Structure and electrochemical properties of Zn and Co dual-doped (Li$_2$Co$_{1-x}$Zn$_x$Mn$_3$O$_8$) as cathode material for rechargeable lithium-ion batteries

Tze Qing Tan$^{1,2}$, Rozana Aina Maulat Osman$^{1,3}$, M. V. Reddy$^4$, Shing Fhan Khor$^5$ and Mohd Sobri Idris$^{1,2*}$

1 Centre for Frontier Materials Research, Universiti Malaysia Perlis, 01000 Kangar, Perlis, Malaysia.
2 School of Materials Engineering, Universiti Malaysia Perlis, Jejawi, 02600 Arau, Perlis, Malaysia.
3 School of Microelectronics Engineering, Universiti Malaysia Perlis, Pauh Putra, 02600 Arau, Perlis, Malaysia.
4 Advanced Batteries Lab, Department of Physics, National University of Singapore, Singapore 117542, Singapore.
5 School of Electrical System Engineering, Universiti Malaysia Perlis, Pauh Putra, 02600 Arau, Perlis, Malaysia.

Abstract. Spinel Zn doped Li$_2$CoMn$_3$O$_8$ (or also known as LiCo$_{0.5}$Mn$_{1.5}$O$_4$) yielding formula Li$_2$Co$_{1-x}$Zn$_x$Mn$_3$O$_8$ ($0 \leq x \leq 1$) were produced via conventional solid state method. XRD results and the variation of cell lattice and volume showed that the solid solution limit of these compositions was at $x=0.6$. Impurities were detected when the amount of Zn was beyond 60%. The discharge capacities deteriorate as Zn content was increased. However, these Zn doped samples exhibited excellent cycle-ability (99.9% capacity retention) throughout 50 charging and discharging cycles which indicated that doping of Zn could possibly stabilised the spinel structure.

1 Introduction

The significant finding of the first Li-ion cells by Sony in the early 1990s has strongly motivated the researches for better performance active materials in order to provide energy storage for some major applications, such as portable electronic devices and other potential applications. Considering cathode materials contributed the most influence on the performance of current Li-ion batteries, a wide variety of studies on cathode materials have been done for the past few decades to fully understand the factors that influence the electrochemical performance of lithium ion batteries and at the same time reducing the cost and simplifying the fabrication process.

An alternative spinel LiMn$_2$O$_4$ based cathode materials have been proposed as one of the most anticipating cathode materials after the discovery of lithium intercalation-deintercalation reversibility in LiMn$_2$O$_4$ by Thackeray and co-workers [1]. In addition, it is low cost, thermally stable and benevolent to the environment. Spinel LiMn$_2$O$_4$ with space group Fd-3m comprises lithium ions on tetrahedral 8a sites and manganese ions on octahedral 16d sites while oxygen ions in 32e sites [2]. However, this spinel suffered from capacity fading which becomes a huge hindrance from feasible use as cathode materials. The capacity fading especially at elevated temperature was due to the existence of cooperative Jahn-Teller distortion when more than 50% of Mn$^{3+}$ appeared [3]. One of the many solutions to reduce this fading is by replacing Mn partially by other elements (M) to increase the Mn valence in the spinel phase, and hence reducing the possibility of the presence of Jahn-Teller distortion. Such doping includes Ru [4], Gd [5], Cu [6], Co [7], Al [8], Mg [9,10], Zn [11], Ni [12] and others. Recently, there are studies focusing on dual substitutions to improve the structural stability and consequently its electrochemical performance [13–15]. On the basis of available literatures, it can be deduced that an interesting composition LiM$_{0.5}$Mn$_{1.5}$O$_4$ where exactly ¼ of the Mn was substituted can favour an ordering of 16d cations. Moreover, it is reported previously that substitution of Zn in LiM$_{0.5}$Mn$_{1.5}$O$_4$ resulted in a superstructure primitive cubic symmetry [11]. In addition, there are reports about Li-Zn cation inversion where partial Zn ions were located at Li ions sites [16,17].

Hence, in this study, we prepared Li$_2$Co$_{1-x}$Zn$_x$Mn$_3$O$_8$ by conventional solid-state reaction and characterized its structure as a function of Zn content. Structure and morphology of the compounds were characterised by X-ray diffraction (XRD) and scanning electron microscopy (SEM). Furthermore, this study also reports the electrochemical performance of Zn doped Li$_2$CoMn$_3$O$_8$.

