High Power High Safety Battery with Electrospun $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ Cathode and $\text{Li}_4\text{Ti}_5\text{O}_{12}$ Anode with 95% Energy Efficiency

Abstract

$\text{Li}_3\text{V}_2(\text{PO}_4)_3$ (LVP) and $\text{Li}_4\text{Ti}_5\text{O}_{12}$ (LTO) were chosen as the cathode and the anode to build a full battery owing to their robust structures. Electrospinning method was adopted to control the electrode materials with the expected microstructures - nanowires that shorten solid state diffusion pathway and enhance the surface area for improving their electrochemical performances. LVP cathode and LTO anode can deliver reversible specific capacities of 108 and 149 mAh/g at a rate of 5 C, respectively. No appreciable degradation can be perceived in both electrodes over 500 cycles. In addition, the relatively high voltage of LTO anode ensures the safe rapid charge and discharge (no dendrite growth) and the minimal or no initial loss of lithium ions as there is no formation of SEI layer. A full battery with LVP cathode and LTO anode delivers a maximum power density of 12,046 W/kg, reaching the strength of supercapacitors, while offers a high energy density of 90 Wh/kg at a power density of 1,350 W/kg with a charging or discharge time of 7 min. This battery demonstrates an energy storage efficiency close to 95 % at a rate of 2 C and maintains > 90 % efficiency at 20 C.

Keywords: $\text{Li}_3\text{V}_2(\text{PO}_4)_3$, $\text{Li}_4\text{Ti}_5\text{O}_{12}$, Energy efficiency, High power, Li ion battery

Introduction

The great advancements have been taking place in the smart portable electronics that make us contact with each other or share information anywhere at any time. At the same time the popularity of electric vehicles has been stimulating to change the approaches on energy harvest and utilization, especially the combustion of fossil fuels induces the globe warming. Both aspects not only reflect the roaring progress of industrial technologies, but also suggest the increasingly public concerns on environment and health. It goes without saying that power sources play a pivotal role in the operations of these electricity-powered devices, and the higher energy density in power sources are required for increasing the lasting mileage or working time. Currently, rechargeable batteries are the main power sources to drive smart electronics or electric vehicles owing to the high energy density of $> 100 \text{ Wh/kg}$ in comparison with another energy storage package, supercapacitors, however, the latter delivers a lower energy density of $\sim 10 \text{ Wh/kg}$ due to ions sorption/desorption mechanism on the surface of materials [1,2]. Batteries rely on the redox reaction in electrode materials accompanying with the working ions insertion/ extraction in crystal lattices and charges poured into / dragged out the $3d$ orbital of cation. Besides, the energy density of batteries is a product of specific capacity and operating voltage, and the specific capacity depends on the number of the reversible working ions and the voltage derives from the difference of electrochemical potentials between cathode and anode [3-5]. Logically, the properties of electrode materials determine the performances of batteries, especially, the cathode materials. Over the past years, great efforts have been devoted to explore reliable materials or modify the properties of the known

materials for coping with the increasingly more challenges in energy storage [6-9]. Unfortunately, there is no cathode with both high specific capacity and electrochemical potential in the current material systems [10,11], albeit the exploration and design of new materials are never ceased. Therefore, choosing and improving the known electrode materials with high-rate capability and stable cyclability is an alternative yet effective approach to save time in the charging process, which satisfies the requirements in practical applications before new high energy density and high power density materials are firmly established.

Lithium cobalt oxide (LiCoO_2 , LCO) is widely used as commercial cathode in Li-ion battery because of its high average potential of ~ 3.7 V and a good specific capacity of ~ 140 mAh/g [12]. However, the toxic and expensive cobalt sources and unstable structure at high-rate process hinder the sustainable development and utilization for high power devices in the future. Lithium iron phosphate (LiFePO_4 , LFP), also a commercial cathode, renders chemical and thermal stability, while the low ion diffusion coefficient ($10^{-14} \sim 10^{-16}$ cm²/s) and electrochemical potential of 3.45 V limit the energy density of batteries [13]. Lithium manganese oxide (LiMn_2O_4 , LMO) presents a high operating potential of 3.8 V, but suffers from the relatively low reversible capacity of 100 mAh/g and the detrimental phase transformation from spinel to cubic [14]. Vanadium pentoxide (V_2O_5) possesses a high theoretical capacity of 443 mAh/g when three Li ions inserted into the crystal lattices, whereas the low working potential and no removable Li ions in pristine lattice restrict the practical

applications at current levels [15,16]. Therefore, amongst the known cathodes, monoclinic lithium vanadium phosphate ($\text{Li}_3\text{V}_2(\text{PO}_4)_3$, LVP) is considered as a promising cathode for Li-ion batteries owing to the high average potential of > 4 V, robust crystal structure, excellent thermal and chemical stability and a three dimensional pathways for ion diffusion [17-19]. In particular, the stable crystal structure and multi-dimensionally ionic channels impart it the excellent cycling stability and high-rate capability. However, the poor electrical conductivity of 2.0×10^{-8} S/cm [20] limits the performance on high-rate operation of LVP electrode.

With respect to anode materials, the categories are abundant on the possibility and can be sorted with three varieties through reactive mechanisms: intercalation, alloying and conversion [21,22]. Graphite, an intercalated anode, plays an irreplaceable role in the currently commercial batteries owing to the high reversible capacity of ~ 300 mAh/g, excellent electrical conductivity of > 50 S/cm and low electrochemical potential that expands the operating voltage of full batteries [23-25]. In practice, the low tap density of ~ 1.0 g/cm³ and limited rate capability inhibit the gravimetric energy density in high-rate full batteries [26,27]. Lithium titanate ($\text{Li}_4\text{Ti}_5\text{O}_{12}$, LTO), the other intercalation compound, works at a high-rate with stable cyclability owing to zero strain in the charge/discharge process, though the electrochemical potential at 1.5 V reduces the working voltage of a full battery [28]. In the alloying category, silicon and tin attract more interests due to the ultrahigh theoretical capacity, such as 4200 mAh/g in $\text{Li}_{22}\text{Si}_5$. Unfortunately, the huge volume expansion induced the cracks of particles

results in a rapid cycling degradation [7]. Among the conversion anodes, oxides, fluorides and nitrides have been studied extensively with a relatively high theoretical capacity ($> 600 \text{ mAh/g}$), but the low coulombic efficiency at the initial cycle, inferior electrical conductivity, and the sloping potential profiles make them with an impossible application in Li-ion batteries [29].

