CHAPTER 2

LITERATURE REVIEW

2.1 Development of lithium ion batteries

The year 1991 marks the beginning of lithium ion battery technology (Ozhuku and Brodd, 2007). Lithium is the lightest metal and is also one of the metals with highest reduction potential. These criteria contribute to theoretical capacity of 3860 Ah/kg. This value is high compared to zinc and lead which is 820 Ah/kg and 260 Ah/kg respectively (Vincent, 2000). Lithium ion batteries become best choice for the fuel cell–battery hybrid devices among other battery systems such as nickel-cadmium, nickel-metal hydride and zinc air. This is due to the high energy density and good cycling performance of lithium ion batteries (Prakash et al., 2009).

2.2 Cathode materials for lithium ion batteries

Being an important component in batteries, cathode materials play a significant role in the electrochemical performance of a battery. The following requirements are key factors for successful cathode materials (Whittingham, 2004):

(a) Contains transition metals that are readily reduced / oxidized;

(b) The material should able to react with lithium reversibly and does not change the host structure when lithium is inserted;

(c) The material is able to react with lithium providing high capacity and high voltage in order to get high energy storage;

(d) Able to react with lithium very rapidly for high power density;
(e) Good electronic conductor enabling easy movement of electrons during chemical reaction;

(f) Stable structure during charge and discharge processes;

(g) Low cost and environmentally friendly.

LiCoO$_2$, LiNiO$_2$, LiMn$_2$O$_4$ are some of the examples of cathode materials used in lithium ion batteries (Ritchie et al., 1999).

**Lithium Cobalt Oxide**

Lithium Cobalt Oxide (LiCoO$_2$) has theoretical capacity of 274 mAh g$^{-1}$ and energy density of 1070 Wh kg$^{-1}$ (Burukhin et al., 2002). There are two types of LiCoO$_2$, low temperature LiCoO$_2$ (LT- LiCoO$_2$) and high temperature LiCoO$_2$ (HT- LiCoO$_2$) (Kang et al., 1999; Yoon and Kim., 1999; Levasseur et al., 2000). LT- LiCoO$_2$ has spinel structure with space group $Fd\bar{3}m$ and HT- LiCoO$_2$ exhibits rhombohedral structure with space group $R\bar{3}m$ (Santiago et al., 2003; Antolini, 2004; Brylev et al., 2003). Fig 2.1 depicts the structure of LiCoO$_2$.

Kang et al (1999) synthesized LT- LiCoO$_2$ and HT- LiCoO$_2$ using citrate sol gel method. XRD from this work is shown in Fig 2.2. The diffractogram of HT- LiCoO$_2$ exhibits (003), (101), (006), (012), (015), (107), (018), (110) and (113) peaks while the LT- LiCoO$_2$ exhibits (111), (311), (222), (400), (331), (333), (440) and (531) reflection peaks.
In practice, due to structural instability during delithiation, only half of the theoretical capacity is achieved (Needham et al., 2007). Cobalt has been substituted with other transition metals metallic elements in order to get better cycling performance and reduce toxicity (Sathiyamoorthi et al., 2008). Aluminium has been used to substitute cobalt (Amdouni et al., 2003; Myung et al., 2001). LiTi$_{0.01}$Co$_{0.99}$O$_2$ delivers an initial charge capacity of 157 mAh g$^{-1}$ and initial discharge capacity 148 mAh g$^{-1}$. The initial discharge capacity is increased with the doping of titanium in LiCoO$_2$. The capacity retained at 135 mAh g$^{-1}$ after 10 cycles. Further increase of dopant content did not improve the capacity (Gopukumar et al., 2003).

Sathiyamoorthi et al (2008) prepared LiCo$_{0.8}$M$_{0.2}$O$_2$ (M= Mg, Ca and Ba). Only LiCo$_{0.8}$Mg$_{0.2}$O$_2$ exhibited slight increase in initial discharge capacity of 196 mAh g$^{-1}$ compared to 191.6 mAh g$^{-1}$ for LiCoO$_2$. Discharge capacity of LiCoO$_2$ reduced to 77.5 mAh g$^{-1}$ after 25 cycles with capacity loss about 22.5 %. LiCo$_{0.8}$Mg$_{0.2}$O$_2$ retained 97.6 % of its capacity at 25$^{th}$ cycle which gives the value of 191.3 mAh g$^{-1}$. LiCo$_{0.8}$Ca$_{0.2}$O$_2$ and LiCo$_{0.8}$Ba$_{0.2}$O$_2$ delivered discharge capacity of 178.5 mAh g$^{-1}$ and 164 mAh g$^{-1}$.
respectively. The capacity loss of both samples is around 2.7 % and 3.5 %. Hence Ga and Ba doping helped reduce capacity loss although initial discharge capacity is lower than LiCoO$_2$ being 183.5 mAh g$^{-1}$ and 170 mAh g$^{-1}$ respectively.

Fig 2.2: XRD of (a) HT- LiCoO$_2$ (b) LT- LiCoO$_2$ (Kang et al., 1999)

Galium has been substituted in LiCoO$_2$ (Tong et al., 2006). Both LiCoO$_2$ and Ga doped
LiCoO$_2$ deliver nearly similar first discharge capacity of ~160 mAh g$^{-1}$ at 2.8 V cut-off. After 50 cycles, the discharge capacity of LiCoO$_2$ only retains 43.7% of its initial capacity. LiCo$_{0.975}$Ga$_{0.025}$O$_2$ retains 87.9% of its initial capacity at the end of 50th cycle.

Manganese doped LiCoO$_2$ has been studied by Suresh et al., (2005a). Charge–discharge cycling shows that LiCo$_{0.8}$Mn$_{0.2}$O$_2$ exhibits the best cycling stability. Initial discharge capacity of 143 mAh g$^{-1}$ was obtained by LiCo$_{0.8}$Mn$_{0.2}$O$_2$ while LiCoO$_2$ delivers 125 mAh g$^{-1}$. The capacity stabilized at 138 mAh g$^{-1}$ from 4th cycle until 25th cycle for LiCo$_{0.8}$Mn$_{0.2}$O$_2$. LiCoO$_2$ only delivers about 120 mAh g$^{-1}$ at 25th cycle.

