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The rechargeable aluminum-ion battery

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We report a novel aluminium-ion rechargeable battery comprised of an electrolyte containing AlCl₃ in the ionic liquid, 1-ethyl-3-methylimidazolium chloride, and a V₂O₅ nano-wire cathode against an aluminium metal anode. The battery delivered a discharge capacity of 305 mAh g⁻¹ in the first cycle and 273 mAh g⁻¹ after 20 cycles, with very stable electrochemical behaviour.

Since the early 1990s, lithium ion batteries based on a carbonaceous material such as graphite as the anode, a lithiated metal oxide (LiMO, *e.g.* LiCoO₂) cathode, and an aprotic liquid electrolyte have been the subjects of intense scientific and commercial interest for portable electronics applications. In recent years, the demand for secondary/rechargeable batteries with higher operating voltages, improved cycling stability, higher power densities, enhanced safety, and lower initial and life cycle costs has increased to meet new needs for smaller, lighter, more powerful electronic devices. Growing interest in hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEVs) designed to simultaneously reduce dependence on fossil fuel-derived energy and to lower the carbon footprint of humans compounds the current need for advanced, cost-effective electrical energy storage technologies.¹ Due to their high energy density and low self-discharge rate, Li-ion batteries are considered the most promising technology for meeting these demands for the foreseeable future.^{2–4}

Aluminium is the most abundant metal and the third most abundant element in the earth's crust. An aluminium-based redox couple, which involves three electron transfers during the electrochemical charge/discharge reactions, provides competitive storage capacity relative to the single-electron Li-ion battery.^{5–7} Additionally, because of its lower reactivity and easier handling, such an aluminium-ion (Al-ion) battery might offer significant cost savings and safety improvements over the Li-ion battery platform. Aluminium has consequently long attracted attention as an anode in the Al-air battery because of its high theoretical Ampere-hour capacity and overall specific energy.^{8–11} Although these values are reduced in a practical battery because of the inability to operate aluminium and the air cathode at their thermodynamic potentials, and because water is consumed in the discharge reaction, the practical energy density still exceeds that of most commercially

available rechargeable battery systems.¹² The inherent hydrogen generation of the aluminium anode in aqueous electrolytes introduces additional limitations, which have been met by designing the batteries as reserve systems with the electrolyte added just before use, or as mechanically rechargeable batteries with the aluminium anode replaced after each discharge. Even with these adjustments, reliable electrically rechargeable aluminium/air batteries are considered unfeasible using aqueous electrolytes, due to the high corrosion and hydrogen evolution of aluminium in the electrolyte, which leads to a sharp reduction of the anodic efficiency. Furthermore, several studies have shown that in aqueous media Al/air batteries an oxide film covers the surface of the aluminium anode, which decreases the anodic voltage and cell efficiency.¹³ The literature is replete with studies investigating the suitability of ionic liquid-based electrolytes for electrodeposition of aluminium.¹⁴ A battery technology exploiting an Al-ion conducting ionic liquid electrolyte has been recently reported to show some promise.¹⁵

Herein, we report on a novel Al-ion battery system using V₂O₅ nano-wires as the cathode against an aluminium metal anode in an ionic liquid (IL), 1-ethyl-3-methylimidazolium chloride, -based electrolyte.¹⁶ To the best of our knowledge, the Al-ion battery configuration reported in this communication is the first to offer evidence of stable electrochemical behaviour with extended cycle life. We attribute these features to the synergistic effect of a suitable electrolyte, V₂O₅ nano-wire cathode and Al anode. Specifically, a key requirement for achieving high energy density of an Al-ion battery is an electrolyte having good ionic conductivity for Al³⁺, a wide electrochemical stability window in the presence of metallic aluminium, and which wets and permeates the pores of the metal oxide cathode. The aprotic electrolyte should also exhibit reversible electrochemical deposition and dissolution of aluminium.

