hybrid as anode material for aqueous rechargeable lithium batteries

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Received: 23 January 2016 / Revised: 16 March 2016 / Accepted: 19 March 2016 © Springer-Verlag Berlin Heidelberg 2016

Abstract V$_2$O$_5$-SiO$_2$ hybrid material was fabricated by heat-treating a mixture of H$_2$SiO$_3$ and V$_2$O$_5$. SEM, TEM, XRD, and N$_2$ isotherm analyses were performed to characterize the morphology and structure details of the as-prepared V$_2$O$_5$-SiO$_2$. The possibility of using the as-prepared V$_2$O$_5$-SiO$_2$ as anode material for aqueous lithium-ion batteries was investigated. Potentiostatic and galvanostatic results indicated that the intercalation/de-intercalation of Li$^+$ in this material in aqueous electrolyte was quasi-reversible. It was also found that a discharge capacity of up to 199.1 mAh g$^{-1}$ was obtained at a current density of 50 mA g$^{-1}$ in aqueous solution of 1 M Li$_2$SO$_4$, a value which is much higher than the available reported capacities of vanadium (+5) oxides in aqueous electrolytes.

Keywords Aqueous rechargeable lithium battery · Vanadium pentoxide · Silica · Anode material · Hybrid materials

Introduction

Lithium ion batteries (LIBs) used as power sources for portable electronic devices and transport applications were first produced in the early 1990s. LIBs commonly consist of three main components, namely, the anode, cathode, and organic liquid electrolyte. The wide potential range of organic electrolytes allows LIBs to operate at high voltages delivering higher specific energy densities than their aqueous counterparts. However, these organic electrolytes are highly flammable, and the use of lithium salts and separators as well as the processing for using organic electrolytes are very expensive [1]. As a safe and cost-effective alternative, a new type of LIBs with an aqueous electrolyte was developed by Dahn’s group in 1994 [2]. This type of battery uses LiMn$_2$O$_4$ as cathode and VO$_2$ as anode in an aqueous electrolyte consisting of 5 M LiNO$_3$ in 0.001 M LiOH. The researchers found that the specific energy density of the newly developed battery was 75 Wh kg$^{-1}$ [2]. They also observed that by using this new type of “chemistry” combination, the disadvantages of conventional LIBs, i.e., the high manufacturing cost and safety problems, could be eliminated. Although the battery’s energy capacity and cycling life are relatively low, the results highlighted a new path for developing aqueous rechargeable lithium-ion batteries (ARLB).

It was found that oxides represent a unique class of important high capacity materials which can be used in ARLB. Among these oxides, considerable attention has been paid to vanadium oxides as a promising anode for ARLB. For example, an ARLB based on LiNi$_{0.81}$Co$_{0.19}$O$_2$ as cathode and LiV$_3$O$_8$ as anode in 1.0 M Li$_2$SO$_4$ (or LiCl) electrolyte was successfully developed by Köhler et al. [3]. The researchers showed that the newly developed ARLB had a capacity of ca. 45 mAh g$^{-1}$ at an output cell voltage of 1.2 V, and ca. 70 % of the discharge capacity remained after 30 charge/discharge cycles. Wang et al. [4] reported that the cycling stability of
LiMn$_2$O$_4$/5 M LiNO$_3$/Li$_x$V$_2$O$_5$ ARLB could be significantly improved by coating polypyrrole (PPy) on the anode. A recent study by Stojkovi et al. [5] showed that the specific capacity of LiMn$_2$O$_4$/saturated LiNO$_3$/V$_2$O$_5$ xerogel ARLB can reach values up to 69 mAh g$^{-1}$, together with improved cycling stability due to its unique structure. Xie et al. [6, 7] prepared several vanadium oxides of unique morphologies via a hydrothermal route and found that specific capacity values can reach up to 80 mAh g$^{-1}$. Recently, there has been some interest in [8–11] preparing and testing vanadium oxides which were found to exhibit large specific capacities of up to 100 mAh g$^{-1}$. Some other researchers such as Li et al. [12] showed that high specific capacity values of up to 234 mAh g$^{-1}$ could be achieved. In their study, they found that using H$_2$V$_3$O$_8$ nanowires as anode materials could significantly enhance the performance of ARLB [12].