Table 2.1: Summary of LiCoO$_2$ and its derivatives

<table>
<thead>
<tr>
<th>Material</th>
<th>Initial Capacity (mAh g$^{-1}$)</th>
<th>Capacity /Cycle (mAh g$^{-1}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiCoO$_2$</td>
<td>134.0</td>
<td>128.0 (10$^{th}$ cycle)</td>
<td>Gopukumar et al., 2003</td>
</tr>
<tr>
<td>LiTi$<em>{0.01}$Co$</em>{0.99}$O$_2$</td>
<td>148.0</td>
<td>135.0 (10$^{th}$ cycle)</td>
<td>Gopukumar et al., 2003</td>
</tr>
<tr>
<td>LiCoO$_2$</td>
<td>191.6</td>
<td>77.5 (25$^{th}$ cycle)</td>
<td>Sathiyamoorthi et al., 2008</td>
</tr>
<tr>
<td>LiCo$<em>{0.8}$Mg$</em>{0.2}$O$_2$</td>
<td>196.0</td>
<td>91.3 (25$^{th}$ cycle)</td>
<td>Sathiyamoorthi et al., 2008</td>
</tr>
<tr>
<td>LiCo$<em>{0.8}$Ca$</em>{0.2}$O$_2$</td>
<td>183.5</td>
<td>78.5 (25$^{th}$ cycle)</td>
<td>Sathiyamoorthi et al., 2008</td>
</tr>
<tr>
<td>LiCo$<em>{0.8}$Ba$</em>{0.2}$O$_2$</td>
<td>170.0</td>
<td>64.0 (25$^{th}$ cycle)</td>
<td>Sathiyamoorthi et al., 2008</td>
</tr>
<tr>
<td>LiCoO$_2$</td>
<td>160.0</td>
<td>69.9 (50$^{th}$ cycle)</td>
<td>Tong et al., 2006</td>
</tr>
<tr>
<td>LiCo$<em>{0.975}$Ga$</em>{0.025}$O$_2$</td>
<td>160.0</td>
<td>140.6 (50$^{th}$ cycle)</td>
<td>Tong et al., 2006</td>
</tr>
<tr>
<td>LiCoO$_2$</td>
<td>125.0</td>
<td>120.0 (25$^{th}$ cycle)</td>
<td>Suresh et al., 2005</td>
</tr>
<tr>
<td>LiCo$<em>{0.8}$Mn$</em>{0.2}$O$_2$</td>
<td>143.0</td>
<td>138.0 (25$^{th}$ cycle)</td>
<td>Suresh et al., 2005</td>
</tr>
</tbody>
</table>
Lithium Nickel Oxide

Lithium Nickel Oxide (LiNiO$_2$) is another cathode material for lithium ion batteries. It has high discharge capacity and is cheaper compared to LiCoO$_2$ (Sun et al., 2006; Choi et al., 1998). LiNiO$_2$ has rhombohedral structure with space group of R3m (Chang and Kumta., 2005; Kalyani and Kalaiselvi., 2005). The structure of LiNiO$_2$ is presented by Fig 2.3. Fig 2.4 indicates XRD pattern of LiNiO$_2$.

![Fig 2.3: Structure of LiNiO$_2$ (Cao et al., 2009)](image-url)
Li$_{1-x}$Ni$_{1+x}$O$_2$ ($x>0$) results in presence of Ni$^{2+}$ in the lithium sites that reduces lithium diffusion. Unstable ideal stoichiometry of LiNiO$_2$ affects the electrochemical performances (Yamada et al., 1995; Delmas et al., 1999; Molenda et al., 2002; Kalyani and Kalaiselvi., 2005; Arai et al., 1997).

LiNiO$_2$ has been substituted with titanium using direct molten salt synthesis (Ha et al., 2006). LiNi$_{0.975}$Ti$_{0.025}$O$_2$ showed better capacity retention compared to LiNiO$_2$. However LiNi$_{0.95}$Ti$_{0.05}$O$_2$ and LiNi$_{0.9}$Ti$_{0.1}$O$_2$ exhibit less capacity retention compared to LiNi$_{0.975}$Ti$_{0.025}$O$_2$ and LiNiO$_2$. This is because titanium is electrochemically inactive and delivers less capacity as the titanium content increases in LiNiO$_2$. Initial capacity of LiNi$_{0.975}$Ti$_{0.025}$O$_2$ is 171 mAh g$^{-1}$ and is retained 164 mAh g$^{-1}$ on the 30$^{th}$ cycle.

Song et al. (2009) reported on LiNiO$_2$, LiNi$_{0.975}$Ga$_{0.025}$O$_2$, LiNi$_{0.975}$Al$_{0.025}$O$_2$, LiNi$_{0.995}$Ti$_{0.005}$O$_2$ and LiNi$_{0.990}$Al$_{0.005}$Ti$_{0.005}$O$_2$. LiNi$_{0.990}$Al$_{0.005}$Ti$_{0.005}$O$_2$ exhibits high initial discharge capacity of 196.3 mAh g$^{-1}$ compared to other compositions. LiNiO$_2$, LiNi$_{0.975}$Ga$_{0.025}$O$_2$, LiNi$_{0.975}$Al$_{0.025}$O$_2$ and LiNi$_{0.995}$Ti$_{0.005}$O$_2$ deliver initial discharge capacity of 161.8 mAh g$^{-1}$, 174.4 mAh g$^{-1}$, 170.5 mAh g$^{-1}$ and 172.9 mAh g$^{-1}$.
respectively. However at the end of 20th cycle, LiNiO$_2$ delivered high discharge capacity of 143.5 mAh g$^{-1}$ while LiNi$_{0.975}$Ga$_{0.025}$O$_2$, LiNi$_{0.975}$Al$_{0.025}$O$_2$, LiNi$_{0.995}$Ti$_{0.005}$O$_2$ and LiNi$_{0.990}$Al$_{0.005}$Ti$_{0.005}$O$_2$ exhibited 117.4 mAh g$^{-1}$, 90.5 mAh g$^{-1}$, 85.5 mAh g$^{-1}$ and 113.8 mAh g$^{-1}$ respectively.

LiNiO$_2$ has been doped with non-transition elements such as gallium and magnesium (Yu et al., 2000). Simultaneous doping of these elements in the LiNiO$_2$ improved cycling performance. LiGa$_{0.02}$Mg$_{0.03}$Ni$_{0.95}$O$_2$ exhibited discharge capacity of 135 mAh g$^{-1}$. This value is almost constant during 20 cycles and the capacity loss is only about 1.5%. While LiNiO$_2$ losses its capacity about 12.2% after 20 cycles.

