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Preparation and characterization of three dimensionally ordered macroporous Li$_5$La$_3$Ta$_2$O$_{12}$ by colloidal crystal templating for all-solid-state lithium-ion batteries

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Abstract

Three dimensionally ordered macroporous (3DOM) membranes of Li$_5$La$_3$Ta$_2$O$_{12}$ (LLTO) for all-solid-state lithium-ion batteries were prepared by using colloidal crystal templating of mono dispersed polystyrene (PS) spheres combined with sol–gel synthesis of LLTO precursor. During the sol–gel synthesis, the appropriate mixtures of CH$_3$COOLi, La(NO$_3$)$_3$·6H$_2$O and Ta(OC$_2$H$_5$)$_5$ were dissolved in two different solvents to prepare garnet-type LLTO. Various sizes of mono dispersed (1, 3 and 5 μm) PS beads were used as a template to investigate the size effect of template on the network formation of LLTO membranes. The transformation from precursor solutions, which are added onto the PS template, to crystalline phase, was investigated by TG analysis and X-ray powder diffraction (XRPD). The morphology of the PS templates and the 3DOM garnet membranes were investigated by Scanning Electron Microscopy. The templates made from 5 μm PS spheres were found to be the most suitable template to obtain 3DOM membranes of LLTO.

Keywords: Macroporous membrane; Solid-state lithium-ion conductors; Garnet; 3DOM; Crystal templating

1. Introduction

Rechargeable lithium-ion batteries are nowadays widely used as energy power supplies in various electronic devices due to their high energy density [1]. However, the conventional rechargeable batteries contain hazardous and flammable organic liquid electrolytes, making them potentially unsafe and reducing the cycle life due to formation of an irreversible solid electrolyte interface [2]. For these reasons, replacement of the liquid electrolyte with a safer and stable solid-electrolyte is necessary to improve the safety by preventing the risk of liquid electrolyte leakage and improving the cycling stability. Research efforts were directed towards finding suitable solid electrolytes for lithium ion batteries with high lithium ion conductivity as well as good chemical stability with commonly used intercalation materials for battery applications [3]. A wide range of compounds with different crystal structure types has been investigated, such as Li$_4$SiO$_4$, Li$_3$SO$_4$, Li$_{2}$ZnGe$_2$O$_{16}$, Li$_{1+y}$Ti$_{2-x}$M$_{x}$(PO$_4$)$_3$ (M=Al, Sc, Y, La), Li-$\beta$-alumina and Li$_{0.34}$La$_{0.5}$TiO$_{2.98}$ with perovskite crystal structure. Some of the reported ionic conductivities are in between $10^{-3}$ and $10^{-7}$ S/cm [4–10]. In addition to the above mentioned compounds, new classes of compounds with garnet-type structure have attracted great interest as potential solid-state lithium-ion conductors in the last few years. Compound series with the chemical formula Li$_5$La$_3$M$_2$O$_{12}$ (M=Nb, Ta),

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Li₆AL₆₂M₂O₁₂ (A=Ca, Sr, Ba; M=Nb, Ta) and Li₇La₃Zr₂O₁₂ have been reported with high lithium ion conductivity ($\sigma_{\text{bulk}} \approx 10^{-4} - 10^{-6}$ S/cm) and good chemical stability towards electrode materials, especially metallic lithium electrode, compared with perovskite and NASICON-type electrolytes [11–15].

On the other hand, using ceramic electrolytes in solid-state lithium-ion batteries causes a problem due to the poor contact between the solid electrolyte and the active electrode material which causes a high internal resistance [16]. Recently, we have investigated the synthesis of nanocrystalline garnet compounds at relatively low temperatures by sol–gel synthesis to reduce the internal resistance in those materials [17,18]. Dokko et al. proposed and reported the Li₀.₃₅La₀.₅₅TiO₃ (LLT) perovskite-type solid electrolyte with three-dimensionally ordered macroporous (3DOM) structure to enlarge the contact area between the solid electrolyte and electrode material [19]. One of the short-comings of this study was that LLT undergoes a reduction of Ti⁴⁺ to Ti³⁺ during the contact with Lithium metal and since LLT has 3D lithium ion mobility only above 400 K [20], the perovskite-type lithium ion conductor is not favorable in those 3DOM network.

In the study reported in this paper we investigated the preparation of 3DOM garnet-type LLTO by PS colloidal crystal templating using two different precursor solutions. Absolute ethanol was used as a solvent in the preparation of the first precursor solution and the second precursor solution contains acetic acid and ethylene glycol mixture as solvent. Those two precursor solutions were employed on three types of template prepared with different sizes mono-dispersed spherical colloidal PS particles (1, 3, 5 μm). The decomposition behavior of the solutions added on PS templates was characterized by TG analysis. The effect of the precursor solution and the PS templates on the 3DOM garnet-type LLTO morphology was characterized by SEM analysis and the crystal structure of the electrolyte materials were characterized by XRD analysis.