By contrasting the strengths and weaknesses between the known cathodes and anodes mentioned above, LVP and LTO are the reliable electrodes for designing and fabricating high-rate Li-ion full battery. However, LVP and LTO also confront with some challenges, such as poor conductivity in LVP and intrinsically high potential for LTO. Thus, modifications or designs are needed to improve or avoid the drawbacks for extending their practical applications. Modifications of a given material can be divided into three aspects: doping, composites and designing microstructures [17]. Doping can tune the atomic environment and electronic structure of the host in virtue of the unique characters of the foreign atoms [3,30]. Composites integrate the strengths of each component to counteract their weakness, and designing microstructures help expose the preferential facets or shorten the pathways for ions and charges transport to improve the kinetics and energetics in electrochemical reactions [17,31]. Electrospinning approach as one of efficient and reliable method is extensively used in the fabrication of nanostructured electrode materials for the application in energy storage owing to its high feasibility, tunable shape, homogeneous product and mass production with low cost [32-34]. In the present

investigation, LVP and LTO with controlled microstructures were fabricated by means of electrospinning followed with pyrolysis and annealing, and the resulting microstructures shorten the pathways for ions transport, at the same time the porous carbon coating on LVP enhance the electrical conductivity of host materials, which renders the electrode a better rate capability. In addition, a full battery was built on these high-rate LVP cathode and LTO anode and displayed an excellent cycling stability at high rate of 5 C over 500 cycles.

Experimental section

Electrospinning $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ nanowires

The precursor solution was prepared by dissolving 7 wt% oxalic acid in a mixture solvent contained N,N-Dimethylformamide (DMF) and deionized water with a volume ratio of 25/75, and then NH_4VO_3 , $\text{LiOH}\cdot\text{H}_2\text{O}$ and H_3PO_4 were added with a molar ratio of 2:3:3 to form a transparent blue solution after continuously stirred for 2 h at room temperature. Poly(4-vinyl) pyridine (PVP) (Alfa Aesar, $M_w = 1,300,000$) was dissolved into the solution to adjust the viscosity of the precursor solution for guaranteeing the expected nanowires to be obtained. The optimal concentration of PVP in precursor solution was 11 wt%, and the total concentration of NH_4VO_3 , $\text{LiOH}\cdot\text{H}_2\text{O}$ and H_3PO_4 was 6.8 wt%. The electrospinning device mainly consists of a high voltage supplier, a plastic syringe with needle of small diameter and a collector. The precursor solution was poured into a 5 mL plastic syringe with a 24-gauge stainless-steel needle, and subsequently electrospun at a constant flow rate of 0.2

mL/h. The applied high voltage and the distance between the injector nozzle and the collector were 14 kV and 18 cm, respectively. The nanowires composite were presintered at 350 °C (5 °C /min) in air for 4h, and then annealed in argon atmosphere at 700 °C (5 °C /min) with 6 h.

Electrospinning $\text{Li}_4\text{Ti}_5\text{O}_{12}$ nanowires

All chemicals from commercial sources were analytical pure grade and used without further purification. First, ethanol (5.0 g), acetylacetone (0.5 g), and acetic acid (1.6 g) were mixed in a glass bottle and stirred for 10 min to form a homogeneous solution. Then, 1.4218 g of tetrabutyl titanate (98 % purity) and 0.2298 g of lithium acetate (99.9 % purity) were added into the above solution. After stirring for 2 hours, 0.55g of PVP ($M_w = 1,300,000$) was dissolved into the solution. A transparent yellow precursor was formed after followed stirring for 24 h at room temperature. The precursor solution was added into a 10 mL plastic needle tube tipped with a 24-gauge stainless-steel needle at a rate of 0.8 mL/h. The applied high voltage between the injector nozzle and the collector was 15 kV, and the distance was about 7 cm. The nanowires composite were annealed in air atmosphere at 700 °C for 6 h with a heating rate of 5 °C /min.

Morphology and structure characterizations

The phase composition of samples were investigated on a X' Pert3 diffractometer (PANalytical, Netherlands) with a Cu-K α radiation source ($\lambda=1.54056 \text{ \AA}$) at a step

size of 0.013° and time per step of 50 s. The microstructures were observed via a cold field emission scanning electron microscope (FESEM, HITACHI SU8200, Japan) with an accelerating voltage of 5 kV and a beam current of 10 μA . The lattice image of LVP crystals was observed by means of high resolution transmission microscopy (HRTEM, FEI/Tecnai G2 F20 S-TWIN TMP) with an accelerating voltage of 200 kV.

Nitrogen sorption analyses were adopted to measure the specific surface area and the analyzer was Micromeritics surface area and porosity analyzer (ASAP 2020 HD88, USA). All the samples were degassed under vacuum of 500 μmHg (~ 0.67 mbar) at 250°C with 4 h, and all measurements were carried out at liquid nitrogen temperature. Mesopore surface area, pore volume and pore diameter were calculated by Barrett-Joyner-Halenda (BJH) method, whereas the specific surface area and the pore volume of micropores were calculated using t-method. The carbon content in the calcined samples was detected through TGA/DSC instrument (Mettler-Toledo STAR^c system) with a flowing oxygen of 50 mL/min, and the electrical conductivity of samples was investigated via a direct current (DC) four-probe technique (ST-2722, Suzhou) under a pressure of 4 MPa.

Batteries fabrication and electrochemical measurements

The electrochemical performances of all samples were investigated using 2032 coin cells. To prepare the working electrode, the slurry contained a mixture of active materials (LVP or LTO), carbon black and carboxymethyl cellulose (CMC) at a weight ratio of 7:2:1 was bladed on an current collector metal foil (LVP on Al foil and

LTO on Cu foil) and then subjected to thermal treatment at 120 °C with 12 h in a vacuum oven. The prepared electrode films were punched to circular disks with a diameter of 8 mm, and the mass loading of active material was 1.0-1.5 mg/cm² on each disk. 80 μL of an organic electrolyte (1 M LiPF₆ in a mixture of ethylene carbonate, dimethyl carbonate and diethyl carbonate, LBC305-01, CAPCHEM, China) was injected in each cell, and a polypropylene film (Celgard 2400) was used as the separator. The lithium foil was used as the counter electrode in half cells for investigating the electrochemical properties of electrode materials. Full batteries, LVP cathode and LTO anode, were also assembled with the same separator and electrolyte, and the amount of electrolyte was also 80 μL. All cells were assembled in an argon-filled glovebox in which both the content of oxygen and water are below 1 ppm.

