Effect of crsyalline structure on the electrochemical properties of $K_{0.25}V_2O_5$ nanobelt for fast Li insertion

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ABSTRACT

Lithium vanadium oxides and vanadates have wide attention as cathode materials for Li ion battery applications, but there has been limited study on other cation substituted vanadium compounds, which could have favorable electrochemical properties. Here we report the synthesis and electrochemical properties of aggregated $K_{0.25}V_2O_5$ nanobelts and the optimization of the crystalline structure for fast Li ion insertion. We propose a partial melting and self-alignment mechanism to produce the aggregated nanobelts. This material can deliver a high discharge capacity of 232 mA h g⁻¹ at 100 mA g⁻¹ and high rate capability. It also exhibits superior long-term cycling performance with no capacity fading over 800 cycles at high current density of 1, 1.5, and 2A g⁻¹. Remarkably, although some work has been devoted to potassium vanadates, there is little work introducing this class of materials with super long lifespan. The results demonstrate that the as-prepared $K_{0.25}V_2O_5$ would be a potential candidate for LIBs.

Keyword: $K_{0.25}V_2O_5$, nanobelt, hierarchical architecture, long-cycle-life, electrochemical property

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1. Introduction

Energy storage is very important for transportation and modern grid [1-6]. Current lithium-ion batteries (LIBs) are the prime candidate for a range of applications [7-12]. There is a great interest to increase specific capacity, power density, life span and safety [13-17]. In the last few years, vanadium-based oxides and their derivative compounds have been extensively investigated as cathode materials due to their high specific capacity, large energy density, and low cost [18-34]. Among the potential candidates, copper vanadates and silver vanadium oxides can deliver high initial specific capacity but suffer from irreversible structure change and rapid capacity fade upon cycling [32, 33, 35-39]. Lithium trivanadate (LiV_3O_8) and sodium vanadium oxides can have good structural stability and high specific capacity [19-28, 40]. $\text{Na}_{1.1}\text{V}_3\text{O}_8$ shows 95% capacity retention after 200 cycles [28]. However, in general vanadium oxide based cathode materials have not become a prime candidate for cathode materials due to poor cycling stability.

Potassium vanadates were investigated since 1980s and have attracted a great deal of attention recently due to their larger interlamellar spacing influenced by potassium ions [41-45], which contributes to fast diffusion of lithium ion and enhances the overall charge storage kinetics. Recently, Mai et al have studied a variety of cations substituted vanadium oxides, and found that the K substituted structure can have good Li insertion properties [43]. Xu et al have reported $\text{K}_{0.23}\text{V}_2\text{O}_5$ crystals with good electrochemical performance because the kinetics of $\text{K}_{0.23}\text{V}_2\text{O}_5$ crystals can be improved by doping with K^+ [46]. However, the electrochemical properties depend on not only the inherent structures, but also the synthetic conditions and detailed crystalline structure as well as morphologies. Compared with the bulk materials, nanostructures, such as nanowires, nanoneedles and nanobelts, can increase the contact area between the electrolyte and electrode and shorten Li^+

diffusion distance [13, 18]. Previously studies have showed that hierarchical microstructure assembled from nanocrystals can effectively mitigate volume [47-50]. Besides, optimization of the crystalline structure may greatly improve the electrochemical performance for electrode materials [51].

Among the potassium vanadates, $K_{0.25}V_2O_5$ has a high theoretical discharge capacity of 341 mA h g⁻¹ based on galvanostatic intermittent titration technique (GITT) test, which shows great potential as cathode material for LIBs [52]. Here, we have synthesized $K_{0.25}V_2O_5$ aggregated nanobelts with enhanced specific capacity, rate capability and long-term cycling performance. We demonstrate that an optimum treatment can improve the crystalline structure and the morphology. The formation of orderly $K_{0.25}V_2O_5$ aggregated nanobelts are proposed by a partial melting and self-alignment mechanism. As a result, long-term cycling stability up to 800 cycles is obtained with no capacity fading in this class of materials. It demonstrates that the as-prepared $K_{0.25}V_2O_5$ is a potential cathode candidate for LIBs.