2. Experimental

2.1. Preparation of polystyrene (PS) colloidal crystal templates

Colloidal crystal templates of PS spheres were formed using gravitational settling in combination with evaporation to prepare the 3DOM Li₂La₇Ta₂O₁₂ solid electrolyte combined with sol–gel method. For gravitational settling in combination with evaporation, 2 ml water suspensions of 50 mg PS/ml (Sigma Aldrich) with various mono-dispersed PS bead sizes (1, 3, 5 μm) were prepared and placed inside a syringe (20 ml PE/PP BD Biscardit II) that was cut in half. Those were left to dry overnight at 333 K under atmospheric conditions. Finally, the PS templates were removed by pushing the plunger of the syringe.

2.2. Preparation of 3DOM Li₇La₃Ta₂O₁₂

Sol–gel synthesis of Li₇La₃Ta₂O₁₂ was done using two different solvents. In the first solution, lithium(I) acetate (99.95%, trace metal basis Aldrich Chemistry) was dissolved in ethanol (99.9%, Technisolve) whereas in the second solution it is dissolved in ethylene glycol (EG) (99% Merck KGaA) and glacial acetic acid (HAc) (100% Merck KGaA) used as chelating agent while stirring and heating at 343 K for 1 h under reflux conditions. The molar ratio of HAc and EG was kept as 3:2. Lanthanum(III) nitrate hexahydrate (99.999%, trace metal basis, Aldrich Chemistry) and tantalum(V) ethoxide (99.999%, Alfa Aesar) were added with molar ratio (Li:La:Ta) 6:3:2 in both solutions. A 20% excess amount of lithium was used to compensate for lithium evaporation and the concentration of the mixture solution was approximately 0.05 M. The whole mixture was stirred and heated at 343 K for 1 h under reflux conditions. Solvent evaporation was induced by heating the mixture to 393 K without refluxing and the concentration of the solutions was increased up to 0.1 M upon evaporating of the solvents. The mixture was left to cool at room temperature, yielding a low viscosity transparent precursor solution. The precursor solutions were added to the previously obtained PS templates using vacuum impregnation. Four drops of solution were added to the PS deposits after which the sample was heated to 303 K for 15 min under vacuum. This was repeated three times. Finally, the samples were heated at 973 K for 1 h under static air atmosphere to decompose the PS particles and to form the solid electrolyte.

2.3. Characterization

Thermogravimetric (TG) analysis using a Mettler Toledo TGA/SDTA 851 instrument was carried out on PS template filled with precursor solution in 70 μl Al₂O₃ crucibles from 300 to 1273 K with a heating rate of 5 K/min in flowing air (50 ml/min). X-ray powder diffraction (XRPD) analysis was performed to investigate the phase purity and crystal structure of the resulting porous membranes. Data were collected at room temperature with a Bruker Endurance D4 diffractometer using CuKα radiation in the 2 theta range 5° to 90° with a step size of 0.01° and a counting time of 1 s. The morphology of the PS templates as well as the porous membranes was investigated by Scanning Electron microscopy (SEM) using a Quanta 3D FEG instrument (FEI Company).

3. Results

3.1. Formation of colloidal crystal templates

Mono-dispersed polystyrene spheres with 1, 3 and 5 μm bead size were used to form the crystal templates by using gravitational settling in combination with evaporation to prepare the 3DOM Li₂La₇Ta₂O₁₂ solid. Fig. 1 shows the SEM pictures of the templates prepared by using various PS sphere sizes. It can be seen in the SEM micrographs that long range ordered templates with some stacking faults was prepared for further manipulations.
3.2. Decomposition of PS templates filled with precursor solution

PS templates were filled with garnet sol–gel precursors and dried at room temperature in a vacuum chamber. The dried samples were annealed under flowing air from room temperature to 1200 K at a rate of 5 K/min. During the removal of polystyrene templates and the crystallization of the garnet phase, the reaction mixtures undergo several processes, such as combustion of the PS template, decomposition of precursor solution, and oxidation. After the addition of precursor solutions onto the templates, the removal of PS and the formation of garnet compound were monitored by thermal analysis (TG/DTA) which is shown in Fig. 2. On the basis of thermal analysis of the sample prepared using HAc/EG as solvent, the weight decreases between 300 and 400 K and between 450 and 600 K are assigned to loss of residual solvents, HAc and EG, respectively. While, when PS is impregnated with EtOH containing precursor, the solvent evaporation is minor due to the low temperature evaporation of EtOH. At around 600 K, the weight loss accelerates for both precursor solutions, till it reaches 650 K due to combustion of the polystyrene. A slow and steady weight loss from 650 K to 950 K can be attributed to decomposition and oxidation of residual organics from the sol–gel precursors. There is no significant weight loss higher than 950 K for both types of precursors which is indicating that the transformation of the precursor to oxides starts above this temperature followed by crystallization of pure LLTO phase. This has also been verified by XRPD analyses.