Mesoporous silicate has attracted considerable attention due to its tuneable pore size, excellent stability, and high surface area, which makes it an ideal candidate as catalyst, support, and electrode materials. For example, Huang et al. [13] found that when SnO$_2$ was mixed with SiO$_2$, very high specific capacity values were obtained due to enhanced interfacial diffusion caused by highly dispersed SiO$_2$ and LiSi$_2$O$_3$ phases. Similar findings were also reported by Liu’s group [14]. Inspired by the aforementioned observations and studies, we report herein the fabrication and testing of a V$_2$O$_5$-SiO$_2$ hybrid material, in which V$_2$O$_5$ blocks were dispersed in cotton-like mesoporous SiO$_2$ (acting as a high surface host for V$_2$O$_5$). The as-prepared V$_2$O$_5$-SiO$_2$ exhibited a high specific capacity value of ca. 200 mAh g$^{-1}$, which is much higher than the specific capacity of V$_2$O$_5$-based electrode materials for ARLBs reported in the literature.

**Experimental**

**Preparation of the samples**

Na$_2$SiO$_3$ (853 mg) was dissolved into 5 mL H$_2$O and stirred for 0.5 h. HCl solution (2 M, 8 mL) was added drop by drop into the above mixture under constant stirring until white colloid was formed. The mixture was filtered and washed with deionized water until pH of the filtrate was ca. 7. After that, 182 mg of commercial V$_2$O$_5$ was added in the above sample and then ground using a pestle and mortar until a homogeneous mixture was obtained. The above mixture was transferred into a furnace and then heated at 150 °C in air for 1 h and increased to 500 °C for 1 h. After cooling down to room temperature, the V$_2$O$_5$-SiO$_2$ hybrid material was obtained. For comparison purposes, the SiO$_2$ was prepared by drying the obtained white colloid, and V$_2$O$_5$ was also prepared by heat-treatment using commercial V$_2$O$_5$.

**Physical characterizations**

X-ray diffraction (XRD) patterns of the as-prepared materials were recorded on a Shimadzu XD-3A (Japan) goniometer, using Cu-Kα radiation operating at 40 kV and 35 mA. Scanning electron microscopy (SEM) images were obtained using a Carl Zeiss Ultra Plus by spraying Au film. Transmission electron microscopy (TEM) measurements coupled with energy-dispersive spectroscopy (EDS) were carried out using a JEM-2010 Electron Microscope (Japan) with an acceleration voltage of 200 kV. The sorption isotherms were obtained using a Quantachrome Autosorb-I volumetric analyzer. Specific surface areas were determined using a Brunauer-Emmet-Teller (BET), and the density functional theory (DFT) was applied for analyzing the full range of pore size distribution. The solubility products of the as-prepared V$_2$O$_5$-SiO$_2$ in the electrolyte after cycling testing was determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES) analysis using IRIS Intrepid II spectrometer (Thermo Fisher).

**Electrochemical characterizations**

Cyclic voltammograms (CVs) and galvanostatic charge/discharge experiments were carried out to evaluate the electrochemical performance of V$_2$O$_5$-SiO$_2$ in 1 mol L$^{-1}$ Na$_2$SO$_4$ using a three-electrode cell. The working electrode was fabricated by pasting a homogeneous slurry made of V$_2$O$_5$-SiO$_2$, carbon black, and polytetrafluoroethylene (mass ratio of 8:1:1) in ethylene glycol. The mixture was then rolled into uniform slices, followed by drying at 80 °C for 6 h. Then, the slice was covered onto a 304 stainless steel plate (1 cm × 1 cm) with a tablet press. Ten milligrams of V$_2$O$_5$-SiO$_2$ was loaded on the electrode. The LiMn$_2$O$_4$ electrode was fabricated in the same way as the V$_2$O$_5$-SiO$_2$ electrode, but the area was 2 cm × 2 cm. The amount of LiMn$_2$O$_4$ on the electrode was approximately 20 mg.

A three-electrode cell and three electrodes were used, in which the reference electrode was a Hg/Hg$_2$SO$_4$ (saturated Na$_2$SO$_4$) electrode. All potentials are shown versus the Hg/Hg$_2$SO$_4$ reference electrode. The electrolyte was a 1.0 mol L$^{-1}$ Li$_2$SO$_4$. Galvanostatic charge/discharge and cycling life tests were measured using a Neware Battery Test System (Shenzhen Neware Technology Company, China).
Results and discussion

The crystal structures of the as-prepared samples were characterized by XRD. As shown in Fig. 1, a broad peak appears in the XRD pattern of SiO$_2$, suggesting that the obtained SiO$_2$ is amorphous [15]. In the case of V$_2$O$_5$ samples, all peaks are consistent with orthorhombic V$_2$O$_5$ (JCPDS files 41-1426) without exhibiting any impurity peaks [16]. After thermal treatment, XRD patterns of V$_2$O$_5$-SiO$_2$ hybrid samples show that the two phases of V$_2$O$_5$ and SiO$_2$ are retained.