2 Experimental

Zn doped Li$_2$CoMn$_3$O$_8$ (Li$_2$Co$_{0.5}$Zn$_{0.5}$Mn$_3$O$_8$) was produced via conventional solid state method [18] using acetate salts as starting materials. Stoichiometric amounts of lithium, cobalt, manganese, and zinc acetates were mixed and ground in acetone to aid homogenous mixing and grounding. Then, the compounds were heated at 400 °C for 12 hours with slow heating rate to
3 Results and discussion

Fig. 1 shows the XRD patterns of Li$_2$Co$_{1-x}$Zn$_x$Mn$_3$O$_8$ (0 ≤ $x$ ≤ 1.0) that were prepared at 800 °C in air. For the parent composition Li$_2$CoMn$_3$O$_8$ ($x=0$), the XRD pattern was matched with the ICDD database (No. PDF card: 01-070-4214). Furthermore, its reflections could be indexed by the cubic spinel structure with the space group of Fd-3m. For the Zn-doped Li$_2$CoMn$_3$O$_8$, the XRD patterns for Li$_2$Co$_{1-x}$Zn$_x$Mn$_3$O$_8$ (0 ≤ $x$ ≤ 0.4) were reasonably similar, except a small shoulder at the (400) reflection getting stronger as the amount of Zn was increased. However, the XRD patterns for $x=0.6$, 0.8 and 1.0 exhibited numerous additional reflections that could be indexed by the primitive symmetry with the space group of P2$_1$3. But three reflections were unable to be indexed (denoted as *) and it was believed that they belong to ZnMn$_3$O$_8$.

In this case, it is speculated that for $x ≥ 0.2$, the presence of relatively higher intensity of 220 reflection (2$θ$=31°) compared to the parent Li$_2$CoMn$_3$O$_8$ was probably due to Li-Zn cation inversion occurred whereby a partial of Zn ions are located at tetrahedral 8 (a) sites instead of octahedral 16 (d) sites as proposed by Ohzuku et al. [16]. This occurrence of Li-Zn cation inversion is plausibly because of the strong tetrahedral preference of Zn$^{2+}$. This partial occupancy of immobile Zn ions in the Li site will probably obstruct the diffusion of Li ions.

The variations of structural parameters and unit cell volume obtained by the least-square refinements of XRD data were shown in Table 1 and Fig. 2. The structural parameter and unit cell volume of the parent composition Li$_2$CoMn$_3$O$_8$ ($x=0$) obtained from least-square refinements were $a=8.1481(1)$ Å and $V=540.96(1)$ Å$^3$, respectively. The structural parameters and unit cell volume increased linearly within the error (3 e.s.d.s) until $x=0.6$, followed by slight reduced for $x=0.8$ and above. The changes of structural parameters obeyed the Vegard’s law as the impurities were observed in the XRD patterns for $x=0.8$ and 1.0. Thus, the solid solution limit for the Li$_2$Co$_{1-x}$Zn$_x$Mn$_3$O$_8$ was $x=0.6$.

The increase of structural parameters is probably due to the octahedral substitution of Zn$^{2+}$ ions (0.74 Å) which have larger ionic radii compared to Co$^{3+}$ (0.545 Å) ions [21]. However, the structural parameters decreased beyond $x=0.6$ was possibly due to the increase of Li/Zn cation inversion as mentioned previously whereby the ionic radii of Zn$^{2+}$ ions at tetrahedral sites is 0.60 Å which is smaller than Zn$^{2+}$ at octahedral sites.
Table 1: Structural parameters, unit cell volume and crystallite size of Li$_2$Co$_{1-x}$Zn$_x$Mn$_3$O$_8$ ($0 \leq x \leq 1.0$).