3.3. Phase formation

Fig. 3 shows the XRPD patterns of calcined 3DOM LLTO prepared with two different solutions at 973 K. The PS template was filled with precursor solutions separately and
they are annealed at 973 K for 1 h reaction time. The diffraction peaks of the 3DOM LLTO samples at 973 K match very well with those of the corresponding garnet phase Li$_5$La$_3$Ta$_2$O$_{12}$ without any other additional peaks. The crystallite sizes of those samples were estimated from the line broadening of the main peaks by using Scherrer equation. [21]

\[ D = \frac{k\lambda}{\beta \cos \theta} \]

where \( \lambda \) is the wavelength of the X-ray, \( k \) is the constant (0.9), \( \theta \) is the diffraction angle and \( \beta \) is the full width at half maximum (FWHM). According to the calculations, the 3DOM LLTO prepared using HAc/EG have larger crystallite size (\( \approx 35 \) nm) than the EtOH used sample (\( \approx 24 \) nm). This can be seen from the sharper X-ray diffraction peaks. These results show that the precursor solutions are completely transformed into garnet-type LLTO phases at 973 K.

3.4. Morphology of 3DOM LLTO

Figs. 4 and 5 show several SEM images of 3DOM LLTO with various colloidal crystal templates sizes (1, 3, 5 \( \mu \)m) by addition of EtOH based or HAc & EG mixture based precursor solutions, respectively. All differently sized PS templates were very well aligned as discussed in Section 3.1 in detail. As can be seen in Fig. 4a and Fig. 5a, starting with very well aligned 1 \( \mu \)m PS template, this is yielding very dense LLTO materials. This can be explained by the fact that the grains of the garnet compound are growing too large and destroy the interstitial space of the 1 \( \mu \)m PS template, which further prevents the formation of the porous network. In addition, Gao et al. showed that the HAc/EG mixture based solutions first decompose to the LiLa$_2$TaO$_6$ phase with a crystal structure different from garnet at 923 K, while above 973 K it is fully transformed into the garnet phase in the sol–gel synthesis of Li$_5$La$_3$Ta$_2$O$_{12}$ [22]. So the coalition and phase transformation to the garnet compound of the intermediate phase above 923 K could lead to agglomeration and result in large grains for garnet phase LLTO. For 3DOM garnet-type LLTO originating from 3 \( \mu \)m PS template, porous network formation is observed as shown in Fig. 4b and Fig. 5b but there is some irregularity in the long range order and there are break downs in the network due to the shrinkage during calcinations. Significantly improved network formation is obtained with the 5 \( \mu \)m PS template compared to the other template sizes (Fig. 4c and Fig. 5c). Moreover, it can be clearly seen in Fig. 4c and Fig. 5c, that when HAc/EG mixture is used for the precursor solution the network formation is further improved compared to the EtOH based precursor. The alternating layers as well as the long range order were obtained with combination of 5 \( \mu \)m PS template and HAc/EG based LLTO precursor solution.

Fig. 4. SEM image of 3DOM LLTO prepared using mono-dispersed PS templates (a) 1 \( \mu \)m, (b) 3 \( \mu \)m and (c) 5 \( \mu \)m combined with EtOH based precursor solution and annealed at 973 K for 1 h.

Fig. 5. SEM image of 3DOM LLTO prepared using mono-dispersed PS templates (a) 1 \( \mu \)m, (b) 3 \( \mu \)m and (c) 5 \( \mu \)m combined with HAc/EG based precursor solution and annealed at 973 K for 1 h.
(Fig. 6). In general, using HAc/EG as a solvent has a positive effect by increasing the grain size which enhances the interconnectivity of the network.

4. Conclusion

Three dimensionally ordered Li$_3$La$_3$Ta$_2$O$_{12}$ membranes with garnet-type structure were prepared by the colloidal crystal templating method using various sizes of mono-dispersed PS spheres, combined with two different sol–gel synthesis methods. Experiments were performed with both ethanol based LLTO precursor solutions as well as an acetic acid and ethylene glycol mixed-base solution. All of above mentioned different PS size templates yielded pure and crystalline garnet phase when they are annealed at 973 K. As we discussed before, three-dimensionally ordered macroporous (3DOM) structures can be used to enlarge the contact area between the solid electrolyte and electrode material when they are impregnated by electrode material. This can be achieved with porous and very well ordered 3DOM materials. Using 1 μm mono-dispersed PS template yielded an undesired dense LLTO membrane which is due to the large grains of the LLTO garnet phase. Porous 3DOM LLTO membranes were obtained with 3 μm spheres with absence of long range order and many defects. Our findings also showed that PS template with 5 μm beads is the optimum size for highly ordered and porous membranes. Further improvement in terms of long range order in network formation is also possible when the ethanol-based precursor solution is replaced with acetic acid and ethylene glycol mixture-based LLTO precursor solution. Unfortunately the mechanical properties of the 3DOM garnet-type LLTO membranes are poor and the membranes are very fragile which currently prevents us to perform the lithium ion conductivity measurements but the impregnation of electrode material would increase the mechanical properties of porous electrolyte materials.

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