Figure 2 shows SEM images of SiO$_2$, V$_2$O$_5$, and V$_2$O$_5$-SiO$_2$ samples. As shown in Fig. 2a, the SiO$_2$ sample displays a loose cotton-like morphology (obtained without spraying the Au film). The V$_2$O$_5$ image in Fig. 2b shows blocks of irregular shapes. Figure 2c, 2d shows the V$_2$O$_5$-SiO$_2$ images at different magnifications. It can be seen that the V$_2$O$_5$ blocks are dispersed among the SiO$_2$ cotton-like structure, indicating that SiO$_2$ and V$_2$O$_5$ exist as separate phases. The morphology of the V$_2$O$_5$-SiO$_2$ sample was also characterized by TEM. It can be observed from Fig. 3a, 3b that the loose cotton-like structure of SiO$_2$ and the V$_2$O$_5$ blocks are present in V$_2$O$_5$-SiO$_2$. The composition of the V$_2$O$_5$-SiO$_2$ samples was analyzed by EDS, and the obtained spectrum is shown in Fig. 3c. The figure clearly shows that Si, V, and O are present; it also shows a weak sodium element signal, suggesting that a little Na$^+$ was retained in SiO$_2$. Quantitative elemental analysis shows that the atomic ratio of Si/V is 2.9:1, which is close to the initial ratio in the precursors. The distribution profile of Si, V, and O elements detected by TEM images (Fig. 3d) is also present in Fig. 3e. Figure 3e shows that the positions and widths of the peaks of the O element match with those of Si and V elements, indicating that the Si and V are in oxide forms. From the same figure, it can be observed that the peak shape for Si in the position from 0 to ca. 800 nm is different from that of the peak shape for V, implying that SiO$_2$ and V$_2$O$_5$ are separated; this observation is in very good agreement with the SEM results.

Figure 4 shows the N$_2$ adsorption-desorption isotherms and the corresponding pore size distribution of SiO$_2$, V$_2$O$_5$, and V$_2$O$_5$-SiO$_2$. The isotherms of SiO$_2$ and V$_2$O$_5$-SiO$_2$ in Fig. 4a are of type IV with H$_2$ hysteresis, indicating that the two samples contained some irregular pore structures [17]. The curve of V$_2$O$_5$ exhibits type I characteristics, corresponding to the well-known Langmuir isotherms indicating the absence of pores in the material [18]. When V$_2$O$_5$ was compounded with SiO$_2$, the pore structure was retained in the structure of V$_2$O$_5$-SiO$_2$. Their pore size distributions are shown in Fig. 4b. The figure also shows the hierarchical pores in the range of micro- to meso-size existing in SiO$_2$. The micropores and mesopores are also present in the V$_2$O$_5$-SiO$_2$ samples. According to the data in the N$_2$ adsorption-desorption isotherms, the calculated BET surface areas of SiO$_2$, V$_2$O$_5$, and V$_2$O$_5$-SiO$_2$ were found to be 214.8, 4.1, and 180.7 m$^2$ g$^{-1}$, respectively.

Figure 5 shows CVs of V$_2$O$_5$-SiO$_2$ at various scan runs. During the first cathodic scan run, two peaks are observed, one at $-0.056$ V and the other at $+0.257$ V, corresponding to a two-step lithiation [5]. The peak at $-0.90$ V corresponds to hydrogen evolution. The negative potential of hydrogen evolution clearly shows that V$_2$O$_5$-SiO$_2$ hybrid materials can be used as anode in ARLB. It was also observed that a weak peak located at $+0.287$ V and a broad peak at $+0.75$ V appear in the anodic scan, corresponding to a two-step de-lithiation process. In total, nine (9) consecutive CV scans were carried out, and all of them exhibited similar CV shapes to the 1st scan, indicating that the structure of V$_2$O$_5$-SiO$_2$ did not significantly change during the Li$^+$ insertion/de-insertion process. The decrease of the peak current, together with a small shift of the peak potential position in the first 9 cycles, indicates capacity loss which is a common feature for ARLBs. This phenomenon could be attributed to the side reactions between...
Li$^+$ and the aqueous solution, as well as the initial irreversible structure change [9].