The properties of Al and Mg doped LiNiO$_2$ have been studied by Kim et al., (2006). LiNi$_{0.9}$Al$_{0.05}$Mg$_{0.05}$O$_2$ delivered high initial discharge capacity of 173 mAh g$^{-1}$ and stabilizes around ~180 mAh g$^{-1}$ at 40th cycle. The capacity fading can be observed when aluminium content increased to 0.10 because aluminium is electrochemically inactive. These results suggest that ratio of 5% aluminium and magnesium substitution to nickel improved the structure stability and raises the capacity.

Table 2.2: Summary of LiNiO$_2$ and its derivatives

<table>
<thead>
<tr>
<th>Material</th>
<th>Initial Capacity (mAh g$^{-1}$)</th>
<th>Capacity /Cycle (mAh g$^{-1}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiNiO$_2$</td>
<td>161.8</td>
<td>143.5 (20th cycle)</td>
<td>Song et al., 2009</td>
</tr>
<tr>
<td>LiNi$<em>{0.975}$Ga$</em>{0.025}$O$_2$</td>
<td>174.4</td>
<td>117.4 (20th cycle)</td>
<td>Song et al., 2009</td>
</tr>
<tr>
<td>LiNi$<em>{0.975}$Al$</em>{0.025}$O$_2$</td>
<td>170.5</td>
<td>90.5 (20th cycle)</td>
<td>Song et al., 2009</td>
</tr>
<tr>
<td>LiNi$<em>{0.995}$Ti$</em>{0.005}$O$_2$</td>
<td>172.9</td>
<td>85.5 (20th cycle)</td>
<td>Song et al., 2009</td>
</tr>
</tbody>
</table>
LiNi$_{0.990}$Al$_{0.005}$Ti$_{0.005}$O$_2$ & 196.3 & 113.8 (20$^{\text{th}}$ cycle) & Song et al., 2009 \\
LiNi$_{0.975}$Ti$_{0.025}$O$_2$ & 171.0 & 164.0 (30$^{\text{th}}$ cycle) & Ha et al., 2006 \\
LiGa$_{0.02}$Mg$_{0.03}$Ni$_{0.95}$O$_2$ & 135.0 & 133.0 (20$^{\text{th}}$ cycle) & Yu et al., 2000 \\
LiNi$_{0.9}$Al$_{0.05}$Mg$_{0.05}$O$_2$ & 173.0 & 180.0 (40$^{\text{th}}$ cycle) & Kim et al., 2006 \\

**Lithium Manganese Oxide**

Lithium manganese oxide (LiMn$_2$O$_4$) is low cost, has high reduction potential and is nontoxic (Hon et al., 2002; Vivekanandhan et al., 2006; Fey et al., 2006a; Ouyang et al., 2009). Fig 2.5 shows the structure of LiMn$_2$O$_4$. LiMn$_2$O$_4$ has spinel structure with Fd3m space group. Its diffractogram shows (111), (311) and (400) reflections (Myung et al., 2000). These peaks correspond to the lithium ions at tetrahedral 8a sites and manganese ions at 16 d sites (Yi et al., 2009). Fig 2.6 displays the XRD pattern of LiMn$_2$O$_4$ as reported in literature (Wu et al., 2006).

Among the problems preventing this material for commercialization are Jahn–Teller distortion and dissolution of Mn ion in the electrolyte during cycling (Li et al., 2007). LiMn$_2$O$_4$ undergoes phase change from cubic to tetragonal during Jahn Teller distortion. As a result, anisotropic volume change occurs, which causes capacity fading (Horn et al., 1999; Verhoeven et al., 2000; Yamada et al., 1999; Li et al., 2009; Chung et al., 2004).
Fig 2.5: Structure of LiMn$_2$O$_4$ (Sugiyama et al., 2001)

Fig 2.6: XRD of LiMn$_2$O$_4$ (a) spray drying method (b) solid state reaction (Wu et al., 2006)
According Tsang and Manthiram., (1996) controlled particle size of LiMn$_2$O$_4$ is one of the ways to overcome this problem. Partial substitution of manganese ions with other metal cations can reduce Jahn-Teller distortion and stabilize the cubic structure and overcome capacity fading (Lee et al., 2000; Deng et al., 2004). Examples include LiM$_x$Mn$_{2-x}$O$_4$ ($M = \text{Co and Al}, \ 0 \leq x \leq 0.3$) (Bakenov and Taniguchi., 2005), LiM$_{0.05}$Mn$_{1.95}$O$_4$ ($M = \text{Al, Co and Zn}$) (He et al., 2006), LiMn$_2$O$_4$ substituted with selenium (Yoon et al., 2002), chromium (Wang and Lu., 2003), aluminium (Julien et al., 2002), magnesium (Subramania et al., 2005) and etc.

Subramania et al., (2005) have studied LiMg$_y$Mn$_{2-y}$O$_4$ ($0 \leq y \leq 0.2$) and obtained an initial discharge capacities for LiMn$_2$O$_4$, LiMg$_{0.05}$Mn$_{1.95}$O$_4$, LiMg$_{0.1}$Mn$_{1.9}$O$_4$, LiMg$_{0.15}$Mn$_{1.85}$O$_4$ and LiMg$_{0.2}$Mn$_{1.8}$O$_4$ as 137 mAh g$^{-1}$, 132 mAh g$^{-1}$, 118 mAh g$^{-1}$, 100 mAh g$^{-1}$ and 90 mAh g$^{-1}$ respectively. After 25 cycles, 75 % of capacity remained in LiMn$_2$O$_4$. LiMg$_{0.05}$Mn$_{1.95}$O$_4$ and LiMg$_{0.1}$Mn$_{1.9}$O$_4$ loss about 12 % and 2.33 % of its capacity respectively. LiMg$_{0.15}$Mn$_{1.85}$O$_4$ and LiMg$_{0.2}$Mn$_{1.8}$O$_4$ retained 93 % and 90.5 % of the first discharge capacity respectively. It can be confirmed that the composition of LiMg$_{0.1}$Mn$_{1.9}$O$_4$ showed better cycling performance.