2. Experimental section:

2.1. Materials synthesis

All reagents were of analytically pure and were used without further purification. $K_{0.25}V_2O_5$ compound was prepared by using ammonium metavanadate (NH_4VO_3 , $\geq 99.0\%$), potassium oxalate monohydrate ($C_2K_2O_4 \cdot H_2O$, $\geq 99.8\%$) and glycine ($C_2H_5NO_2$, $\geq 99.5\%$) as starting materials. In a facile soft chemistry method, 1.0528g NH_4VO_3 and stoichiometric $C_2K_2O_4 \cdot H_2O$ were added into a beaker containing 40 mL de-ionized water under magnetically stirring at 60 °C to make a light yellow slurry. Then desirable amount of $C_2H_5NO_2$ was mixed with sequentially stirring for several hours to get a gel. After that, the gel was dried overnight in an oven at 60 °C to get light

brown solid. The as-obtained solid was further annealed at various temperatures for 4 h to get the final products. The $K_{0.25}V_2O_5$ synthesized at 450°C, 500°C and 550°C are noted as samples K450, K500 and K550, respectively.

2.2. Materials characterization

X-ray diffraction (XRD) measurements were performed to investigate the crystallographic phase of the as-synthesized $K_{0.25}V_2O_5$ compound using X-ray power diffraction (XRD, Rigaku D/max 2500). The morphologies and sizes of the as-prepared products were characterized by scanning electron microscopy (SEM, Quanta FEG 250). Transmission electron microscope (TEM) images and High-resolution transmission electron microscope (HRTEM) images were recorded by using JEOL JEM-2100F transmission electron microscope.

2.3. Electrochemical measurements

The electrochemical properties were carried out via stainless-steel coin cells (CR 2016). Cathode electrodes were obtained with 70% as-synthesized $K_{0.25}V_2O_5$ compound, 20% acetylene black, and 10% polyvinylidene fluoride (PVDF) binder. The cells were assembled in a glove box (Mbraun, Germany) filled with ultra-high purity argon using polypropylene membrane as the separator, Lithium metal as the anode, and 1M $LiPF_6$ in ethylene carbonate/dimethyl carbonate (EC/DMC) (1:1 v/v) as the electrolyte (Shenzhen Capchem Technology Co., Ltd.). Cyclic voltammetry (CV) of $Li/K_{0.25}V_2O_5$ coin cell was tested using an electrochemical workstation (CHI660C, China) at a scan rate of 0.05 mV s^{-1} in the voltage range of 1.5 V-4 V (vs. Li^+/Li). The galvanostatic charge/discharge experiments were studied in a potential range of 1.5 V-4 V (vs. Li^+/Li) using a multichannel battery testing system (Land CT 2001A). Since there are no Li ions in the original $K_{0.25}V_2O_5$ structure, the first procedure of electrochemical tests in this work is discharge process. The electrochemical impedance spectrometry (EIS) was performed on a ZAHNER-IM6ex

electrochemical workstation (ZAHNER Co., Germany) in the frequency range of 100 kHz to 10 m Hz on a cell. The loading of the $K_{0.25}V_2O_5$ cathode material for coin cell test is about 1-2 mg. The specific capacity and current density are calculated on the basis of the weight of active material only.