Galvanostatic charge-discharge tests of all cells were carried out on a Land CT2001A system (Wuhan, China) with various current densities. The operating voltage windows for LVP, LTO half cells and LTO//LVP full batteries are 3.0-4.3 V (vs. Li/Li⁺), 1.0-2.0 V (vs. Li/Li⁺) and 1.5-2.8 V (LTO//LVP), respectively. Cyclic voltammograms (CVs) were conducted on a Solartron SI 1287 at the various scanning rates for characterizing the redox reaction and analyzing ions diffusion of electrode materials in the process of charge/discharge. The current densities applied to the half cells were calculated on the mass of active materials of electrodes and full batteries were determined based on the mass of LVP cathodes. All electrochemical measurements were carried out at room

temperature.

Results and discussion

Characterizations and measurements on LVP cathode

The phase composition of calcined sample was detected via an X-ray diffractometer at a step size of 0.026° , and the resulting pattern agrees very well with the standard peaks of LVP (space group P1 21/c 1, JCPDS No.96-223-7424) as shown in [Figure 1a](#). The inset of [Figure 1a](#) presents the crystal structure of LVP, VO_6 octahedrons alternately connect with PO_4 tetrahedrons through sharing their corners, which obstructs electrons jump between vanadium ions and leads to the inferior electrical conductivity of 2.0×10^{-8} S/cm [20]. SEM image ([Figure 1b](#)) shows the resulting sample with conformal nanowires and the diameter of the nanowires approximates to 300 nm, demonstrating that the strong electric field help the repulsive electrostatic forces overcome the surface tension of a droplet of precursor solution to form a wire-like product [35]. As described in the experimental section, the precursor solution contained an amount of organic solvents that is inevitable to introduce carbon in the final sample. Energy dispersive X-ray spectroscopy (EDS) was used to collect the elements distribution in the sample, and the mapping plots ([Figure S1](#)) reveal a homogeneously elemental distribution. In particular, carbon was also detected with an expected distribution that suggests the organic additives in synthesis process was remained partially and provided a continuous conductive network. [HRTEM image](#)

(Figure S2) acquired at the edge of the sample shows that LVP particle is coated with a conformal carbon layer of ~5 nm in thickness and the corresponding lattice fringes with inter-planar spacing of 4.93 and 4.05 Å are in accord with the planar distances of (01 $\bar{2}$) and (02 $\bar{1}$) in LVP, respectively. Furthermore, the result from TG/DTA curves presented in Figure 1c corroborates with the above observation and displays a carbon content of 2.73 wt%. The water evaporation leads to an initial weight drop of 0.45 wt% around 100 °C and a distinct exothermal peak at 400 °C is in accord with the carbon combustion. However, a weight gain can be observed at 425 °C and the weight curve holds a stable state, implying that V(III) was oxidized to a high chemical valence state and a phase transition was induced in this process [36]. The XRD pattern in Figure S3 supports the explanation corresponding to the phase transition of LVP in the measurement with a flowing oxygen gas. The measured carbon content verifies that the organic solvents confined partially among electrospun particles and decomposed in the following heating treatment. DC four probe technique was adopted to measure the electrical conductivity and the value reaches 1.2×10^{-2} S/cm that is 6 orders of magnitude higher than that of the pristine LVP [20]. Assuming that a nanowire with a diameter of 300 nm and a length of 10,000 nm, the surface area can be calculated and the value closes to 4.45 m²/g, where the density of 3.03 g/cm³ for LVP was used to the calculation (Details of the calculation is given in the supporting information).

Nitrogen sorption curves (Figure 1d) were tested for analyzing the surface area of the calcined sample and the hysteresis loop between adsorption and desorption curves presents the electrospun nanowires with the porous structures owing to the total

surface area and pore volume are 20.18 m²/g and 0.012 cm³/g, respectively. The specific area is lower than the others' reports because the high specific surface area is often due to the highly porous carbon coating [37,38], whereas the carbon content of 2.73 wt% in present work is lower than the value of >10 wt% in the reported [38,39].

The considerable surface area increase the contact between electrode material and electrolyte, and the pores in the nanowires play a role in reserving electrolyte to facilitate the electrochemical reaction during the charge/discharge process. More importantly, the huge enhancement in electrical conductivity guarantees electrons transport that is a limiting factor in the pristine LVP.

Figure 1. (a) XRD pattern of the calcined LVP, the characteristic peaks are accord with the standard positions. (b) SEM photograph of LVP nanowires. (c) TG/DTA curves of LVP nanowires measured with a flowing oxygen. (d) Nitrogen sorption curves of LVP samples. (e) CV curves of LVP electrode at various scanning rate. (f) The relationship between peak currents and square root of scanning rate. (g) Rate capability and (f) Cycling performance of LVP electrode in Li-ion half cells.

Figure 1e exhibits the CV curves measured at various scanning rates from 0.1 mV/s to 0.8 mV/s. Three couples of redox peaks were detected and those correspond to the phase transitions during different steps of Li-ion insertion or extraction. Peaks α and β correlate with the first Li-ion extraction and peak γ relates to the second Li-ion extraction, and the difference among site energy of Li-ion positions leads to the difference of peak positions in CV curves or discharge potentials in the discharging potential profiles [17]. Besides, the separations between redox peaks of α - α' , β - β' and γ - γ' are 0.04, 0.05 and 0.06 V, respectively (Table 1), at a scanning rate of 0.1 mV/s. These small separations suggest an excellent reversibility in the LVP nanowires. With the increase of scanning rates, the peaks positions shift towards higher and lower potentials in anodic and cathodic processes, respectively. These shifts derive from the electrochemical polarization as widely reported [40]. In order to evaluate the ion diffusion in the LVP electrode, the relationship between peaks current (I_p) and the square root of the scan rate ($v^{1/2}$) was plotted in Figure 1f, and the linear fitting among the same group points implies the diffusion-controlled process in the electrochemical reactions. Randles-Sevcik equation stemmed from semi-infinite diffusion processes can be used to calculate Li-ion diffusion coefficients in each reduction/oxidation step [41],

$$I_p = 0.4463 \left(\frac{F^3}{RT} \right)^{1/2} n^{3/2} A D^{1/2} C_0 v^{1/2} \quad (1)$$

$$\Rightarrow \text{Slope} = I_p / v^{1/2} = 0.4463 \left(\frac{F^3}{RT} \right)^{1/2} n^{3/2} A D^{1/2} C_0 \quad (2)$$