Based on the aforementioned studies of electrodeposition of aluminium in room temperature ILs,¹⁴ AlCl₃ dissolved in 1-ethyl-3-methylimidazolium chloride ([EMIm]Cl) was used as the electrolyte in the current study to examine the operation of the Al-ion battery at room temperature (25 °C). This electrolyte possesses different degrees of Lewis acidity depending on the [EMIm]Cl:AlCl₃ ratio, which provides an additional degree of freedom in tuning its properties. During discharge the prevalent AlCl₄⁻ anion in the electrolyte will react with the Al anode to form Al₂Cl₇⁻ complex species, which reacts with the cathode to form an aluminium intercalated V₂O₅ discharge product. An acidic electrolyte composition with 1.1:1 molar

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ratio of AlCl_3 to $([\text{EMIm}]\text{Cl})$ was found to yield effective electrochemical deposition and dissolution of aluminium and was therefore used for the study. To verify the role played by the AlCl_3 - $([\text{EMIm}]\text{Cl})$ electrolyte, electrochemical investigation of the same battery system was also performed with an electrolyte containing aluminium trifluoromethanesulfonate (Al triflate) dissolved in a conventional aprotic liquid mixture PC/THF (1:1 v/v). In contrast to the AlCl_3 - $([\text{EMIm}]\text{Cl})$ electrolyte system, no electrochemical activity was observed in the measured voltage range -0.75 – 4.2 V, underscoring the importance of the IL-based electrolyte.

The V_2O_5 nanowires used for the cathode were prepared by a hydrothermal method.¹⁷ In a typical synthesis, 0.364 g of commercial V_2O_5 powder (Sigma-Aldrich) and 30 ml of DI H_2O were mixed under vigorous magnetic stirring at room temperature, and then 5 ml 30% H_2O_2 (Sigma-Aldrich) was added to this mixed solution and kept continuously stirred for 30 min. Finally a transparent orange solution was obtained. The resultant solution was then transferred to a 40 ml glass lined stainless steel autoclave and heated at 205 °C for 4 days. The product was washed with anhydrous ethanol and distilled water several times. Finally, it was dried at 100 °C for 12 h and then annealed at 500 °C for 4 h in air. The synthesized product was characterized by Transmission Electron Microscopy (TEM, Tecnai, T12, 120 kV), powder X-ray diffraction (Scintage X-ray diffractometer with $\text{Cu K}\alpha$ radiation), cyclic voltammetry (Solartron's Cell Test model potentiostat under the scan rate of 0.2 mV s^{-1}), and galvanostatic electrochemical charge–discharge analysis (Maccor cycle life tester, under the potential window 2.5 – 0.02 V).

The V_2O_5 cathode slurry was made by mixing 85% of the synthesized V_2O_5 nano-wires, 7.5% super-p carbon and 7.5% of PVDF binder in NMP dispersant. Electrodes were produced by coating the slurry onto a 10 micron stainless steel current collector at 105 °C for 1 h initially and at 100 °C for 4 h in a vacuum oven. Since the acidic electrolyte used has the tendency to etch copper, stainless steel (301 type stainless steel, McMaster Carr, USA) was used as the current collector. The resulting slurry-coated stainless steel foil was roll-pressed and the electrode was reduced to the required dimensions with a punching machine. Preliminary cell tests were conducted on 2032 coin-type cells, which were fabricated in an argon-filled glove box (AlCl_3 is highly reactive), using 10 micron Al metal as the counter electrode and a Whatman glass microfiber separator. The electrolyte solution was 1.1:1 anhydrous AlCl_3 in 1-ethyl-3-methylimidazolium chloride.

The phase purity and degree of structural order of the synthesized V_2O_5 was studied using a powder X-ray diffraction (XRD) pattern shown in Fig. 1a. The XRD obtained is in good agreement with the standard JCPDS pattern (File No. 89-0612) and shows the existence of phase pure orthorhombic V_2O_5 with $Pnmm$ space group. The absence of any undesirable peaks demonstrates the presence of a phase pure product and the miller indices (hkl) of all the characteristic peaks are marked as per the standard pattern. Fig. 1b and c shows the transmission electron microscopy (TEM) image of the as synthesized V_2O_5 nano-wires. It is apparent that the synthesis procedure yields uniform and nearly monodispersed nanostructures having uniform diameters throughout their entire length and sharp, well-defined surfaces.



Fig. 1 (a) XRD pattern and (b, c) TEM images of the V_2O_5 nano-wires used for the Al-ion secondary battery cathode.



Fig. 2 Typical cyclic voltammograms of Al-ion battery using V_2O_5 nano-wire cathode and aluminium anode in (a) 1:1 v/v of Al triflate in PC/THF and (b) 1.1:1 molar ratio of AlCl_3 in $([\text{EMIm}]\text{Cl})$ at a sweep rate of 0.2 mV s^{-1} .