The structural and electrochemical properties of chromium substituted LiMn$_2$O$_4$ was studied by Su et al., (2004). Initial discharge capacity of LiMn$_2$O$_4$ was 118.9 mAh g$^{-1}$ which decreased to 87.5 mAh g$^{-1}$ after 30 cycles. LiCr$_y$Mn$_{2-y}$O$_4$ at $y = 0.03$ and 0.05 delivered discharge capacity of 123.1 mAh g$^{-1}$ and 121.6 mAh g$^{-1}$ respectively. LiCr$_{0.03}$Mn$_{1.97}$O$_4$ loses its capacity about 14.4 % to 105.3 mAh g$^{-1}$ while LiCr$_{0.05}$Mn$_{1.95}$O$_4$ only lost about 12.2 % at 30th cycle. These results are stating that the doping of chromium improved the structural stability during lithium intercalation.
Electrochemical studies have been performed on LiM_{0.05}Mn_{1.95}O_4 with M = B, Al, Co and Ni (Lee et al., 2000). Initial discharge capacity of LiMn_2O_4, LiB_{0.05}Mn_{1.95}O_4, LiAl_{0.05}Mn_{1.95}O_4 LiCo_{0.05}Mn_{1.95}O_4 and LiNi_{0.05}Mn_{1.95}O_4 is 136 mAh g^{-1}, 95 mAh g^{-1}, 133 mAh g^{-1}, 122 mAh g^{-1} and 125 mAh g^{-1} respectively. After 100 cycles, the capacity loss of the materials stated earlier is 16 %, 44 %, 5 %, 8 % and 2 % respectively. From the results, it can be explained that the substitution improved the capacity retention except for Boron-substituted sample. Structural instability was the reason for this fading.

LiMn_2O_4 was doped with aluminium, cobalt and zinc (He et al., 2006). Undoped sample exhibits initial capacity of 119 mAh g^{-1}. LiAl_{0.05}Mn_{1.95}O_4 delivers initial capacity of 110 mAh g^{-1} while LiCo_{0.05}Mn_{1.95}O_4 exhibits around 106 mAh g^{-1}. Lowest initial discharge capacity of 96 mAh g^{-1} was exhibited by LiZn_{0.05}Mn_{1.95}O_4. However capacity of LiMn_2O_4 decreased to 25 mAh g^{-1} after 30 cycles. Capacity loss of LiAl_{0.05}Mn_{1.95}O_4, LiCo_{0.05}Mn_{1.95}O_4 and LiZn_{0.05}Mn_{1.95}O_4 were reported as 11 %, 3 % and 6 % respectively at the end of 30 cycles. Co doped LiMn_2O_4 exhibits better cycling performance. Structural distortion was reduced by the substitution.

Table 2.3: Summary of LiMn_2O_4 and its derivatives

<table>
<thead>
<tr>
<th>Material</th>
<th>Initial Capacity (mAh g^{-1})</th>
<th>Capacity /Cycle (mAh g^{-1})</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiMn_2O_4</td>
<td>137.0</td>
<td>102.8 (25th cycle)</td>
<td>Subramania et al., 2005</td>
</tr>
<tr>
<td>LiMg_{0.05}Mn_{1.95}O_4</td>
<td>132.0</td>
<td>116.2 (25th cycle)</td>
<td>Subramania et al.,2005</td>
</tr>
<tr>
<td>LiMg_{0.1}Mn_{1.9}O_4</td>
<td>118.0</td>
<td>115.3 (25th cycle)</td>
<td>Subramania et al., 2005</td>
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<tr>
<td>LiMg_{0.15}Mn_{1.85}O_4</td>
<td>100.0</td>
<td>90.0 (25th cycle)</td>
<td>Subramania et al., 2005</td>
</tr>
<tr>
<td>Olivines (LiMPO₄_x M = Fe, Co)</td>
<td></td>
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<tr>
<td>--------------------------------</td>
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<tr>
<td>Olivine type lithium iron phosphate (LiFePO₄) is one of the cathode materials getting attention worldwide because of its high theoretical specific capacity of 170 mAh g⁻¹ and operates at flat voltage of 3.4 V versus lithium (Luo et al., 2008; Li et al., 2007; Kwon et al., 2004). The flat discharge voltage of LiFePO₄ enables safety usage for organic electrolytes (Kim et al., 2007b). Apart from that, it is also inexpensive, less toxic and</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Compound</th>
<th>Voltage (1st cycle)</th>
<th>Voltage (2nd cycle)</th>
<th>Reference</th>
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<tr>
<td>LiMg₀.₂Mn₁.₈O₄</td>
<td>90.0</td>
<td>81.5 (25th cycle)</td>
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<tr>
<td>LiMn₂O₄</td>
<td>118.9</td>
<td>87.5 (30th cycle)</td>
<td>Su et al., 2004</td>
</tr>
<tr>
<td>LiCr₀.₀₃Mn₁.₉₇O₄</td>
<td>123.1</td>
<td>105.3 (30th cycle)</td>
<td>Su et al., 2004</td>
</tr>
<tr>
<td>LiCr₀.₀₅Mn₁.₉₅O₄</td>
<td>121.6</td>
<td>106.8 (30th cycle)</td>
<td>Su et al., 2004</td>
</tr>
<tr>
<td>LiMn₂O₄</td>
<td>136.0</td>
<td>114.2 (100th cycle)</td>
<td>Lee et al., 2000</td>
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<td>LiB₀.₀₅Mn₁.₉₅O₄</td>
<td>95.0</td>
<td>53.2 (100th cycle)</td>
<td>Lee et al., 2000</td>
</tr>
<tr>
<td>LiAl₀.₀₅Mn₁.₉₅O₄</td>
<td>133.0</td>
<td>126.4 (100th cycle)</td>
<td>Lee et al., 2000</td>
</tr>
<tr>
<td>LiCo₀.₀₅Mn₁.₉₅O₄</td>
<td>122.0</td>
<td>112.2 (100th cycle)</td>
<td>Lee et al., 2000</td>
</tr>
<tr>
<td>LiNi₀.₀₅Mn₁.₉₅O₄</td>
<td>125.0</td>
<td>122.5 (100th cycle)</td>
<td>Lee et al., 2000</td>
</tr>
<tr>
<td>LiMn₂O₄</td>
<td>119.0</td>
<td>25.0 (30th cycle)</td>
<td>He et al., 2006</td>
</tr>
<tr>
<td>LiAl₀.₀₅Mn₁.₉₅O₄</td>
<td>110.0</td>
<td>97.9 (30th cycle)</td>
<td>He et al., 2006</td>
</tr>
<tr>
<td>LiCo₀.₀₅Mn₁.₉₅O₄</td>
<td>106.0</td>
<td>102.8 (30th cycle)</td>
<td>He et al., 2006</td>
</tr>
<tr>
<td>LiZn₀.₀₅Mn₁.₉₅O₄</td>
<td>96.0</td>
<td>90.2 (30th cycle)</td>
<td>He et al., 2006</td>
</tr>
</tbody>
</table>
Chapter 2 Literature Review

exhibits better thermal stability compared to LiNiO$_2$, LiCoO$_2$ and LiMn$_2$O$_4$ (Bauer et al., 2005; Chang et al., 2006; Chen et al., 2008). The structure of LiFePO$_4$ is as depicted in Fig 2.7.