$$\Rightarrow D = \left(\frac{\text{Slope}}{0.4463 \left(\frac{F^3}{RT} \right)^{1/2} n^{3/2} A C_0} \right)^2 \quad (3)$$

where I_p is the peak current (A), R (8.314 J/mol·K) is the gas constant, T (298 K) is

the absolute temperature, F (96500 C/mol) is the Faraday constant, n (2) is the number of electrons transferred per molecule, A (0.50 cm^2) is the active surface area of the electrode, C_0 ($3.687 \times 10^{-3} \text{ mol cm}^{-3}$) is the concentration of removable Li-ion in LVP lattice, D is the apparent ion diffusion coefficient (cm^2/s), and v is the scanning rate (V/s). From the slope of the fitting line collected from anodic/cathodic peak current (I_p) (Figure 1f), Li-ion diffusion coefficients (D) of anodic peaks (α , β and γ) are 7.60×10^{-10} , 9.05×10^{-10} and $2.76 \times 10^{-9} \text{ cm}^2/\text{s}$, respectively. While the diffusion coefficients in cathodic peaks of (α' , β' and γ') are 5.40×10^{-10} , 9.18×10^{-10} and $1.83 \times 10^{-9} \text{ cm}^2/\text{s}$, respectively (Table 1). These results close to the reported LVP/C composite [42] or are higher than those of pristine LVP [43]. There are remarkable differences between these coefficients in different anodic or cathodic peaks, which derive from the differences of the occupying positions for Li-ion in LVP lattice. Three occupying positions distribute in crystal structure and each site displays a unique site energy that determines the ordering of Li-ion insertion/extraction and the electrochemical potentials. Li-ion at the highest energy site will be extracted at the initial of charging process, but the electrostatic interactions between anionic and cationic ions limit the Li-ion diffusion in the whole crystal lattice. However, if Li-ion at higher energy sites is removed, the limitations will decrease or counteract for the following extraction. In reverse, the lowest energy sites prefer to occupy in the discharging process and all Li-ion channels are feasible with the weak limitation from the surrounding atoms, which lead to the fast ion migration. Besides, the largest energy difference exhibits the highest electrochemical potential when Li-ion inserts

the lowest energy sites. Figure 1 g shows the rate capability of LVP cathode in a half cell in which metal lithium was used as counter electrode. LVP cathode delivers specific capacities of 116.3, 112.1, 108.3, 106.8, 105.1, 92.2 and 50.2 mAh/g at rate of 0.5 C, 1 C, 2 C, 5 C, 10 C, 20 C and 50 C, respectively. The specific capacity retains 116.1 mAh/g when the rate turns back to 0.5 C, implying the LVP cathode with an excellent rate capability. In particular, specific capacity decreases slightly with the increase of the rate. The results have the competitive strength in comparison with reported LVP, such as 83.7 mAh/g at 0.3 C in pristine LVP [44] or 70 mAh/g at 20 C in LVP/C composite [45]. More importantly, the LVP nanowires cathode was cycled at 5 C and no appreciable degradation can be observed after 400 cycles as shown in Figure 1h. The charging or discharging time closes to 10 min, implying that the LVP cathode can store or deliver a specific capacity of 108 mAh/g within a short time. This highlight is important and useful for saving users' time and raising working efficiency in practice.

Table 1. Peaks gaps and Li ion diffusion coefficient from CV curves

Peaks	Peaks gaps (V)	Li ion diffusion coefficient (cm ² /s)
α/α'	0.04	$7.60 \times 10^{-10}/5.40 \times 10^{-10}$
β/β'	0.05	$9.05 \times 10^{-10}/9.18 \times 10^{-10}$
γ/γ'	0.06	$2.76 \times 10^{-9}/1.83 \times 10^{-9}$

Characterizations and measurements on LTO anode

The anode was also prepared through electrospinning method, and Figure 2a verifies the resulting product with a spinel structure and phase composition agrees with the

characteristics of $\text{Li}_4\text{Ti}_5\text{O}_{12}$. The inset shows the crystal lattice of LTO and all octahedrons connect each other through sharing edges and corners to build a robust three-dimensional framework. The calcined sample consists of nanowires with a broad distribution in diameter as displayed in SEM photograph (Figure 2b). The broad distribution in size of nanowires benefits to increase the tap density owing to the complementarity facilitates to fill the space between nanowires. In addition, the result from nitrogen sorption curves (Figure S4) displays LTO nanowires with a specific surface area of $6.65 \text{ m}^2/\text{g}$. Assuming that nanowires are cylinder with the diameter of 500 nm and length of 10,000 nm, it can be calculated that the nanowires with a specific surface area of $2.30 \text{ m}^2/\text{g}$ (Details of the calculation is given in the supporting information). The difference between measurement and calculation suggests LTO nanowires possessing a porous microstructure. It is understandable the formation of pores in LTO nanowires because the organic additives could be decomposed completed in the calcinations and resulted in the space voids. The enhanced surface area provides more sites for fast ion diffusion that helps improve the kinetic of electrode reaction. CV curves were collected with various scanning rate for demonstrating the kinetics of LTO electrode. The anodic peaks shift towards the higher potential and the cathodic peaks move to lower potential with the increase of the scanning rate (Figure 2c). Electrochemical polarization leads to these shifts as mentioned in LVP electrode above. Figure 2d exhibits the relationship between peak currents and the square root of scanning rate collected from Figure 2c. The fitted line (Figure 2d) reveals that the solid state diffusion limits the electrochemical reaction in

LTO electrode. Li-ion diffusion coefficient can also be calculated by equation 3, and the values are 6.33×10^{-10} and 4.25×10^{-10} cm^2/s for anodic and cathodic reactions, respectively. These results are one order magnitude higher than the value of 3.2×10^{-11} cm^2/s in other reports [46]. [Figure 2e](#) exhibits the rate performance of LTO electrode that delivers specific capacities of 160.0, 155.5, 149.2, 141.3, 129.8 112.7 and 80.1 mAh/g at the rate of 0.5 C, 1 C, 2 C, 5 C, 10 C, 20 C and 50 C, respectively. It reveals the LTO electrode with an excellent rate capability that displays competitive strength in comparison with the hollow LTO of 104 mAh/g at 20 C [47]. More importantly, the specific capacity returns to 156.2 mAh/g when the current rate is reduced back to 0.5 C, which suggests LTO anode with a good reversibility. The long-term cycling performance of the LTO nanowires and corresponding Coulombic efficiency at a rate of 5 C are presented in [Figure 2f](#). The initial specific capacity reaches 149.4 mAh/g and retains 139.6 mA/h/g after 500 cycles. The degradation rate is 0.013 % per cycle, implying a superior cycling stability in LTO nanowire electrode. In addition, the voltage-time curves are shown in the inset of [Figure 2f](#), and the charging or discharge time approximates to 10 min that demonstrates a short time exhausted on energy storage.