3. Results and discussion

The detailed synthesized process of $K_{0.25}V_2O_5$ aggregated nanobelts was shown in experimental section. In brief, the precursors with some rods (**Fig. S1a in Electronic Supporting Information (ESI[†])**) were prepared by a facile mild chemical method using NH_4VO_3 , $C_2K_2O_4 \cdot H_2O$ and $C_2H_5NO_2$ as starting materials. The samples calcined at 450°C, 500°C, and 550°C are referred to as K450, K500, and K550, respectively. The aggregated nanobelts were produced through a partial melting and self-alignment mechanism. When heating, the physical and chemical water and the gas were evaporated from the precursor (**Fig. S1a**). On the other hand, the precursor was forming nucleus for crystal growth to form nanobelts. The growth of nanobelts in precursor is isotropous and then the disordered and randomly oriented nanobelt aggregates were formed at 450°C (**Fig. 1a(i)**). In this case, the surface energy of each nanobelt is high and it may tend to aggregate to reduce the surface energy. For another thing, the stress concentration in the intersection points between belts and belts would aggravate and cause the cracks in the intersection points when calcination temperature was improved or other conditions were changed. At a higher temperature around the melting temperature, some nanobelts begin to breakdown near intersections and the whole nanobelts become self-aligned (**Fig. 1a (ii) and (iii)**). Transmission electron microscopy (TEM) images of K500 in (**Fig. S2 in ESI[†]**) proved that partial melting of nanobelts happened

during heating, in particular at intersections. Furthermore, TG and DSC results for the precursor (**Fig. 2a**) with an obvious endothermic peak after 535°C and no mass loss suggests that large quantity of nanobelts broke off and self-aggregated to form a stable structure with order nanobelts arrays at 550°C for reducing the overall surface energy. The detailed structure of K550 was further analyzed using scanning electron microscopy (SEM) and TEM. As shown in **Fig. 1b**, the sample is composed of a large quantity of nanobelts with a thickness of ~57 nm, which is much thinner than that of K450 and K500 (**Fig. S1b and c in ESI†**). Obviously, the nanobelts with clear surface are separated by ~100 nm. **Fig.1c** shows TEM image of several nanobelts about 200 nm in width. The SAED pattern (**inset Fig. 1d**) confirms that each individual $K_{0.25}V_2O_5$ nanobelt is a single crystal. HRTEM image (**Fig. 1d**) shows a lattice spacing of ~0.74 nm, corresponding to the (00-2) interplanar distance of the monoclinic $K_{0.25}V_2O_5$ phase. TEM data revealed that the nanobelts were a single-crystalline structure with faster growth direction along the *b*-axis [010] orientation. Chemical bonding theory of single-crystal growth shows the same prior crystallographic orientation [010] for the growth of V_2O_5 [53]. Choi et al. confirmed that the optimum Li-ion diffusion pathway for $LiMnPO_4$ nanoplates is along [010] direction [51]. The preferred growth of $K_{0.25}V_2O_5$ nanobelts is along 3D-tunnel orientation of $K_{0.25}V_2O_5$, which facilitates Li-ion diffusion.

More evidence about the phase purity and crystal structure of the as-prepared products are provided by X-ray diffraction (XRD) as shown in **Fig. 2b**. The XRD patterns of all the samples are indexed to the monoclinic crystalline $K_{0.25}V_2O_5$ phase [space group: $A2/m$, JCPDS Card No. 39-0889] with the lattice parameter listed in **Table 1**. $K_{0.25}V_2O_5$ has a specific layer structure with two kinds of layers, one formed by layers of VO_5 square pyramids sharing two edges and corners, another with 3D tunnel structure formed by VO_6 and VO_5 frameworks along the *b* axis. Triangular