![Fig 2.7: Structure of LiFePO$_4$ (Nyten et al., 2006)](image)

However poor electronic conductivity and low lithium diffusion have limited its application (Lee and Teja., 2005; Ojczyk et al., 2007; Zheng et al., 2008a; Gao et al., 2009; Konarova et al., 2009). Slow diffusion of lithium ions at the interface of LiFePO$_4$ can be improved by particle size reduction (Lee et al., 2005; Yang et al., 2005). Many efforts have been taken towards increasing the conductivity such as carbon coating (Shin et al., 2006; Kuwahara et al., 2008; Prosini et al., 2001; Chung and Kim., 2004; Belharouak et al., 2005) and doping (Wang et al., 2005; Liu et al., 2006; Shin et al., 2008; Sun et al., 2009; Ou et al., 2008).
LiCoPO$_4$ is another interesting cathode material in olive type structure group (Kishore et al., 2005; Bramnik et al., 2005; Wolfenstine, 2006; Huang et al., 2005). High theoretical capacity of LiCoPO$_4$ about 167 mAh g$^{-1}$ is considered as one of the main factors to be applied in lithium ion batteries (Rabanal et al., 2006; Wolfenstine et al., 2007; Li et al., 2009). It has higher energy density $\sim 800$ Wh kg$^{-1}$ compared to LiCoO$_2$ which shows $\sim 540$ Wh kg$^{-1}$ (Martin et al., 2008; Han et al., 2009; Wolfenstine et al., 2005). However LiCoPO$_4$ undergoes partial decomposition beyond 4.3 V (Martin et al., 2008) and poor lithium ion diffusion (Grigoronova et al., 2005; Han et al., 2009). This problem can be overcome by doping (Kishore et al., 2005; Li et al., 2009) and reduced particle size (Rabanal et al., 2006).

**Lithium Nickel Vanadate**

Lithium nickel vanadate also known as lithium nickel vanadium oxide (LiNiVO$_4$) is getting attention as a potential candidate for cathode material with its high voltage of 4.8 V versus Li$^+$ (Prabaharan et al., 1997; Fey et al., 1997). High voltage of cathode materials promise great energy density in batteries which is an important aspect in rechargeable batteries among other aspects such as long cycling, safety, stable charge-discharge etc (Lu et al., 1999; Liu et al., 2002). An inverse spinel structure of LiNiVO$_4$ is found to be another attractive factor compared to spinels. The structure of LiNiVO$_4$ is shown in Fig 2.8.

In inverse spinels Li and Ni atoms occupy the octahedrally coordinated interstices equally and randomly and the V atoms occupy the tetrahedrally coordinated interstices (Liu et al., 2002; Bhuvaneswari et al., 2005; Kalyani et al., 2002). On comparison to normal spinels such as LiMn$_2$O$_4$, Li and Ni atoms in LiNiVO$_4$ replace the two Mn
atoms and the V atoms replace the Li atom in LiMn$_2$O$_4$ (Liu et al., 2002; Raveendranath et al., 2006).

![Diagram of LiNiVO$_4$](image)

**Fig 2.8: Structure of LiNiVO$_4$ (Fey et al., 1999)**

Deep interest in this inverse spinel LiNiVO$_4$ enables research on various types of synthesis methods as it is main point to produce good physical and electrochemical properties (Kalyani et al., 2002).

LiNiVO$_4$ has been prepared by the solution precipitation method by Fey et al., (1999). pH value was adjusted during preparation by adding diluted nitric acid or ammonium hydroxide solution. XRD confirmed that only the product obtained at pH=3 gave pure LiNiVO$_4$ as confirmed by JCPDS data. The samples at pH=7 and pH=11 contain NiO impurities as stated in Fig 2.9.
Initial discharge capacity of LiNiVO$_4$ with pH=3, pH=7 and pH=11 is 24 mAh g$^{-1}$, 19 mAh g$^{-1}$ and 23 mAh g$^{-1}$ respectively. The values decrease to 22 mAh g$^{-1}$, 18 mAh g$^{-1}$ and 16 mAh g$^{-1}$ at second cycle. The sample of pH=3 exhibits better cycling performance.

Soft chemistry approach to prepare LiNiVO$_4$ has been carried out by Kalyani et al., (2002). Starch was added as carbonaceous fuel in this method. Impurities such as NiO and Li$_3$VO$_4$ were found to be absent for all the samples sintered from 400°C to 800°C. First discharge capacity of 90 mAh g$^{-1}$ decreased to nearly 20 mAh g$^{-1}$ at the end of fifth cycle as displayed by the Fig 2.10. Oxidation of electrolyte at high voltage is considered as one of the reasons for this capacity fading.
Glycerol assisted gel combustion was used to synthesis LiNiVO₄ (Vivekanandhan et al., 2004). Product obtained at 450°C for 12 hours was free from impurities and showed crystallite size of 39 nm. Cycling studies was not reported in this work.

Lu et al. (1999) synthesized LiNiVO₄ using solid state reaction. Impurities such as LiVO₃, LiVO₂·0.5H₂O and NiO were present at quenching temperatures of 500°C and 600°C. NiO was still present at the quenching temperatures of 700°C, 800°C and 1000°C. Calcination at 700°C for 6 hours diminished the impurity completely. Higher calcination temperature of 800°C required only 4 hours for the formation of pure LiNiVO₄. Microstructured LiNiVO₄ was obtained after calcination at low temperature. Electrochemical studies were not included in this work.

Lai et al. (2001) obtained LiNiVO₄ by solid state reaction and complex-precipitate gel method. Both samples were cycled in the range of 3.0 – 4.8 V under the current drain of 0.2 mA/cm². Fig 2.11 presents the curve of specific capacity as reported. Eventhough the first discharge capacity of LiNiVO₄ by solid state reaction is around 59.8 mAh g⁻¹.
and by complex-precipitate gel method is nearly 47.0 mAh g\(^{-1}\), the capacity loss is high after the first cycle.