Figure 2. (a) XRD pattern of LTO. (b) SEM photograph of LTO nanowires. (c) CV curves at various scanning rate. (d) The relationship between peak currents and square root of the scanning rate. (e) Rate capability and (f) Cycling performance of LTO nanowires in Li-ion half cells.

Performances of full battery

Discussion on performances of LVP cathode and LTO anode suggest that the stable cyclability in the long term and excellent rate capability render both electrodes to fabricate a high rate full battery for satisfying the demands in practice. Meanwhile, building the full battery helps understand the scientific basics in comparison with a half cell. [Figure 3a](#) illustrates the configuration of full battery and the underlying

applications. In this tentative work, LTO electrode with Cu collector and LVP electrode with Al collector are separated with a Celgard polymer film and immersed into organic electrolyte. All the components are sealed into a stainless steel coin case as the fabrication of commercial products. In general, LTO anode presents a potential plateau at 1.5 V *vs.* Li/Li⁺, and LVP cathode displays a step discharge curve between 3.0-4.3 V *vs.* Li/Li⁺. On the basis of electrochemistry, the working voltage of full battery should lie in the range of 0-2.8 V, and the CV curves support the speculation (Figure 3b). The redox couple located at 1.5 V *vs.* Li/Li⁺ reveals the electrochemical reaction of LTO in the process of energy storage, and three couples appear between 3.3 and 4.3 V *vs.* Li/Li⁺ agree with the phase transition of LVP during the period of Li-ion insertion or extraction. It is worth noting that these CV curves measured in the half cells in which lithium metal were used as counter electrodes. However, the CV curve exhibited in the range of 1.5-2.8 V was collected from the LVP//LTO full battery. The complete redox couples disclose the electrochemical reaction in the full battery corresponding to the characteristics of cathode. Although the measurements were conducted on the range of 0.01-2.8 V, the redox couples are also the characters of LVP cathode as shown in Figure S5. However, it does not imply no reactions occurred in LTO anode. In a full battery, the reactions in both electrodes occur simultaneously, for example, Li-ion extracts from LVP cathode and inserts into the lattice of LTO anode during the charging process. The electrochemical reaction can be described as [48,49] :

Lithium metal was replaced by LTO in LVP full battery in comparison with a half cell so that the reference line is changed and the characteristic of cathode stands for that of full battery. Based on the results of CV measurements, the working voltage range was set at 1.5-2.8 V for testing the performance of full battery. However, a small difference also can be observed in CV curves, such as, the peak at the lowest voltage of 2.0 V in full battery presents a weaker current density than that of the corresponding peak at 3.5 V in half cell (Figure 3b), indicating a reactive difference between two sorts of electrochemical devices. Although the exact explanation requires further study, it is possible that the difference stems from the reactive condition and extent of reaction in cathode. In the half cell, LVP worked with lithium metal as a counter electrode, whereas it operated with LTO anode in the full battery. Lithium metal can provide sufficient Li source to ensure the complete reaction throughout the entire voltage window, but Li-ion in LTO could be extracted at certain voltage and might not be able to provide the needed lithium source to complete the reaction of LVP at the lowest potential leading to a weak current density. In addition, the kinetics of lithium ion release from lithium metal foil would be rather different from that from LTO. Figure 3c shows the rate capability of LTO//LVP full battery in which the mass ratio between cathode and anode was set at 1: 1 that implies an excessive capacity in anode for guaranteeing LVP cathode with a completely electrochemical reaction. The full battery can deliver specific capacities of 93 and 47 mAh/g at the rate of 1 C and 100 C, respectively. At the same time, the specific

capacity retains 90 mAh/g when the rate was reduced to 1 C, showing an excellent reversibility of full battery as LVP and LTO in half cells. The charge and discharge curves (Figure 3d) present the voltage profiles of full battery at different rates. The voltage difference between the discharge and charge plateaus of 2.5 V is 0.02 V at a rate of 1 C, indicating a small overpotential and good reversibility in the electrochemical reaction. With the increase of the rates, the voltage plateaus disappear and the reversible capacities decrease, which are induced by the electrochemical polarization and sluggish kinetics as observed in half cells. However, the full battery still delivers a reversible capacity of 47 mAh/g within 13 s at 100 C without safety issue, demonstrating the excellent stability of both electrodes. It is worth noting that the specific capacities of full battery are lower than those of LVP cathode in half cell, though the mass of LTO anode was sufficiently provided in the full battery. This difference possibly stems from the extent of reaction of LVP cathode in both devices as verified and discussed in the CV curves (Figure 3b). Figure 3e shows the cycling performance of full battery at a rate of 5 C and the charging or discharging time closes to 8 min. Remarkably, the delivered specific capacity of LVP approximates to 75 mAh/g that is lower than the value of 115 mAh/g in the half cell (Figure 1h), suggesting that the fabrication of full battery are complex and how to maximize the utilization of electrode materials should be further investigated. Inset of Figure 3e exhibits the voltage-time curves of full battery, which agree with CV results. Remarkably, the voltage profiles are in accord with those of LVP cathode, but locate at the different voltage range. It is no doubt that the voltage profiles of the full battery

derive from the coupling effect between potential profiles of the anode and cathode. Combining the specific capacity, working voltage with discharge time, we calculate and draw the Ragone plot that present the relationship between energy and power densities of full battery (Figure 3f). Here, energy and power densities are calculated with the following equations [4,5],

$$E = \int_0^{\Delta t} IU(t)dt = \int_0^C U(c)dc \approx UC \quad (6)$$

$$P = E/t \quad (7)$$

Where I is discharge current (A), U is discharge voltage (V), C is the total charge per unit weight (Ah/kg), and t is discharge time (h). LTO//LVP full battery delivers maximum energy and power density of 103 Wh/kg and 12,046 W/kg, respectively. The maximum energy density is lower than the commercial LiCoO₂//graphite battery owing to the latter displays a higher operating voltage of 3.7 V [17]. However, the surprising power density can compete with supercapacitors because the complete discharge was finished within several seconds. For example, MnO₂//CNT aqueous supercapacitor exhibits the high power density, but a low energy density due to the lower operating voltage [50]. Although organic electrolyte can wide the working voltage window and increase the energy density of devices, the limited kinetics of oxides electrodes hinder the power density with an expected value [51]. A Na-ion hybrid capacitor built on robust Na₃V₂(PO₄)₃ (NVP) anode and activated carbon cathode delivers a competitive energy density, but the power density still is limited [52]. By contrasting the strengths of various energy storage devices, LTO//LVP full battery demonstrates the best performances as the integration of secondary battery and

