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MXene: a promising transition metal carbide anode for lithium-ion batteries

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1. Introduction

Li-ion batteries (LIB) are a key technology and play a dominant role in today’s world, especially for transportation [1] and renewable energy storage [2]. Extensive research efforts have been dedicated to exploring and developing new anode materials for LIBs [3]. The goal of much of the research is to develop new materials with higher capacities and lifetimes than current graphite or lithium titanate anodes. With Si insertion anodes receiving much attention in the past decades due to their improved safety and high-rate performances [2], the steady state capacity was 225 mAh g−1 at 1C, it was 110 mAh g−1 after 80 cycles; at 3C, it was 80 mAh g−1 after 120 cycles; at 10C, it was 70 mAh g−1 after 200 cycles. Since TiC is a member of the MXene family – where M is an early transition metal and X is C and/or N – that to date includes Ti3C2, TaC2, TiNbC, and (V0.5,C0.5)C2, our results suggest that MXenes are promising as anode materials for Li-ion batteries.

2. Experiment

2.1. Synthesis of Exfoliated Ti3C

Pre-reacted, −325 mesh, Ti3AlC powders were commercially obtained (3-ONE-Z, Voorhees, NJ, >92 wt.% purity). The exfoliation process was carried by immersing the Ti3AlC powder in diluted (10%) hydrofluoric acid, HF, (Fisher Scientific, Fair Lawn, NJ) for 10 h at room temperature, as described elsewhere [12].
2.2. Characterization

A scanning electron microscope, SEM, (Zeiss Supra 50VP, Germany) equipped with an energy-dispersive spectrometer, EDS, (Oxford Inca X-Sight, Oxfordshire, UK) was used to obtain high magnification images of the treated powders and estimate the chemistry of the HF treated Ti$_2$AlC. Gas sorption analysis was carried out using a Quantachrome Autosorb-1 with nitrogen, N$_2$, adsorbate. Prior to the analysis, the samples were outgassed under vacuum at 200 °C for 48 h. Nitrogen sorption analysis at 77 K was used for calculating the specific surface area (SSA) using the Brunauer–Emmet–Teller (BET) equation.

2.3. Electrochemical testing

To investigate the electrochemical behavior of exfoliated Ti$_2$AlC in Li batteries, coin cells (CR 2016) were assembled. The working electrodes were made with 80 wt.% Ti$_2$C (as described above) and 10 wt.% Super P carbon black mixed with 10 wt.% poly(vinylidene fluoride) dissolved in 1-methyl-2-pyrrolidinone. The mixture was then spread onto a copper foil and dried at ≈200 °C for 12 h, under a mechanical vacuum. CR 2016 coin-type cells were assembled using MXene as the positive electrode and Li metal foil as the negative electrode, separated by a sheet of borosilicate glass fiber (Whatman GF/A) separator saturated with 1 M LiPF$_6$ solution in a 1:1 weight mixture of ethylene carbonate and diethyl carbonate (EC:DEC) as the electrolyte. The cells were assembled inside an Ar-filled glove box with H$_2$O and O$_2$ contents <1 ppm, to avoid any moisture contamination.

The cells were subjected to cyclic voltammetry and galvanostatic charge–discharge cycling using a potentiostat (VMP4, Biologic, S.A.). Electrochemical characterization was typically performed between 0.05 V and 2.5 V vs. Li.

3. Results and discussions

X-ray diffraction, XRD, of the reacted powders indicated that the Al was selectively etched from the structure [12]. EDS confirmed that the Al layers were replaced by O and F. The presence of the latter was explained by assuming that the Ti-surfaces, exposed by the removal of the Al, were terminated by oxygen and possibly fluoride surface groups [12]. SEM images of Ti$_2$AlC particles after HF treatment (Fig. 1a) resemble images of exfoliated graphite and clearly show HF-induced delamination that is typical of MXenes [11,12].

The N$_2$ sorption isotherm of the treated powders (Fig. 2b) has a hysteresis loop with indications of the presence of mesopores and a shape typical for slit pores [14]. The SSA calculated using the BET equation [15] for the HF treated Ti$_2$AlC was 23 m$^2$ g$^{-1}$. This value is about an order of magnitude higher than the as-received Ti$_2$AlC powders measured at ≈2.5 m$^2$ g$^{-1}$.