Fig 2.11: Specific capacity of (a) complex-precipitate gel method (b) solid state reaction (Lai et al., 2001)

2.3 Sol gel method

The sol gel method is proven as an effective method to produce electrode materials compared to traditional solid state reaction in terms of (Fu et al., 2005):

(a) Homogeneity

(b) Lower synthesis temperature

(c) Shorter sintering time

(d) Better crystallinity
(e) Uniform particle distribution

(f) Smaller particle size

Based on these properties, sol gel method is used widely to synthesise electrode materials for lithium ion batteries (Khomane et al., 2008; Liu et al., 2004; Yi et al., 2006 and Sun, 1997). Spinel Li$_{1.03}$Mn$_2$O$_4$ was prepared by sol gel method using glycolic acid as chelating agent by at lower temperature and shorter synthesis time (Sun, 1997). Better electrochemical performance was exhibited using LiMn$_2$O$_4$ prepared by the sol gel method (Yi et al., 2006).

2.4 Coating of cathode materials

Cathode materials were further improved by coating with oxides. The coatings avoid direct contact of active material with electrolyte (Li et al., 2006). A lot of research were carried out on ZnO coated Li$_{0.9}$Mn$_{0.9}$Ni$_{0.1}$O$_2$ (Suresh et al., 2005), TiO$_2$ coated Li[Li$_{0.2}$Mn$_{0.54}$Ni$_{0.13}$Co$_{0.13}$]O$_2$ (Zheng et al., 2008), La$_2$O$_3$ coated LiNi$_{1.8}$Co$_{0.2}$O$_2$ (Fey et al., 2005), TiO$_2$ coated LiMn$_2$O$_4$ (Yu et al., 2006), ZnO coated LiNi$_{0.5}$Mn$_{1.5}$O$_4$ (Sun et al., 2003), CeO$_2$ coated LiMn$_2$O$_4$ (Ha et al., 2007), ZnO coated LiCoO$_2$ (Fang et al., 2004), Co$_3$O$_4$ coated LiCoO$_2$ (Fey et al., 2005), Al$_2$O$_3$ coated LiCoO$_2$ (Liu et al., 2002) and etc.

Li$_{0.9}$Mn$_{0.9}$Ni$_{0.1}$O$_2$ was coated with ZnO to improve the electrochemical performance (Suresh et al., 2005). Even though initial discharge capacity of bare and ZnO coated Li$_{0.9}$Mn$_{0.9}$Ni$_{0.1}$O$_2$ was about 215 mAh g$^{-1}$, the discharge capacity of bare Li$_{0.9}$Mn$_{0.9}$Ni$_{0.1}$O$_2$ decreased about 25% at 50$^{th}$ cycle. Discharge capacity of ZnO coated
Li$_{0.9}$Mn$_{0.9}$Ni$_{0.1}$O$_2$ still maintained at 210 mAh g$^{-1}$ at the end of 50th cycle. ZnO coating stabilized the capacity of Li$_{0.9}$Mn$_{0.9}$Ni$_{0.1}$O$_2$ as reported by Suresh and co-workers.

Cycle efficiency of LiNi$_{0.8}$Co$_{0.2}$O$_2$ was improved when coated with La$_2$O$_3$. Initial charge and discharge capacity of pristine LiNi$_{0.8}$Co$_{0.2}$O$_2$ was found to be 203 mAh g$^{-1}$ and 185 mAh g$^{-1}$ respectively. The values were higher for 1.0 wt. % La$_2$O$_3$ coated LiNi$_{0.8}$Co$_{0.2}$O$_2$ which reached charge capacity of 206 mAh g$^{-1}$ and discharge capacity of 199 mAh g$^{-1}$. The initial cycle efficiency was also higher at about 96.6 % for coated LiNi$_{0.8}$Co$_{0.2}$O$_2$ compared to 91.1 % for pristine. According to Fey and co-workers (2005) LiNi$_{0.8}$Co$_{0.2}$O$_2$. La$_2$O$_3$ coating protects the active material from HF attack and improved the capacity (Fey et al., 2005).

Pristine LiMn$_2$O$_4$ exhibited high initial discharge capacity of 107 mAh g$^{-1}$ at 0.5 C and decreased to 98 mAh g$^{-1}$ at 40th cycle. While 2 % CeO$_2$ coated LiMn$_2$O$_4$ released 101 mAh g$^{-1}$ at initial discharge capacity and 97 mAh g$^{-1}$ at 40th cycle. Capacity retention of pristine sample is only 92 % compared to 96 % for coated sample. This shows that the CeO$_2$ coating is able to improve capacity retention (Ha et al., 2007).

ZnO was coated on LiCoO$_2$ to prevent surface reaction which occurs at high cutoff voltage and results in capacity fading. 0.2 wt. % ZnO coated LiCoO$_2$ showed capacity loss of 10.4 % after 30 cycles. Capacity loss of pristine LiCoO$_2$ was about 30.6 % at the end of 30th cycle. Although initial capacity of coated LiCoO$_2$ is slightly lower than pristine but it has better capacity retention. The coating of ZnO reduced the capacity fading faced by LiCoO$_2$ (Fang et al., 2004).

Improvements on structure and cycling were studied on Al$_2$O$_3$ coated LiCoO$_2$ (Liu et al., 2002). Bare LiCoO$_2$ exhibited 198 mAh g$^{-1}$ in the first cycle and capacity loss was about 40 % in the 20th cycle. Although the first discharge capacity of coated LiCoO$_2$...
was only about 185 mAh g\(^{-1}\), but the capacity tends to increase in the first four cycles. The discharge capacities of coated LiCoO\(_2\) were more stable compared to bare LiCoO\(_2\) because the value of 196 mAh g\(^{-1}\) at fourth cycle decreased to 190 mAh g\(^{-1}\) in the 20\(^{th}\) cycle. Surface coated LiCoO\(_2\) avoid Co\(^{4+}\) to react with electrolyte directly which causes capacity loss.

Son and co-workers (2004) coated LiMn\(_2\)O\(_4\) with silver metal and found better cycling performance. 3.2 wt. % Ag showed improved charge-discharge capacity due to its low resistance and improved electron conduction between LiMn\(_2\)O\(_4\) particles.