supercapacitor [53,54]. In addition, the energy conversion efficiency is defined and evaluated through the following equation [4],

$$\eta = \frac{E_{\text{output}}}{E_{\text{input}}} = \frac{\int_0^{C_{\text{dis}}} U_{\text{dis}}(c)dc}{\int_0^{C_{\text{cha}}} U_{\text{cha}}(c)dc} \approx \frac{U_{\text{discharge}} \times C_{\text{discharge}}}{U_{\text{charge}} \times C_{\text{charge}}} \quad (8)$$

where E, U and C stand for energy density, midpoint voltage and specific capacity, respectively. The calculated values are listed in Table 2, and suggest a full battery with very high energy conversion efficiency though varies with charge and discharge rates.

It is worth noting that the maximum efficiency was not obtained at the lowest or highest rates. The reason attributes to overpotential (or voltage hysteresis) that results in more energy exhausted in the charge process but little energy release in the discharge process [3]. Overpotential is induced by the energy difference between particles, including ions and electrons, extraction and insertion from/in crystal lattice and 3d orbitals of cations [55]. Besides, internal resistance also exhausted energy in both processes [4].

Figure S6 shows the EIS spectrum of the full battery after activation with charge-discharge 5 cycles at a rate of 1 C. The intercept of Z'-axis stands for the internal resistance from the electrolyte and cell case and the resistance value closes to 2.5 Ω that easily induces the overpotential.

A very high energy conversion efficiency of close to 95 % was achieved at a rate of 2 C and the battery retains >90 % energy conversion efficiency at 20 C. The long-term cycling measurements at 5 C demonstrate LTO//LVP full battery with an excellent stability and reliable safety that originate from the chemical and thermal stability of LVP and zero-strain in LTO during the charge/discharge process. The great strengths in LVP//LTO full battery make it a promising and reliable power sources to drive electric

vehicles and smart electronics or store intermittent energy from renewable sources in the future market.

Figure 3. (a) Schematic of full battery with LVP cathode and LTO anode. (b) CV curves of LTO anode, LVP cathode and LTO/LVP full battery. (c) Rate capability and (d) Voltage curves profiles at different rates. (e) Cycling stability of a LTO/LVP full battery. (f) Ragone plot of LTO/LVP full battery with other reported energy storage devices, such as MnO_2 //CNT aqueous supercapacitor [50], NVP//AC sodium ion capacitor [52], Mn_3O_4 @AC//AC [51] and CMK//HTO [56] Li ion capacitors.

Table 2. Energy conversion efficiency and discharge time of LTO/LVP full battery

Rate	1C	2C	5C	10C	20C	50C	100C
Energy conversion efficiency (%)	93.4	94.6	93.8	92.6	90.6	86.0	78.5

Conclusions

Monoclinic lithium vanadium phosphate and spinel lithium titanate nanowires were prepared through electrospinning method. The controlled microstructures shorten ion diffusion pathway, and the enhanced surface area improves the kinetics of electrode materials and increases the ion diffusion coefficients in both electrodes. At the same time, combining the intrinsically stable crystal structures of both materials, a full battery was designed and fabricated on nanowires electrode materials, and delivered an energy density of 90 Wh/kg at a power density of 1,350 W/kg with a short charging or discharging time of 7 min. Besides, the full battery was cycled at this high rate without an appreciable degradation over 500 cycles. The maximum power density reached 12,046 W/kg that compete with supercapacitors. On the battery also demonstrated very high energy conversion efficiency (~95% at 2 C and > 90% at 20 C). The strengths bring a bright future for LTO//LVP battery as power source to drive smart portable devices and electric vehicles in commercial market.

References

- [1] M.S. Whittingham. Materials challenges facing electrical energy storage. MRS Bulletin 33 (2008) 411-419.
- [2] Y. Gogotsi, P. Simon. True Performance Metrics in Electrochemical Energy Storage. Science 334 (2011) 917-918.
- [3] C. Liu, Z.G. Neale, G. Cao. Understanding electrochemical potentials of cathode materials in rechargeable batteries. Mater. Today 19 (2016) 109-123.
- [4] J.B. Goodenough, K. S. Park. The Li-Ion Rechargeable Battery: A Perspective. J. Am. Chem. Soc. 135 (2013) 1167-1176.
- [5] J.B. Goodenough. Energy storage materials: A perspective. Energy Storage Materials 1 (2015) 158-161.
- [6] R. Massé, E. Uchaker, G. Cao. Beyond Li-ion: electrode materials for sodium- and

magnesium-ion batteries. *Sci. China Mater.* 58 (2015) 715-766.

[7] M. Zhang, T. Zhang, Y. Ma, Y. Chen. Latest development of nanostructured Si/C materials for lithium anode studies and applications. *Energy Storage Materials* 4 (2016) 1-14.

[8] Z. Lu, X. Wu, M. Jiang, J. Wang, J. Liu, X. Lei, X. Sun. Transition metal oxides/hydroxides nanoarrays for aqueous electrochemical energy storage systems. *Sci. China Mater.* 57 (2014) 59-69.

[9] W. Lv, Z. Li, Y. Deng, Q.H. Yang, F. Kang. Graphene-based materials for electrochemical energy storage devices: Opportunities and challenges. *Energy Storage Materials* 2 (2016) 107-138.

[10] B.L. Ellis, K.T. Lee, L.F. Nazar. Positive Electrode Materials for Li-Ion and Li-Batteries. *Chem. Mater.* 22 (2010) 691-714.

[11] M.S. Whittingham. Ultimate limits to intercalation reactions for lithium batteries. *Chem. Rev.* 114 (2014) 11414-11443.

[12] E. Antolini. LiCoO₂: formation, structure, lithium and oxygen nonstoichiometry, electrochemical behaviour and transport properties. *Solid State Ion.* 170 (2004) 159-171.

[13] J. Wang, X. Sun. Understanding and recent development of carbon coating on LiFePO₄ cathode materials for lithium-ion batteries. *Energy Environ. Sci.* 5 (2012) 5163-5185.