prism in voids are formed by six oxygen atoms around K^+ cations, as shown in **Fig. 2c**. The sixth V-O bond in the c -direction consists of weak electrostatic interactions, which facilitate the insertion of cations and molecules along the a - b plane (i.e., between the layers). K atoms act as structural element to connect the adjacent V-O layers as “pillars” [54]. K pre-intercalated $K_{0.25}V_2O_5$ shows significant lattice expansion and the perpendicular distance from the bottom of unit cell to the top of first layer along c direction is about 7.41 Å, which is much larger than those of V_2O_5 (4.37 Å) [55]. Apparently, larger layer separation can effectively alleviate strain during lithiation/de-lithiation and suppress structural destruction. $K_{0.25}V_2O_5$ also possesses optimized structure compared to other similar 3D tunnel structure such as $Li_{0.3}V_2O_5$ and β - $Na_{0.33}V_2O_5$ [54, 56]. Since the size of K ion (3.04 Å) is larger than Li ion’s (1.80 Å) and Na ion’s (2.32 Å), the stronger “pillars” lead to more stable interlayer structure and prevent the relative slippage of two adjacent V-O layers [43]. In comparison to K450 and K500, K550 exhibits a higher c' value, suggesting larger layer space, which is beneficial for lithium transport and improve the electrochemical kinetic. Moreover, the XRD results showed that the relative strength of (100) diffraction peak of K550 is declining, which is consistent with the SEM results showing decreased size in thickness (a direction) for K550 nanobelts. Since the insertion of Li ions into vanadium oxides-based compounds is along the a - b plane, the reduction in a -direction size of K550 nanobelts is convenient for fast Li-ion insertion inside K550 crystals and improves ion conductivity (**Fig. S1d in ESI†**) [57], which is also evidenced by impedance spectroscopy to be discussed later.

The Raman spectrums of $K_{0.25}V_2O_5$ samples (**Fig. 2d**) and pure V_2O_5 (**Fig. S3 in ESI†**) were conducted. The Raman spectrum recorded for K550 (**Table 2**) exhibits 14 modes located at 115, 147, 220, 260, 320, 408, 444, 501, 551, 699, 776, 870, 940, and 972 cm^{-1} . The phonon modes in

low-frequency region originate from the bond bending vibrations, while the medium- and high-frequency modes are due to the O-V-O and V-O-V bending vibrations and V-O stretching vibrations [44]. In comparison to the Raman spectra of pure V_2O_5 in **Table 2**, there are several spectroscopic changes: the typical translational mode, which is located at 144 cm^{-1} for V_2O_5 and reflects the long range order in the plane of the V_2O_5 sheets [58] is shifted toward 147 cm^{-1} . Several modes in medium-frequency region are also shifted. On the contrary, the V-O stretching mode along the c axis decreases from 994 to 972 cm^{-1} . This shift in frequency means the V-O bonds are weakened by the K atoms intercalation. At the same time, some extra peaks were recorded in the Raman spectrum at 776 to 870 cm^{-1} . This result suggests new K-O chemical bands are formed for $K_{0.25}V_2O_5$. Similar phenomenon was also shown in those of lithiated V_2O_5 and Na pre-intercalated V_2O_5 , like $Na_{0.33}V_2O_5$ [20, 58, 59].

Electrochemical tests were carried out based on half-cell coin batteries using as-prepared products as positive electrodes, metal Li as negative, polypropylene membrane as the separator, and 1M LiPF_6 in ethylene carbonate/dimethyl carbonate (EC/DMC) (1:1 v/v) as the electrolyte. The loading of the $K_{0.25}V_2O_5$ active material was 1-2 mg. **Fig. 3a** shows typical cyclic voltammetry curves in the voltage range of 4.0-1.5 V (vs Li^+/Li). Taking the CV curve of K550 for example, the electrochemical process of electrodes is illustrated. There are mainly six reduction peaks located at 3.68V, 3.48V, 3.22 V, 2.89 V, 2.50 V, and 2.00V, which are ascribed to multi-step lithium intercalation process, and six oxidation peaks at 2.73V, 2.88V, 2.95V, 3.26V, 3.49V, and 3.71V, due to multi-step lithium de-intercalation. Apparently, the K550 electrode has a larger area under the curve and its peak current densities are larger than those of K450 and K500, suggesting K550 has a faster electrochemical reactivity and higher capacity [60]. The high capacity for K550 is