To estimate the electrochemical performance of V$_2$O$_5$-SiO$_2$ anode, V$_2$O$_5$-SiO$_2$/LiMn$_2$O$_4$ ARLB was assembled using 1.0 M Li$_2$SO$_4$ solution as aqueous electrolyte. The CVs of V$_2$O$_5$-SiO$_2$ and LiMn$_2$O$_4$ in 1.0 M Li$_2$SO$_4$ aqueous solution are shown in Fig. 6. In the case of the LiMn$_2$O$_4$ electrode, two anodic peaks are observed: a very weak peak at ca. +1.15 V and the other at ca. +1.29 V, corresponding to the de-lithiation of the LiMn$_2$O$_4$ electrode. In the negative scan, a redox peak at +0.82 V was observed, corresponding to the lithiation of LiMn$_2$O$_4$. These findings are in good agreement with the two-step Li$^+$ de-intercalation/intercalation process of LiMn$_2$O$_4$ in aqueous electrolyte [19]. For V$_2$O$_5$-SiO$_2$ anode, two redox peaks are also observed at +0.32 and −0.12 V corresponding to the Li$^+$ insertion into V$_2$O$_5$-SiO$_2$. A broad anodic peak at +0.52 V can be ascribed to the Li$^+$ extraction from V$_2$O$_5$-SiO$_2$. It can be noted from the CVs that the evolution of hydrogen in the aqueous electrolyte occurs at much lower potentials, i.e., at ca. −0.9 V, suggesting that V$_2$O$_5$-SiO$_2$ remains stable during the lithium insertion/extraction process in the aqueous solution. It was found that due to the electrode overpotentials, the oxygen and hydrogen evolution potential shifted anodically and cathodically, respectively, in turn increasing the working potential window of the aqueous electrolyte. Cyclic voltammetry properties of V$_2$O$_5$-SiO$_2$ and LiMn$_2$O$_4$ prove that, in our conditions, it is possible to use LiMn$_2$O$_4$ and V$_2$O$_5$-SiO$_2$ as cathode and anode, respectively, in an aqueous LIB without causing hydrogen and oxygen evolutions in the potential range used.

The typical galvanostatic discharge/charge curves of the V$_2$O$_5$-SiO$_2$ sample in aqueous electrolyte (1 M Li$_2$SO$_4$) at a current density of 25 mA g$^{-1}$ are shown in Fig. 7a. The curves obtained in aqueous electrolyte show similar galvanostatic discharge-charge profiles with pseudo-plateaus, revealing that the lithium insertion/extraction proceeds in several steps. The shapes of the charge/discharge curves

![Fig. 2 SEM images of a SiO$_2$, b V$_2$O$_5$, and c, d V$_2$O$_5$-SiO$_2$ samples](image-url)
are different from those reported by Ivana and co-workers [5]. In their work, V₂O₅ xerogel samples in aqueous LiNO₃ solution did not display plateaus or pseudo-plateaus in the discharge curve region due to its amorphous structure. The pseudo-plateaus in the curve of the V₂O₅-SiO₂ sample can be related to the phase transitions of its crystal structure, such as the change in organic electrolyte that was reported by Taegyeong and co-workers [16]. The initial discharge
and charge capacity values of the V₂O₅-SiO₂|1.0 M Li₂SO₄|LiMn₂O₄ cell based on the weight of total anode material were found to be 70.4 and 70.3 mAh g⁻¹, respectively.

To study the effect of the composition of V₂O₅-SiO₂ on its performance, a series of V₂O₅-SiO₂ hybrid samples containing various Si/V molar ratios were prepared using the same procedure. The corresponding galvanostatic discharge curves at a current density of 50 mA g⁻¹ are presented in Fig. 7b. Here, the trend of the capacity with the V/Si molar ratio is plotted in the inset of Fig. 7c. According to a recent report by Wang and co-workers [20], SiO₂ was not active for the Li⁺ intercalation/de-intercalation into the anode, thus V₂O₅ is the active material in V₂O₅-SiO₂ during the charge/discharge process. The initial discharge and charge capacity values of the V₂O₅-SiO₂ at a current density of 50 mA g⁻¹ were calculated based on the anode active material of V₂O₅. It was observed that the initial discharge capacity value for V₂O₅-SiO₂ (199.1 mAh g⁻¹) is higher than that of pure V₂O₅. This finding could be due to the presence of porous SiO₂ at the anode. As shown in the SEM and TEM images, the V₂O₅ blocks are dispersed on the SiO₂ matrix, implying that the area on the V₂O₅ blocks in contact with the electrolyte is increased, which could lead to the observed enhanced capacity. Moreover, the mesoporous SiO₂ could facilitate the mass transfer during the charge/discharge process, resulting in the improved capacity. As shown in Fig. 7b, with the increase of the content of SiO₂, the capacity increases and reaches a maximum value with the Si/V molar ratio of 3:1. This indicates that the SiO₂ support plays an important role in the improvement of performance.