[14] R. Koksang, J. Barker, H. Shi, M.Y. Saïdi. Cathode materials for lithium rocking chair batteries. *Solid State Ion.* 84 (1996) 1-21.

[15] Q. Liu, Z.F. Li, Y. Liu, H. Zhang, Y. Ren, C.J. Sun, W. Lu, Y. Zhou, L. Stanciu, E.A. Stach, J. Xie. Graphene-modified nanostructured vanadium pentoxide hybrids with extraordinary electrochemical performance for Li-ion batteries. *Nat. Commun.* 6 (2015) 6127.

[16] C. Delmas, H. Cognac-Auradou, J.M. Cocciantelli, M. Ménétrier, J.P. Doumerc. The Li_xV₂O₅ system: An overview of the structure modifications induced by the lithium intercalation. *Solid State Ion.* 69 (1994) 257-264.

[17] C. Liu, R. Massé, X. Nan, G. Cao. A promising cathode for Li-ion batteries: Li₃V₂(PO₄)₃. *Energy Storage Materials* 4 (2016) 15-58.

[18] Y.Q. Qiao, X.L. Wang, Y.J. Mai, J.Y. Xiang, D. Zhang, C.D. Gu, J.P. Tu. Synthesis of plate-like Li₃V₂(PO₄)₃/C as a cathode material for Li-ion batteries. *J. Power Sources* 196 (2011) 8706-8709.

[19] L.L. Zhang, G. Liang, G. Peng, F. Zou, Y.H. Huang, M.C. Croft, A. Ignatov. Significantly Improved Electrochemical Performance in Li₃V₂(PO₄)₃/C Promoted by SiO₂ Coating for Lithium-Ion Batteries. *J Phys Chem C* 116 (2012) 12401-12408.

[20] S.C. Yin, H. Grondy, P. Strobel, M. Anne, L.F. Nazar. Electrochemical property: Structure relationships in monoclinic Li_{3-y}V₂(PO₄)₃. *J. Am. Chem. Soc.* 125 (2003) 10402-10411.

[21] M.R. Palacin. Recent advances in rechargeable battery materials: a chemist's perspective. *Chem. Soc. Rev.* 38 (2009) 2565-2575.

[22] H.D. Yoo, E. Markevich, G. Salitra, D. Sharon, D. Aurbach. On the challenge of developing advanced technologies for electrochemical energy storage and conversion. *Mater. Today* 17 (2014) 110-121.

[23] N. Deprez, D.S. McLachlan. The analysis of the electrical conductivity of graphite conductivity of graphite powders during compaction. *J. Phys. D* 21 (1988) 101.

[24] S. Goriparti, E. Miele, F. De Angelis, E. Di Fabrizio, R. Proietti Zaccaria, C. Capiglia. Review on recent progress of nanostructured anode materials for Li-ion batteries. *J. Power Sources* 257 (2014) 421-443.

[25] J.R. Owen. Rechargeable lithium batteries. *Chem. Soc. Rev.* 26 (1997) 259-267.

- [26] <http://www.canadacarbon.com/tapped-skeletal-density>.
- [27] J.K. Park: *Principles and Applications of Lithium Secondary Batteries*; Wiley-VCH Germany, 2012. pp. 22-26.
- [28] T.F. Yi, S.Y. Yang, Y. Xie. Recent advances of $\text{Li}_4\text{Ti}_5\text{O}_{12}$ as a promising next generation anode material for high power lithium-ion batteries. *J. Mater. Chem.A* 3 (2015) 5750-5777.
- [29] J. Cabana, L. Monconduit, D. Larcher, M.R. Palacín. Beyond Intercalation-Based Li-Ion Batteries: The State of the Art and Challenges of Electrode Materials Reacting Through Conversion Reactions. *Adv. Mater.* 22 (2010) E170-E192.
- [30] E. Uchaker, G. Cao. The Role of Intentionally Introduced Defects on Electrode Materials for Alkali-Ion Batteries. *Chem.Asian J.* 10 (2015) 1608-1617.
- [31] Y.G. Guo, J.S. Hu, L.J. Wan. Nanostructured Materials for Electrochemical Energy Conversion and Storage Devices. *Adv. Mater.* 20 (2008) 2878-2887.
- [32] J.W. Jung, C.L. Lee, S. Yu, I.D. Kim. Electrospun nanofibers as a platform for advanced secondary batteries: a comprehensive review. *J. Mater. Chem.A* 4 (2016) 703-750.
- [33] B. Zhang, F. Kang, J.M. Tarascon, J.K. Kim. Recent advances in electrospun carbon nanofibers and their application in electrochemical energy storage. *Prog. Mater. Sci.* 76 (2016) 319-380.
- [34] W. Li, L. Zeng, Y. Wu, Y. Yu. Nanostructured electrode materials for lithium-ion and sodium-ion batteries via electrospinning. *Sci. China Mater.* 59 (2016) 287-321.
- [35] H.G. Wang, S. Yuan, D.L. Ma, X. B. Zhang, J.M. Yan. Electrospun materials for lithium and sodium rechargeable batteries: from structure evolution to electrochemical performance. *Energy Environ. Sci.* 8 (2015) 1660-1681.
- [36] X. Nan, C. Zhang, C. Liu, M. Liu, Z.L. Wang, G. Cao. Highly Efficient Storage of Pulse Energy Produced by Triboelectric Nanogenerator in $\text{Li}_3\text{V}_2(\text{PO}_4)_3/\text{C}$ Cathode Li-Ion Batteries. *ACS Appl. Mater. Inter.* 8 (2016) 862-870.
- [37] L.F. Shen, H.S. Li, E. Uchaker, X.G. Zhang, G.Z. Cao. General Strategy for Designing Core-Shell Nanostructured Materials for High-Power Lithium Ion Batteries. *Nano Lett.* 12 (2012) 5673-5678.
- [38] C. Liu, C. Zhang, H. Song, X. Nan, H. Fu, G. Cao. MnO nanoparticles with cationic vacancies and discrepant crystallinity dispersed into porous carbon for Li-ion capacitors. *J. Mater. Chem.A* 4 (2016) 3362-3370.
- [39] L. Chen, B. Yan, J. Xu, C. Wang, Y. Chao, X. Jiang, G. Yang. Bicontinuous Structure of $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ Clustered via Carbon Nanofiber as High-Performance Cathode Material of Li-Ion Batteries. *ACS Appl. Mater. Inter.* 7 (2015) 13934-13943.
- [40] S. Liang, X. Cao, Y. Wang, Y. Hu, A. Pan, G. Cao. Uniform $8\text{LiFePO}_4 \cdot \text{Li}_3\text{V}_2(\text{PO}_4)_3/\text{C}$ nanoflakes for high-performance Li-ion batteries. *Nano Energy* 22 (2016) 48-58.
- [41] A.J. Bard, L.R. Faulkner: *Electrochemical Methods: Fundamentals and Applications, 2nd Edition*; Wiley-VCH, 2001. pp. 236.
- [42] J.T. Xu, S.L. Chou, C.F. Zhou, Q.F. Gu, H.K. Liu, S.X. Dou. Three-dimensional-network $\text{Li}_3\text{V}_2(\text{PO}_4)_3/\text{C}$ composite as high rate lithium ion battery cathode material and its compatibility with ionic liquid electrolytes. *J. Power Sources* 246 (2014) 124-131.
- [43] X.H. Rui, N. Ding, J. Liu, C. Li, C.H. Chen. Analysis of the chemical diffusion coefficient of lithium ions in $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ cathode material. *Electrochim. Acta* 55 (2010) 2384-2390.
- [44] J.W. Wang, X.F. Zhang, J. Liu, G.L. Yang, Y.C. Ge, Z.J. Yu, R.S. Wang, X.M. Pan.