confirmed by the charge/discharge curves of the typical cycle at a current density of 100 mA g⁻¹ (**Fig. S4 in ESI†**). We can see from **Fig. S4** that there are four obvious discharge plateaus at 3.2, 2.9, 2.5, and 1.95 V for K550, which is in good agreement with the CV results and indicates a good reversibility. For the K450 and K500, however, the discharge plateaus are subdued, which corresponds to their weak and broad CV peaks, suggesting a slow electrochemical reactivity. Moreover, K550 electrode exhibits lower charge voltage plateaus and higher discharge voltage plateaus than those of K450 and K500, corresponding to higher specific capacity of K550 electrode. The better electrochemical performance of K550 may be due to the good crystallinity and the ordered aggregated nanobelts that facilitate ion conductivity. The assumption is confirmed by impedance spectroscopy and the measured Li⁺ ion diffusion coefficient (**Table 3 and Fig. 4**). R_s stands for the combination of electrolyte resistance and ohmic resistances of cell components. R_{ct} stands for charge-transfer resistance. R_{ct} of electrochemical reaction for K550 is 73.47Ω, lower than that of K450 (153.1Ω) and K500 (121.6Ω). The Warburg factors σ obeys the relationship $Z_{real} = R_s + R_{ct} + \sigma \omega^{-1/2}$, where ω is angle frequency. The calculated Warburg factors σ shows that K550 possesses higher Li⁺ ion diffusion coefficient. The results demonstrate that the ordered nanobelts arrays and the good crystallinity greatly facilitate the ion diffusion kinetics and reduce the R_{ct} value. **Fig. 3b** shows the cycling performances of K450, K500 and K550 at 500 mA g⁻¹. All electrodes show increasing capacity over long cycles at the beginning. In order to understanding the mechanism of capacity increasing, a series of tests were performed. The ex-situ XRD of K550 electrode after 25 cycles (**Fig. S5 in ESI†**) shows that all diffraction peaks, except for two typical peaks of Al phase, can well be indexed to the monoclinic crystalline K_{0.25}V₂O₅ phase [JCPDS Card No. 39-0889], indicating no phase change during cycling. In fact, like other β-vanadium bronzes

(e.g. $\text{Na}_{0.33}\text{V}_2\text{O}_5$ and $\text{Na}_{0.282}\text{V}_2\text{O}_5$), K ions act as structural element to connect the adjacent V-O layers as “pillars” to maintain the structural stability of $\text{K}_{0.25}\text{V}_2\text{O}_5$ and K ion would not join in the chemical process during lithiation and delithiation [20, 40, 61]. **Fig. S6a (in ESI†)** shows the cycling performances of K550 electrodes at 500 mA g^{-1} following two cycles at low current density. Notably, when electrodes discharged at 50 and 100 mA g^{-1} for the first two cycles, the subsequent cycles at 500 mA g^{-1} showed stable capacity. When the first two cycles were measured at 200 and 300 mA g^{-1} , it showed slightly capacity increasing at 500 mA g^{-1} . There was longer rising trend when measured at 500 mA g^{-1} directly (**Fig. S6a in ESI†**). Thus the activation of materials may lead to the capacity increasing. As electrode was measured at low current density (e.g. 50 mA g^{-1}) for the first two cycles, it is enough time to make material activated adequately. However, high current density would shorten the electrochemical reaction time of per cycle, so it need more cycles for electrode to activate. As the number of cycles increasing, the Li^+ diffusion paths become more and more flexible, and the capacity tends to stable [25]. This was confirmed by the discharged curves (**Fig. S6b in ESI†**) measured directly at 500 mA g^{-1} , which shows that discharge platforms become more and more apparent with the cycles going on. It is worth noting that the capacity for K550 increases much faster than others, further indicating faster electrochemical reactivity and better ion conductivity of K550 electrode. After 200 cycles, even though all three electrodes exhibit excellent cycling stability with no capacity fading, K550 electrode has a higher capacity with a specific capacity of 172 mA h g^{-1} than K450 (143 mA h g^{-1}) and K500 (154 mA h g^{-1}). The above results indicate that the sample calcined at 550°C exhibits the best electrochemical performance and will be studied in detail in the following section.