In addition, the V₂O₅-SiO₂|1.0 M Li₂SO₄|LiMn₂O₄ cell shows higher utilization of the capacity with respect to the cases of other vanadium(+5)-oxide-based anode and LiMn₂O₄ as cathode in ARLB. For example, at a charging/discharging rate similar to the ones observed in this study, the V₂O₅ xerogel|saturated LiNO₃|LiMn₂O₄ cell prepared by Ivana and co-workers [5] showed the initial discharge and charge capacity of 69 and 73 mAh g⁻¹, respectively. The crystalline Li₃V₆O₁₆ rod anode prepared by Vivek Sahadevan et al. [11] displayed the initial discharge...
and charge capacity of 120 and 110 mAh g\(^{-1}\) with the LiMn\(_2\)O\(_4\) cathode in 3.0 M LiNO\(_3\) aqueous solution at a current density of 0.5 mAh g\(^{-1}\) respectively. The Li\(_3\)V\(_6\)O\(_{16}\)/PTFOIL cell fabricated by Wang et al. [21] exhibited an initial discharge and charge capacity of 55.1 and 61.8 mAh g\(^{-1}\) at a charge/discharge current density of 0.2 mA cm\(^{-2}\). The higher capacity of the V\(_2\)O\(_5\)-SiO\(_2\) hybrid can be ascribed to the large surface area achieved by the presence of the SiO\(_2\) support and short diffusion distances provided by the porous structure of SiO\(_2\).

The cycle performances of the V\(_2\)O\(_5\)-SiO\(_2\) hybrid and pure V\(_2\)O\(_5\) in aqueous electrolyte are shown in Fig. 8. It was found that the capacities of V\(_2\)O\(_5\)-SiO\(_2\) and pure V\(_2\)O\(_5\) rapidly decrease, maintaining 12 and 18 % of the initial capacity after 60 cycles of charge/discharge in the aqueous electrolyte, respectively. In fact, capacity decay upon cycling was extensively observed for negative electrode materials of ARLB [3, 5, 11, 12, 22]. It was suggested that the loss of capacity could be caused by the transition metal ion dissolution, the phase transformation of the electrode material, the chemical reaction between the active material and water, or the decomposition of the electrolyte. In our case, the decrease in capacity of V\(_2\)O\(_5\)-SiO\(_2\) is most likely to be due to the dissolution of vanadium in aqueous solution (as observed by the change of color of the electrolyte from colorless to light yellow). SEM images of the electrode and the content of vanadium in the electrolyte after cycling performance were obtained in order to determine the dissolution of vanadium (Fig.9). As shown in Fig. 9, irregular V\(_2\)O\(_5\) blocks are observed in the SEM images of the V\(_2\)O\(_5\)-SiO\(_2\) (Fig. 9a) and V\(_2\)O\(_5\) (Fig. 9c) electrodes prior to the cycling test. After 60 cycling tests, it can be observed that V\(_2\)O\(_5\) blocks disappeared as clearly shown in SEM images of the V\(_2\)O\(_5\)-SiO\(_2\) (Fig. 9b) and V\(_2\)O\(_5\) (Fig. 9d) electrodes, indicating that most of the material dissolved in the electrolyte during the cycling test. To support this finding, it was observed that the color of the electrolyte changed from colorless to light yellow after the cycling test. To further confirm this finding, the content of vanadium in the electrolyte after the cycling test was quantitatively analyzed by ICP-AES. The data showed that the vanadium content in the electrolytes were ca. 88.5 and 85 % of its original amounts in V\(_2\)O\(_5\)-SiO\(_2\) (Fig. 9b) and V\(_2\)O\(_5\), respectively, clearly proving that most of the vanadium had dissolved in the electrolyte. As previously discussed, the dispersion of V\(_2\)O\(_5\) with SiO\(_2\) increases the contact area between V\(_2\)O\(_5\) blocks and the aqueous electrolyte, which may worsen the dissolution of V\(_2\)O\(_5\). This observation also suggests that the porous SiO\(_2\) support can enhance the capacity of V\(_2\)O\(_5\), but not benefit its cycling life.