Long-term cyclability and high-rate capability of $\text{Li}_3\text{V}_2(\text{PO}_4)_3/\text{C}$ cathode material using PVA as carbon source. *Electrochim. Acta* 55 (2010) 6879-6884.

[45] X.H. Rui, D.H. Sim, K.M. Wong, J.X. Zhu, W.L. Liu, C. Xu, H.T. Tan, N. Xiao, H.H. Hng, T.M. Lim, Q.Y. Yan. $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ nanocrystals embedded in a nanoporous carbon matrix supported on reduced graphene oxide sheets: Binder-free and high rate cathode material for lithium-ion batteries. *J. Power Sources* 214 (2012) 171-177.

[46] J. Sugiyama, H. Nozaki, I. Umegaki, K. Mukai, K. Miwa, S. Shiraki, T. Hitosugi, A. Suter, T. Prokscha, Z. Salman, J.S. Lord, M. Mansson. Li-ion diffusion in $\text{Li}_4\text{Ti}_5\text{O}_{12}$ and LiTi_2O_4 battery materials detected by muon spin spectroscopy. *Phys. Rev. B* 92 (2015).

[47] L. Yu, H.B. Wu, X.W. Lou. Mesoporous $\text{Li}_4\text{Ti}_5\text{O}_{12}$ Hollow Spheres with Enhanced Lithium Storage Capability. *Adv. Mater.* 25 (2013) 2296-2300.

[48] X.H. Rui, Q.Y. Yan, M. Skyllas-Kazacos, T.M. Lim. $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ cathode materials for lithium-ion batteries: A review. *J. Power Sources* 258 (2014) 19-38.

[49] B. Zhao, R. Ran, M. Liu, Z. Shao. A comprehensive review of $\text{Li}_4\text{Ti}_5\text{O}_{12}$ -based electrodes for lithium-ion batteries: The latest advancements and future perspectives. *Mater. Sci. Eng. R: R.* 98 (2015) 1-71.

[50] Z. Zhang, F. Xiao, L. Qian, J. Xiao, S. Wang, Y. Liu. Facile Synthesis of 3D MnO_2 -Graphene and Carbon Nanotube-Graphene Composite Networks for High-Performance, Flexible, All-Solid-State Asymmetric Supercapacitors. *Adv. Energy Mater.* 4 (2014) 1400064.

[51] C. Liu, H. Song, C. Zhang, Y. Liu, C. Zhang, X. Nan, G. Cao. Coherent Mn_3O_4 -carbon nanocomposites with enhanced energy-storage capacitance. *Nano Res.* 8 (2015) 3372-3383.

[52] R. Thangavel, K. Kaliyappan, K. Kang, X. Sun, Y.S. Lee. Going Beyond Lithium Hybrid Capacitors: Proposing a New High-Performing Sodium Hybrid Capacitor System for Next-Generation Hybrid Vehicles Made with Bio-Inspired Activated Carbon. *Adv. Energy Mater.* (2016) 1502199.

[53] V. Augustyn, P. Simon, B. Dunn. Pseudocapacitive oxide materials for high-rate electrochemical energy storage. *Energy Environ. Sci.* 7 (2014) 1597-1614.

[54] C. Liu, C. Zhang, H. Song, C. Zhang, Y. Liu, X. Nan, G. Cao. Mesocrystal MnO cubes as anode for Li-ion capacitors. *Nano Energy* 22 (2016) 290-300.

[55] M. Tang, W.C. Carter, Y.M. Chiang. Electrochemically Driven Phase Transitions in Insertion Electrodes for Lithium-Ion Batteries: Examples in Lithium Metal Phosphate Olivines. *Annu. Rev. Mater. Res.* 40 (2010) 501-529.

[56] Y. Wang, Z. Hong, M. Wei, Y. Xia. Layered $\text{H}_2\text{Ti}_6\text{O}_{13}$ -Nanowires: A New Promising Pseudocapacitive Material in Non-Aqueous Electrolyte. *Adv. Funct. Mater.* 22 (2012) 5185-5193.

High Power High Safety Battery with Electrospun $\text{Li}_3\text{V}_2(\text{PO}_4)_3$ Cathode and $\text{Li}_4\text{Ti}_5\text{O}_{12}$ Anode with 95% Energy Efficiency

Chaofeng Liu^{1,†}, Shuhua Wang^{1,†}, Changkun Zhang¹, Haoyu Fu¹, Xihui Nan¹, Ya Yang^{1*},

Guozhong Cao^{1,2*}

¹Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing,
100083, China

²Department of Materials Science and Engineering, University of Washington, Seattle,
Washington, 98195, USA

Corresponding Author: Guozhong Cao (E-mail: gzcao@u.washington.edu), Ya Yang (yangya@binn.cas.cn)

Acknowledgements

This work was supported by the "Thousands Talents" program for the pioneer researcher and his innovation team, China. This work was also supported by the National Science Foundation of China (51374029) and the National Science Foundation (NSF, DMR-1505902), Program for New Century Excellent Talents in University (NCET-13-0668), Fundamental Research Funds for the Central Universities (FRF-TP-14-008C1) and China Postdoctoral Science Foundation (2015M570987).

Author contributions

[†] Chaofeng Liu and Shuhua Wang equally contribute to this work.