AlF\(_3\) was coated on Li[Ni\(_{0.8}\)Co\(_{0.15}\)Al\(_{0.05}\)]O\(_2\) to investigate the effects on electrochemical properties (Kim et al., 2008). The initial discharge capacity of Li[Ni\(_{0.8}\)Co\(_{0.15}\)Al\(_{0.05}\)]O\(_2\) and AlF\(_3\) coated Li[Ni\(_{0.8}\)Co\(_{0.15}\)Al\(_{0.05}\)]O\(_2\) is 183 mAh g\(^{-1}\) and 188 mAh g\(^{-1}\) respectively. At the same time coated sample exhibited excellent capacity retention about 96 % of its initial capacity while the uncoated only remain 86.5 % of its initial capacity. The results reveal that the AlF\(_3\) coating lowered and stabilized the interfacial resistance between cathode and electrolyte. It protects the core material during intercalation.

Similar coating which was carried out on LiCoO\(_2\) improved the cycling performance when cycled in 3.0-4.5 V (Sun et al., 2006). Both pristine and AlF\(_3\) coated LiCoO\(_2\) delivered similar initial discharge capacity of 180 mAh g\(^{-1}\). However the capacity of pristine sample faded after 50 cycles and became 30 mAh g\(^{-1}\). AlF\(_3\) coated LiCoO\(_2\) exhibited excellent capacity retention of 98 % and showed better cycling stability.

Li[Co\(_{0.1}\)Ni\(_{0.15}\)Li\(_{0.2}\)Mn\(_{0.55}\)]O\(_2\) was applied with Co\(_3\)(PO\(_4\))\(_2\) coating (Lee et al., 2008). Sintering temperature of the sample was proved as another factor that affects electrochemical performance of the battery. Samples sintered at low temperature such as 500 °C showed low capacities which caused by structural instability. At the same time,
high sintering temperature of 1000 °C resulted in aggregates of samples and leads to poor Li\(^+\) transport. However the samples coated with 2 wt. % and 3 wt. % of Co\(_3\)(PO\(_4\))\(_2\) sintered at 800 °C reveal high cycling stability.

SrF\(_2\) was used as coating material for LiMn\(_2\)O\(_4\) because of its stability in HF (Li et al., 2009). Increase of SrF\(_2\) coating amount on LiMn\(_2\)O\(_4\) resulted in decrease of discharge capacity. Inactive SrF\(_2\) coating may causes capacity fading when the coating amount increased. It can be explained that difference between voltage at charge and discharge curves increases which exhibits high polarization at higher coating level. The results obtained in this work relate increase of polarization of the electrode with decrease of discharge capacity. 2.0 mol% SrF\(_2\) coated LiMn\(_2\)O\(_4\) showed better capacity retention about 86.9 % after 50 cycles compared to uncoated LiMn\(_2\)O\(_4\) which only remain 79.3 % at 50\(^{th}\) cycle.

LiCo\(_{1/3}\)Ni\(_{1/3}\)Mn\(_{1/3}\)O\(_2\) was coated with TiO\(_2\) (Wu et al., 2009). Bare and 0.5 wt. % TiO\(_2\) coated samples delivered similar discharge capacity about 167.1 mAh g\(^{-1}\) and 165.7 mAh g\(^{-1}\) respectively. The first discharge capacity of 1.0 wt. % TiO\(_2\) coated LiCo\(_{1/3}\)Ni\(_{1/3}\)Mn\(_{1/3}\)O\(_2\) is 171.2 mAh g\(^{-1}\) but decreased to 161.3 mAh g\(^{-1}\) when the coating amount increases to 2.0 wt. % TiO\(_2\). The improved capacity proved that thin layer of TiO\(_2\) enables the effective lithium intercalation that results in better electrochemical behaviour. The coating layer also prevents harmful reaction at the surface of cathode material.

ZrO\(_2\) coating was applied on Li(Co\(_{1/3}\)Ni\(_{1/3}\)Mn\(_{1/3}\))O\(_2\) (Huang et al., 2009). Pristine sample exhibited 168.4 mAh g\(^{-1}\) at first cycle and become 132.7 mAh g\(^{-1}\) at 100\(^{th}\) cycle when cycled at 0.5C. 1 % ZrO\(_2\) coated Li(Co\(_{1/3}\)Ni\(_{1/3}\)Mn\(_{1/3}\))O\(_2\) showed initial discharge capacity of 166.1 mAh g\(^{-1}\) and only loss about 1 % and become 164.6 mAh g\(^{-1}\) at 100\(^{th}\)
cycle. The capacity fading of the pristine sample can be due to the change of lattice volume during cycling, cation mixing, dissolution of metal ion and electrolyte reaction at the interface of electrode as reported in this work.

LiNi$_{0.8}$Co$_{0.2}$O$_2$ has been coated with 1 wt.% of Li$_2$O-2B$_2$O$_3$ glass (Ying et al., 2001). Bare sample exhibited first discharge capacity of 161 mAh g$^{-1}$ with irreversible capacity of 47 mAh g$^{-1}$. About 9.3 % of capacity loss was observed at the 50th cycle. Li$_2$O-2B$_2$O$_3$ coated sample showed initial discharge capacity of 177 mAh g$^{-1}$. It remains capacity retention of 97.8 % after 50 cycles. Li$_2$O-2B$_2$O$_3$ is found to be good Li$^+$ ionic conductor which transfer Li$^+$ ion across the interface of the electrode. The Li$_2$O-2B$_2$O$_3$ coating layer protects the core material from corroded by the electrolyte.

Gold was used as coating layer on LiMn$_2$O$_4$ (Tu et al., 2006). Eventhough initial discharge capacities of bare and uncoated samples are similar, the gold coated LiMn$_2$O$_4$ exhibits improved cycling performance. When LiPF$_6$ react with water, HF is formed. HF dissolves the manganese ions which cause the capacity fading. Thin gold layer on the surface of LiMn$_2$O$_4$ reduces direct contact between electrode and electrolyte. So that the dissolution of manganese ions have been reduced. This results in better electrochemical properties.

Li$_{1.03}$Mn$_{1.97}$O$_4$ was modified with SiO coating (Zheng et al., 2002). Earlier few cycles of coated sample showed lower capacity than uncoated sample. From fifth cycle, the specific capacity of SiO coated Li$_{1.03}$Mn$_{1.97}$O$_4$ higher than the bare sample. The layer of SiO avoids the core material from being corroded by the electrolyte. Besides that SiO$_2$ is also able to trap HF which gives rise to the dissolution of Mn$^{2+}$. It was confirmed that SiO$_2$ coating improved cycling properties.
TiO$_2$ was coated on LiNi$_{0.8}$Co$_{0.2}$O$_2$ with the mole ratio Ti: LiNi$_{0.8}$Co$_{0.2}$O$_2$ is 0.03 (Zhang et al., 2004). It was reported that bare sample lost about 49% of its initial capacity after 100 cycles when cycled between 3.0 to 4.6 V range. Capacity of coated sample retains about 80% of its initial capacity at the end of 100th cycle. In the bare sample, Ni$^{4+}$ which formed at high potential could oxidize the electrolyte because Ni$^{4+}$ has strong oxidation ability. Ti$^{4+}$ in the coating layer which is not strong oxidizer suppresses the electrolyte oxidation and improved the capacity fading of coated samples.