Fig. 5a shows the cycling performance of K550 electrode at 300 mA g^{-1} . The electrode also

shows the increasing capacity from 150 mA h g⁻¹ to the maximum of 203 mA h g⁻¹ in the 7th cycle, which further supports the fact that the increased capacity is due to the activation process of electrode materials. Interestingly, the capacity of 187 mA h g⁻¹ is maintained after 100 cycles, meaning 92.1% of capacity retention in terms of the maximum. Moreover, around 99% of the coulombic efficiency and the large overlap of the selected charge/discharge curves (**inset Fig. 5a**) indicate good reversibility of the electrode, which is ascribed to its unique morphology as well as its excellent structural stability. A desirable high rate performance (**Fig. 5b**) was obtained for K550 electrode. At various rates of 100, 300, 500, and 1000 mA g⁻¹, the electrode exhibits high discharge capacities of 232, 196, 175, and 133 mA h g⁻¹ in 2nd cycle, respectively. Remarkably, the capacity at 1500 mA g⁻¹ still reached 100 mA h g⁻¹. Even with rapid change of the current density, the electrode exhibits stable capacity at each specific rate, indicating the excellent rate performance of K_{0.25}V₂O₅ electrode. Moreover, after the high-rate measurement, the electrode is able to deliver a high capacity of 221 mA h g⁻¹ at 100 mA g⁻¹ and a retention capacity of 201 mA h g⁻¹ after 70 cycles. High-rate with long-cycle-life performances of K550 electrodes at high current densities of 1, 1.5, and 2 A g⁻¹ are subsequently shown in **Fig. 5c**. All of the specific discharge capacities increased at the beginning of cycles. As can be seen for 1 A g⁻¹, after 50 cycles, the cycling tends to stabilization with a maximum capacity of 137 mA h g⁻¹. Interestingly, the capacity of 120 mA h g⁻¹ is remained over 800 cycles, with no capacity loss compared to the initial discharge capacity and 87.6% of the maximum. Furthermore, when tests were carried out at higher current densities of 1.5 and 2 A g⁻¹, high capacities of 99 and 88 mA h g⁻¹ are achieved after 800 cycles with no capacity loss.

As discussed earlier, vanadate cathode materials have been widely investigated in recent years. K₃V₅O₁₄, KV₃O₈, K₂V₈O₂₁, K_{0.5}V₂O₅, K_{0.25}V₂O₅, etc. have been studied [41, 45]. K-V-O nanowires

reported by Mai et al. exhibit good cycling performance with 76% capacity retention after 900 cycles at 1 A g^{-1} , but has a lower discharge capacity [43]. Furthermore, the cycling performance at higher rates ($>1 \text{ A g}^{-1}$) has not been reported. In addition, our results are much better than most of other metal vanadate cathodes. The cycle life of silver vanadates (*e.g.* $\text{Ag}_2\text{V}_4\text{O}_{11}$, AgVO_3 , $\text{Ag}_{0.33}\text{V}_2\text{O}_5$) [32, 62-64] and copper vanadates (*e.g.* CuV_2O_6 , $\text{Cu}_{2.33}\text{V}_4\text{O}_{11}$, $\text{Cu}_{1.1}\text{V}_4\text{O}_{11}$) [33, 35, 36, 65, 66] for rechargeable lithium batteries is extremely poor. High capacity and rate capability are achieved for LiV_3O_8 and sodium vanadium oxides, but also suffer from limited cycle-life when compared to the aggregated $\text{K}_{0.25}\text{V}_2\text{O}_5$ nanobelts reported in this work studied under similar conditions [21-24, 28, 67]. These results demonstrate that $\text{K}_{0.25}\text{V}_2\text{O}_5$ would be a potential candidate as cathode materials for LIBs.