Typical cyclic voltammetry curves, at a rate of 0.2 mV s$^{-1}$, for the exfoliated Ti$_2$C are shown in Fig. 2a. A broad, irreversible peak was observed around 0.6 V, during the first lithiation cycle (reduction); it was absent in subsequent cycles. It is reasonable to preliminarily assign this irreversible peak to the formation of a solid electrolyte interphase (SEI) and to an irreversible reaction with the electrode material. In all subsequent cycles, broad reversible peaks were observed at 1.6 V and 2.0 V vs. Li$^+/Li$. During lithiation and delithiation, respectively. Because these peak potentials are similar to those reported for TiO$_2$ and lithiated titania [9] we tentatively assign these peaks to the following redox reaction:

$$\text{Ti}_2\text{C}_2\text{O}_4 + y\text{Li}^+ + ye^{-} \rightarrow \text{Li}_y\text{Ti}_2\text{CO}_4$$

The rationale for this assignment is that drying at 200 °C, prior to assembling the coin cells, rids the MXene of water or any OH species and leads to an oxygen terminated surface [16]. In other words: the assumption is made that the Ti$_2$CO$_4$ surface is similar to that of titania. Like in the case of the titanates, even if the potentials vs. Li are relatively high, it is an advantage from a safety standpoint [17]. Ex situ XRD results (not shown) after lithiation produced no new peaks, but a downshift of the MXene peaks was observed, with an increase of the c parameter by 19.5% which indicates intercalation of Li between the MXene layers and not a conversion reaction.

Fig. 2b shows the galvanostatic charge/discharge curves at a rate of C/10 (1 Li$^+$ per formulae exchanged in 10 h). The capacity loss in the first cycle can again be attributed to a SEI layer formation at potentials below 0.9 V vs. Li$^+/Li$ [18], as well as to the irreversible reduction of electrochemically active surface groups such as fluorine or possibly hydroxyl. The specific capacity stabilized after five cycles at ≈160 mAh g$^{-1}$. This value corresponds to y ≈ 0.75 in reaction (1).

At 160 mAh g$^{-1}$, the capacity of the treated powders is about 5 times higher than that of the as-received Ti$_2$AlC (≈30 mAh g$^{-1}$ at C/10) powders. This increase in capacity is traceable to the higher surface area, more open structure and weaker bonds between the MX layers after HF treatment. In addition to the morphological changes, the Li insertion sites are also now different (i.e., the site binding energies) which could also explain the differences in capacity.

The specific capacities vs. cycle number at different cycling rates (C/25, C/6, 1C, 3C, and 10C) calculated from galvanostatic curves are shown in Fig. 2c. The highest capacity was obtained at a rate of
intercalate Li$^+$ ions in the interlayer spaces between exfoliated Ti$_3$C sheets, and achieve stability. These results, while not yet at the level of thoroughly studied and optimized titanate anodes that have similar Ti–O surface chemistries [9,19–21], are to be considered promising when compared to any currently used anode materials, including graphite or titania – based anodes, at comparable – i.e., first report – stages of development. It is reasonable to assume that with further work on these new materials significant improvement will be made. Fruitful research avenues include optimizing the grain size of the original MAX phases as was reported for other systems [22–25], and/or tuning the MXene compositions [26–28].

With more than 60 MAX phases known, this study opens the door to exploring a large family of promising electrode materials. It is worth noting here that we have already exfoliated Ti$_3$C$_2$T$_x$, Ta$_4$C$_3$, TiNbC, and (V$_{0.5}$Cr$_{0.5}$)$_3$C$_2$ [12], and are currently exploring their potential as Li anodes.

4. Conclusions

In conclusion, exfoliated Ti$_3$C, produced by HF treatment of Ti$_3$AlC powders, showed reversible capacity about 5 times higher than pristine Ti$_3$AlC, due to its open structure, weaker interlaminar forces, and higher SSA. Electrochemical measurements showed intercalation and deintercalation of Li$^+$ ions at 1.6 V and 2 V vs. Li$^+$/Li, respectively. The exfoliated Ti$_3$C material exhibited a stable capacity of 225 mAh g$^{-1}$ at a C/25 rate, corresponding to about one Li per Ti$_3$CO$_2$ formula unit. A stable cycling capacity of 80 mAh g$^{-1}$ was observed after 120 cycles at a 3C rate, and 70 mAh g$^{-1}$ was observed after 200 cycles at a 10C rate. These results are encouraging and suggest that the MXenes could be used as Li$^+$ intercalation electrodes in LIBs.

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References