To evaluate the feasibility of the electrolyte and the synthesized V_2O_5 nano-wires for Al-ion battery applications, electrochemical properties were examined by cyclic voltammetry and galvanostatic cycling analysis. Fig. 2a and b show the cyclic voltammograms of the V_2O_5 cathode against the Al metal anode in two different electrolytes: 1:1 v/v of Al triflate in PC/THF (Fig. 2a) and 1.1:1 molar ratio of AlCl_3 in $([\text{EMIm}]\text{Cl})$ (Fig. 2b) at room temperature. As mentioned earlier, no electrochemical activity was observed for the Al-ion battery using Al triflate in PC/THF as the electrolyte and V_2O_5 nano-wire cathode in the measured voltage range of -0.75 – 4.2 V. On the other hand, a pair of cathodic and anodic peaks were observed for the Al-ion battery with V_2O_5 nano-wire cathode and AlCl_3 in the $([\text{EMIm}]\text{Cl})$ electrolyte under the potential window of 2.5 – 0.02 V. The CV pattern shown in Fig. 2b exhibited a cathodic peak at ~ 0.45 V and a corresponding anodic peak at ~ 0.95 V, respectively, which may be attributed to the insertion/deinsertion of Al^{3+} ions into and from the orthorhombic crystal lattice structure of V_2O_5 nano-wires. Virtually no change in the peak position or peak current value was observed in the cyclic voltammogram shown in Fig. 2b even after 20 scans, which substantiates the electrochemical stability of the battery. For this reason, AlCl_3 in $([\text{EMIm}]\text{Cl})$ was chosen as the electrolyte for discharge/charge studies.

To further evaluate the electrochemical properties of the designed Al-ion battery, a galvanostatic discharge/charge reaction was performed at the cell voltage of 2.5 – 0.02 V at a constant current drain of 125 mA g^{-1} . The open circuit voltage



Fig. 3 (a) Voltage vs. time (b) voltage vs. sp. capacity and (c) cycle life plot of Al-ion battery containing aluminium anode, V₂O₅ nano-wire cathode in ionic liquid under the potential window 2.5–0.02 V and at a constant current drain of 125 mA g⁻¹.

of the Al-ion battery was found to be 1.8 V. Fig. 3a displays the voltage vs. time plot of the Al-ion battery, wherein no change in the potential of the Al³⁺ insertion/extraction plateau was observed. Fig. 3b shows the voltage vs. capacity plot of the Al-ion battery which demonstrates a well defined and very stable Al³⁺ insertion plateau at ~0.55 V. In the first cycle, the battery exhibited an Al³⁺ ion insertion capacity of 305 mAh g⁻¹ against 273 mAh g⁻¹ at the end of 20 cycles. These values are somewhat lower than the theoretical capacity of V₂O₅ against the Al³⁺ ion, which is estimated to be 442 mAh g⁻¹ considering a simple three electron transfer reaction (Al + V₂O₅ ↔ AlV₂O₅). Fig. 3c shows the galvanostatic cycling performance of the Al-ion battery, which nicely shows a high degree of reversibility and good capacity retention. The coulombic efficiency of the cell is not as high as would be needed for long-term practical use in a secondary battery, but its stability is quite encouraging. Significant crystallography and voltammetry studies are underway to understand intercalation of aluminium into V₂O₅ and other layered oxides. These studies will help shed light on the effect of variables such as the cell current density and electrolyte formulation on the coulombic efficiency and practical specific energy achievable in the Al-ion battery. Indeed based on the specific capacities observed experimentally, one might conclude that only about 0.7 moles of Al³⁺ ions participate in the actual redox reaction. As in the case of Li-ion secondary batteries, we anticipate significant opportunities for nanoscale engineering and chemical design of the Al-ion battery cathode to increase the overall cell potential. Additionally, we anticipate as significant efforts to pioneer ionic liquid and

other Al-conducting electrolytes to enhance cell performance at high voltages and high current drains.

In conclusion, we report the first example of a functional Al-ion rechargeable battery. The battery uses V₂O₅ as the cathode against an aluminium metal anode in an ionic liquid-based electrolyte. When evaluated in galvanostatic cycling and cyclic voltammetry measurements, the battery displayed promising electrochemical features with stable cycling behaviour over 20 charge–discharge cycles. The theoretical energy density of the Al-ion battery with V₂O₅ as the cathode against aluminium metal as the anode was determined to be 240 Wh kg⁻¹, which is not enough to power very much. But considering the other attractive attributes of an aluminium based secondary battery platform, the energy density of this first Al-ion cell is enough to initiate a global search for new materials and cell designs which we anticipate will lead to rapid and sustained improvements.

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