<table>
<thead>
<tr>
<th>$x$ in Li$<em>2$Co$</em>{1-x}$Zn$_x$Mn$_3$O$_8$</th>
<th>Space group</th>
<th>Lattice parameter, $a$ (Å)</th>
<th>Unit cell volume (Å$^3$)</th>
<th>Crystallite size (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x = 0.0$</td>
<td>Fd-3m</td>
<td>8.1481(1)</td>
<td>540.96(1)</td>
<td>661.3</td>
</tr>
<tr>
<td>$x = 0.2$</td>
<td>Fd-3m</td>
<td>8.1602(1)</td>
<td>543.39(1)</td>
<td>604.7</td>
</tr>
<tr>
<td>$x = 0.4$</td>
<td>Fd-3m</td>
<td>8.1812(1)</td>
<td>547.59(1)</td>
<td>594.1</td>
</tr>
<tr>
<td>$x = 0.6$</td>
<td>P2,3</td>
<td>8.1938(1)</td>
<td>550.12(2)</td>
<td>597.9</td>
</tr>
<tr>
<td>$x = 0.8$</td>
<td>P2,3</td>
<td>8.1821(2)</td>
<td>547.76(2)</td>
<td>510.8</td>
</tr>
<tr>
<td>$x = 1.0$</td>
<td>P2,3</td>
<td>8.1780(3)</td>
<td>546.95(3)</td>
<td>493.7</td>
</tr>
</tbody>
</table>

The average crystallite sizes of Li$_2$Co$_{1-x}$Zn$_x$Mn$_3$O$_8$ were calculated by the Dybye-Scherrer equation from the line width of the strongest reflection plane which refers to the (311) plane. The average crystallite size for all the samples obtained from the calculations are listed in Table 1. The parent composition Li$_2$CoMn$_3$O$_8$ ($x=0$) exhibited the largest crystallite size (661.3 Å) and the size decreased as Zn content increased whereby $x=1$ possessed the smallest size of 493.7 Å.

Microstructural images observed by SEM analysis of spinel Li$_2$Co$_{1-x}$Zn$_x$Mn$_3$O$_8$ ($0 \leq x \leq 1$) compounds synthesised at 800 °C are shown in Fig. 3. The images show typical solid state samples with random particle size distribution. Obviously, all the samples exhibit well developed particles of regular shape. The micrographs were taken at an appropriate magnification to emphasize the morphology of the samples. It is noticeable that all the particles are in micron size (<5 μm). From observation, the primary particle size increases as the Zn content increases.

Fig. 4 depicted the galvanostatic charge-discharge profile for 1st, 2nd, and 50th cycle of Li$_2$Co$_{1-x}$Zn$_x$Mn$_3$O$_8$ compounds that were synthesised at 800 °C. The cycling tests were carried out at a current rate of 15 mA g$^{-1}$ in the voltage window of 2.5-4.6 V vs. Li. All the cells possessed ~3.0 V of open circuit voltage and a flat voltage profile at ~4.0 V where the oxidation and reduction reaction occurs (except for $x=0.8$ and 1.0).

The discharge capacities vs cycle number plots were shown in Fig. 5. The discharging capacities deteriorated as doping of Zn increased. The initial discharging capacity of undoped Li$_2$CoMn$_3$O$_8$ is ~115.7 mAh g$^{-1}$ which was comparable to the theoretical capacity value (~147 mAh g$^{-1}$). The discharge capacity faded about 11.11 % after 50 cycles. Furthermore, the initial discharging capacity decreased from ~115.7 mAh g$^{-1}$ to ~68.1 mAh g$^{-1}$, ~63.7 mAh g$^{-1}$ and ~48.4 mAh g$^{-1}$ when 20%, 40% and 60% of Co was replaced by Zn, respectively. The discharging capacity dropped to ~15.6 mAh g$^{-1}$ and ~7.7 mAh g$^{-1}$ when 80% and 100% of Zn was doped. Although the discharging capacities continue to decrease as more Co was replaced by Zn, the discharge capacities can be retained approximately 99.9 % after 50 cycles for all the Zn doped samples. It is speculated that the capacities were affected by the immobile Zn ions in the Li site which obstructed the diffusion of Li ions. Nonetheless, the doping of Zn stabilized the structure during charging and discharging cycle.
4 Conclusion

Zn doped Li$_2$Co$_{1-x}$Zn$_x$Mn$_3$O$_8$ (Li$_2$Co$_{1-x}$Zn$_x$Mn$_3$O$_8$) were synthesised via simple conventional solid state route. In this systematic study, the relationship of the Zn content and electrochemical performance of Zn doped Li$_2$Co$_{1-x}$Zn$_x$Mn$_3$O$_8$ (Li$_2$Co$_{1-x}$Zn$_x$Mn$_3$O$_8$) was established. Li/Zn cation inversion is believed to impede the diffusion of Li ion and hence influenced the discharge capacity. However, Zn was found to stabilise the spinel structure as these Zn-doped compositions demonstrated a stable cycle-ability in Li-ion batteries. Further investigation will be done to determine or estimate the amount of Li-Zn cation inversion.

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References