Compared to the capacity decay upon cycling for the vanadium oxide as anode for ARLB such as 25 % of the original capacity after 100 cycles for Li\(_3\)V\(_6\)O\(_{16}\)/LiNi\(_{0.81}\)Co\(_{0.19}\)O\(_2\) [3], 89 % after 100 cycles for V\(_2\)O\(_5\) xerogel/LiMn\(_2\)O\(_4\) [5], ~52 % after 100 cycles for the Li\(_3\)V\(_6\)O\(_{16}\)/Pt foil [11], and 72 % after 50 cycles for H\(_2\)V\(_3\)O\(_8\)/carbon [12], the capacity decay of the V\(_2\)O\(_5\)-SiO\(_2\) hybrid is serious. This is due to the fact that the dispersion of V\(_2\)O\(_5\) with SiO\(_2\) increases the contact area between the V\(_2\)O\(_5\) blocks and the aqueous electrolyte, which could aggravate the dissolution of V\(_2\)O\(_5\). In addition, the beaker-type cell that was used in our experiments requires a large amount of electrolyte (ca. 30 mL), which could trigger the dissolution of V ion.

Fig. 7 a Galvanostatic discharge-charge profiles of V\(_2\)O\(_5\)-SiO\(_2\)/1.0 M Li\(_2\)SO\(_4\)/LiMn\(_2\)O\(_4\) ARLB at a current density of 25 mA g\(^{-1}\). b Galvanostatic discharge profiles of V\(_2\)O\(_5\)-SiO\(_2\)/1.0 M Li\(_2\)SO\(_4\)/LiMn\(_2\)O\(_4\) ARLB for the second cycle at a current density of 50 mA g\(^{-1}\); inset the trend of the capacity of V\(_2\)O\(_5\)-SiO\(_2\)/1.0 M Li\(_2\)SO\(_4\)/LiMn\(_2\)O\(_4\) ARLB for the second cycle at a current density of 50 mA g\(^{-1}\).
in the electrolyte [12]. However, Tang and co-workers successfully improved the cycle stability of V$_2$O$_5$ [8] and MoO$_3$ [23] by surface polymerization of pyrrole. Wang et al. [4] coated the Li$_x$V$_2$O$_5$ anode with PPy, which was shown to greatly improve the cycling stability of the Li$_x$V$_2$O$_5$/LiMn$_2$O$_4$ cell. In the light of these works, further modification such as surface coating on V$_2$O$_5$-SiO$_2$ and lower electrolyte amount may lead to improvement in the cycling stability of V$_2$O$_5$-SiO$_2$ in aqueous electrolytes.

**Fig. 8** Cycling performance of V$_2$O$_5$-SiO$_2$|1.0 M Li$_2$SO$_4$|LiMn$_2$O$_4$ (a) and V$_2$O$_5$|1.0 M Li$_2$SO$_4$|LiMn$_2$O$_4$ ARLBs (b) at a current density of 50 mA g$^{-1}$

**Fig. 9** SEM images of a, b V$_2$O$_5$-SiO$_2$ and c, d V$_2$O$_5$ electrodes before and after 60 cycles at a current density of 50 mA g$^{-1}$, respectively
Conclusions

The V₂O₅-SiO₂ hybrid was obtained via a facile thermal treatment method using commercial V₂O₅ together with as-prepared SiO₂. When used as the electrode material for ARLBs, V₂O₅-SiO₂ showed that the intercalation and de-intercalation of lithium ions are similar to those of other vanadium oxide anodes in aqueous electrolytes. The porous SiO₂ support can enhance the initial capacity of V₂O₅ (up to 199.1 mAh g⁻¹) at 50 mA g⁻¹ due to the increased contact area between V₂O₅ and the electrolyte. However, at the same time, a decrease in the cycling life was observed. Thus, for future work, the surface coating on V₂O₅-SiO₂ could be an effective way to improve both the capacity and cycling stability of vanadium oxide in aqueous electrolytes.

Acknowledgments Financial support from the National Natural Science Foundation of China (grant nos. 21163018, 21363022, and 51362027) and JCYJ20140418095735600 is greatly appreciated.

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