LiNi$_{0.5}$Co$_{0.25}$Mn$_{0.25}$O$_2$ was treated with ZnO with different weight percentage (Guo et al., 2009). The initial charge capacity of bare sample and 0.5 wt. % ZnO coated samples similar which is about 210 mAh g$^{-1}$. The charge capacities of 1.5 wt. % ZnO and 3.0 wt. % ZnO coated samples are 204 mAh g$^{-1}$ and 196 mAh g$^{-1}$ respectively. Discharge capacity delivered by bare sample is 179 mAh g$^{-1}$. 0.5 wt. % ZnO coated sample exhibited discharge capacity of 175 mAh g$^{-1}$. This value decreases for 1.5 wt. % ZnO coating which is about 162 mAh g$^{-1}$ and become 152 mAh g$^{-1}$ at 3.0 wt. % ZnO. The discharge capacity decreases with increasing coating amount. Even though initial discharge capacity of coated samples is lower compared to uncoated sample, but it shows better improvement in long term cycling. Capacity loss of uncoated sample is about 19.6% after 30 cycles. Capacity loss of ZnO coated samples only 6.3%, 4.3% and 4.6% for 0.5 wt. % ZnO, 1.5 wt. % ZnO and 3.0 wt. % ZnO respectively. ZnO gives more stable SEI layer in order to improve electrochemical properties.

LiMn$_2$O$_4$ was used to coat with TiO$_2$ (Yu et al., 2006). Uncoated sample only retained about 70% of initial capacity after 40 cycles. Capacity loss of coated LiMn$_2$O$_4$ is less than 15% at the end of 60th cycle. Initial discharge capacity of coated sample is found to be 104 mAh g$^{-1}$ while bare sample only exhibits 96 mAh g$^{-1}$. These results proved
that the TiO$_2$ coating improved the capacity retention by covering the surface of the LiMn$_2$O$_4$. The coating enables the structure stability during charge and discharge.

LiNi$_{0.5}$Co$_{0.5}$VO$_4$ was modified with SiO$_2$ to overcome side reaction at the surface (Mai et al., 2003). The initial discharge capacity of bare sample was found to be 90 mAh g$^{-1}$ while SiO$_2$ coated sample exhibits 100 mAh g$^{-1}$. Capacity retention of coated sample is about 87 % after 10 cycles. Uncoated sample showed fast decline in capacity and reached 38.7 mAh g$^{-1}$ at the 10th cycle which shows retention only about 43 %. This improved capacity retention may be due to the SiO$_2$ layer on the cathode material prevents core material reacts with electrolyte.

Carbon from table sugar was applied as coating material to treat LiNi$_{1/3}$Mn$_{1/3}$Co$_{1/3}$O$_2$ (Kim et al., 2007). The results proved that 1 wt.% carbon coated LiNi$_{1/3}$Mn$_{1/3}$Co$_{1/3}$O$_2$ delivers initial capacity of 153.7 mAh g$^{-1}$, 150.0 mAh g$^{-1}$, 145.7 mAh g$^{-1}$, 142.6 mAh g$^{-1}$ and 134.3 mAh g$^{-1}$ at current rate of 0.2C, 0.5C, 1C, 2C and 5C respectively. The initial discharge capacity of uncoated sample is about 151.4 mAh g$^{-1}$, 147.0 mAh g$^{-1}$, 141.2 mAh g$^{-1}$, 137.0 mAh g$^{-1}$ and 128.6 mAh g$^{-1}$ at the given current rates above. From these results it can be confirmed that the capacity is improved with the carbon coating. 3 wt.% carbon coated sample exhibits initial discharge capacity of 144.6 mAh g$^{-1}$, 139.5 mAh g$^{-1}$, 132.3 mAh g$^{-1}$, 123.5 mAh g$^{-1}$ and 113.2 mAh g$^{-1}$ at current rate of 0.2C, 0.5C, 1C, 2C and 5C respectively. These values are lower compared to bare and 1 wt.% carbon coated LiNi$_{1/3}$Mn$_{1/3}$Co$_{1/3}$O$_2$. The capacity is reduced when the carbon coating exceeds 1 wt.%. The 1 wt.% carbon coated sample exhibits better capacity due to the improved conductivity by the coating.

Active LiCoO$_2$ and inactive MgO were selected as coating materials for LiNi$_{0.8}$Co$_{0.2}$O$_2$ (Zheceva et al., 2006). Initial discharge capacity delivered by LiNi$_{0.8}$Co$_{0.2}$O$_2$ is 175
mAh g\(^{-1}\). MgO coated sample and LiCoO\(_2\) coated sample exhibit initial discharge capacity of 155 mAh g\(^{-1}\) and 179 mAh g\(^{-1}\) respectively. Eventhough MgO coated LiNi\(_{0.8}\)Co\(_{0.2}\)O\(_2\) delivered low initial discharge capacity than bare sample, but it has better capacity retention after 30 cycles. Capacity loss of LiNi\(_{0.8}\)Co\(_{0.2}\)O\(_2\) is 22 % after 30 cycles compared to only 8 % for MgO coated LiNi\(_{0.8}\)Co\(_{0.2}\)O\(_2\). LiCoO\(_2\) coated LiNi\(_{0.8}\)Co\(_{0.2}\)O\(_2\) shows capacity retention of 87 % after 30 cycles. This reveals that LiCoO\(_2\) coated LiNi\(_{0.8}\)Co\(_{0.2}\)O\(_2\) improved the cycling stability. The coating of LiCoO\(_2\) on LiNi\(_{0.8}\)Co\(_{0.2}\)O\(_2\) enables the structure stability and avoids the harmful reaction at the interface of electrode and electrolyte.

**Summary**

Literature review in this chapter opens the window to the world of cathode materials for lithium ion batteries. Different types of cathode materials with their unique properties have been explored. On the other hand, the problems faced by these cathode materials have also been introduced. This work will concentrate on inverse spinel structure of lithium nickel vanadium oxide or known as lithium nickel vanadate. It is to be noted that the review is no means by exhaustive.