To further understand the mechanism of structural stability of K550 electrode, the morphologies after different cycles have been investigated. The aggregated nanobelts structure was maintained at 300 mA g^{-1} over 5 and 50 cycles (**Fig. 6**), and even after 300 cycles, the morphology of K550 is still retained. Schematic of K550 electrode during lithiation and de-lithiation is shown in **Fig. S7 in ESI†**. For one thing, orderly nanobelts with large specific surface area shorten the distance of Li-ion diffusion and ensure a plenty of Li^+ ion across the interface [68]; for another thing, the whole structure of ordered aggregated nanobelts stabilize during lithiation/delithiation contributing to super long-cycle-life [47, 48]. In addition, calcination temperature plays a vital role for the excellent performance providing the most suitable crystal structure and leading to desired hierarchical ordered aggregated nanobelts morphology. Moreover, the intrinsic crystal structure with 3D tunnel can prevent inner structure collapse, which enhances the reversibility [20].

4. Conclusions

In summary, we have prepared aggregated $K_{0.25}V_2O_5$ nanobelts with optimal crystalline structure. The formation mechanism of the unique hierarchical architecture was studied. This material exhibits high discharge capacities at high rates and superior long-term cycling performance up to 800 cycles with no capacity loss. Such an excellent cycling performance with high discharge capacity is seldom reported for vanadate materials. The excellent electrochemical performances suggest that $K_{0.25}V_2O_5$ would be a potential candidate for high capacity cathode materials for lithium ion batteries.

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Table 1 The calculated lattice parameters of $K_{0.25}V_2O_5$ compound annealed at 450°C, 500°C and 550°C

$K_{0.25}V_2O_5$	a (Å)	b (Å)	c (Å)	β (deg)	V (Å ³)
K450	10.12	3.62	15.65	109.33	540.18
K500	10.12	3.62	15.64	109.16	540.66
K550	10.12	3.62	15.66	109.25	540.88

Table 2 Raman wavenumbers (cm⁻¹) of K550 with pure V_2O_5 , LiV_2O_5 [59] and $Na_{0.33}V_2O_5$ [20] reported for comparison

Pure V_2O_5	LiV_2O_5 (ref 54)	$Na_{0.33}V_2O_5$ (ref 18)	K550[this work]
		124	115
144		151	147
193	229	223	220
		256,275	260
281	286	288	
300	322	333	320
	350		
406	422	390	408
	440	440	444
479		462	
		516	501
525	530	556	551
	639	657	
693	681	697	699
	722	747	776
	832		870
	957		940
993	975	990	972

Table 3 The EIS simulation parameters and Warburg factor of K450, K500, and K550 electrodes

Samples	R_s	R_{ct}	σ
K450	5.774	153.1	117.16904
K500	1.335	121.6	96.37682
K550	1.67	73.47	61.037

Figures and Captions

Fig. 1 (a) Aggregated $K_{0.25}V_2O_5$ nanobelts obtained at 450°C, 500°C, and 550°C; (b) SEM image, (c) TEM image, and (d) HRTEM image of aggregated $K_{0.25}V_2O_5$ nanobelts obtained at 550°C. Inset in (d): the corresponding SAED pattern.

Fig. 2 (a) TG and DSC results for the as-obtained solids dried at 60°C, (b) XRD patterns for standard K_{0.25}V₂O₅, K450, K500, and K550, (c) Illustration of the crystal structure relationship of K_{0.25}V₂O₅ and (d) Raman spectrums of K450, K500, and K550.

Fig. 3 (a) Typical cyclic voltammetry curves at a scan rate of 0.05 mV s⁻¹, and (b) Cycling performances at 500 mA g⁻¹ of K450, K500, and K550.

Fig. 4 (a) Nyquist plots; and (b) The relationship curves between Z' and $\omega^{-1/2}$ in the low frequency range of K450, K500, and K550 electrodes.

Fig. 5 (a) Cycling performances at 300 mA g^{-1} , inset: the selected charge/discharge profiles, (b) Rate performance, and (c) Long-term cycling performances at high current densities of K550 electrodes.

Fig. 6 The morphology of K550 electrodes after (a and b) 5 cycles, (c and d) 50 cycles, and (e and f) 300 cycles at 300 mA g⁻¹.