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Atomic Layer Deposition of LiCoO₂ Thin-Film Electrodes for All-Solid-State Li-Ion Micro-Batteries

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One of the remaining challenges in the field of portable electronics is the miniaturization of lithium-ion batteries. To prepare all-solid-state batteries with a sufficiently high storage capacity it is vital to prepare high quality thin films for battery stacks on 3D-structured substrates. A remote plasma atomic layer deposition (ALD) process has therefore been developed for LiCoO₂ which can serve as a cathode material. A combination of CoCp₂ as cobalt precursor, LiOtBu as lithium precursor and O₂ plasma as oxidant source was used to create super-cycles to deposit LiCoO₂ from Co₃O₄ and Li₂CO₃ cycles. The thin films were deposited at a temperature of 325°C and showed linear growth with a rate of 0.06 nm/cycle. After annealing the samples at 700°C for 6 minutes high temperature phase LiCoO₂ was obtained, as was demonstrated by XRD and Raman spectroscopy. A new procedure was proposed to obtain the composition of all three chemical elements in the LiCoO₂ films. Elastic Backscattering Spectroscopy (EBS) measurements turned out to be very convenient and reliable to obtain the quantities of all chemical elements, including lithium. Moreover, the ALD-deposited LiCoO₂ thin film electrodes were electrochemically characterized, revealing good backscattering performance. To the best of our knowledge this paper provides the first evidence that electrochemically active LiCoO₂ can be deposited by ALD.

During the past decade, portable electronic devices have become considerably more widespread, complex and powerful, and new challenges have been encountered, especially in the field of medical and autonomous devices. To power these future devices, thin-film, all-solid-state, lithium-ion micro-batteries have been prepared. To facilitate the required energy demand, both a high energy-to-weight and energy-to-volume ratio is essential. Lithium-ion batteries fulfill these demands. As packaging requirements become more dominant at smaller dimensions, one of the remaining challenges is miniaturization of lithium-ion batteries without decreasing the storage capacity. This formed the basis of the integrated batteries concept.

Step conformal deposition of films onto etched structures in silicon is an excellent method to tackle this challenge and to facilitate the integration of these high capacity energy storage devices into microelectronics. Chemical vapor deposition (CVD) has been proposed as deposition method. However, CVD has a limited step-conformal deposition capability in highly structured geometries due to the delicate interplay between kinetics and diffusion. By using atomic layer deposition (ALD) this effect can be counteracted as this deposition method is based on a reaction-limited surface saturation, opening up numerous possibilities for the use of more complex substrate structures such as nanowires.

Industrial scale implementation of ALD has already been proven in micro-electronics and this technique is rapidly penetrating new fields, such as solar cells, catalysis and recently also energy storage devices. In the field of battery technology several interesting materials have been prepared which show much promise. However, work on lithium-containing solid-state electrolytes and electrode materials is still very exploratory. Even though several lithium-containing compounds have recently been prepared by ALD, no reports of electrochemical investigations are available to date. An overview of Li-containing compounds prepared by ALD is presented in Table I. This paper demonstrates the electrochemical activity for ALD-prepared LiCoO₂, which is, to the best of our knowledge, the first active Li-containing battery material, deposited by ALD, which is electrochemically characterized in detail. Therefore, for reference, also LiCoO₂ CVD processes are included in Table I.

Evidently, analyzing the chemical composition of thin films is essential to evaluate the electrochemical properties of the LiCoO₂. Although it is most uncommon to use backscattering techniques such as Rutherford backscattering spectroscopy (RBS) for the determination of the Li content in thin films, this has been achieved by making use of non-Rutherford cross sections. The as-obtained results will be verified by Nuclear Reaction Analyzes (NRA). This is another novelty within this paper.

Experimental

Film preparation.— The LiCoO₂ films were deposited using an open-load thermal and remote plasma ALD reactor as described previously for the deposition of Co₃O₄. An inductively coupled plasma (ICP) source that is operated on O₂ is connected to a deposition chamber along with a pump unit through gate valves. The pump unit consists of a rotary and turbo molecular pump, which can reach a base pressure of <10⁻⁵ Torr by overnight pumping. The CoCp₂ and LiOtBu precursors (both 98%, Strem Chemicals) were heated to 80°C and 120°C respectively (Table II) and they were bubbled with Ar at a reactor pressure of 0.02 Torr. The substrate was heated to 325°C, while the reactor walls, Ar lines, and CoCp₂ precursor lines were maintained at a temperature of 105°C, the LiOtBu precursor lines were kept at 150°C to prevent precursor condensation. Si(100) with native oxide and Si(100) with 400 nm thermally grown SiO₂ were used as substrates for materials analyzes. For the electrochemical characterization, Si/TiO₂/Pt substrates were prepared by ALD as described in Ref. and schematically shown in Fig. 1 with thicknesses of 5 and 20 nm for TiO₂ and Pt respectively.

The remote plasma ALD process for LiCoO₂ consists of the two individual ALD processes for the deposition of Co₃O₄ and Li₂CO₃ which are combined in a so-called super-cycle (Fig. 2). Here the previously described remote plasma ALD process for Co₃O₄ is combined with a novel ALD process, using a lithium precursor reported recently for the deposition of LLT and Li₂CO₃. In this paper a super-cycle is defined as a combination of A cycles of Co₃O₄ and B cycles Li₂CO₃ (Fig. 2), resulting in a dosing ratio of A:B (e.g. 4:1), where B is consistently kept as 1 throughout the paper. x is defined as A/B, e.g. for a dosing ratio of 4:1, x equals 4. In both processes a precursor dosing time of 2 s is applied combined with an O₂ plasma at 100 W for 5 s
Table I. Overview of ALD processes for the deposition of lithium-containing compounds and CVD processes for LiCoO2. The growth rates have not been reported for the CVD processes. The abbreviation LLT stands for lithium lanthanum titanate.

<table>
<thead>
<tr>
<th>Deposited material</th>
<th>Lithium precursor</th>
<th>Other Precursor(s)</th>
<th>Reactant(s)</th>
<th>Deposition temperature</th>
<th>Growth rate</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALD</td>
<td>Li2CO3</td>
<td>LiO'Bu</td>
<td>H2O</td>
<td>225 °C</td>
<td>0.08 nm/cycle</td>
<td>9, 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>La(thd)3</td>
<td>O3</td>
<td>225 °C</td>
<td>0.05 nm/cycle</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>LiOH</td>
<td>LiO'Bu</td>
<td>H2O</td>
<td>225 °C</td>
<td>0.09 nm/cycle</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>LiCoO2</td>
<td>LiO'Bu</td>
<td>CoCp2</td>
<td>325 °C</td>
<td>0.06 nm/cycle</td>
<td>This work</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>O2 plasma</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CVD</td>
<td>LiCoO2</td>
<td>1BuLi</td>
<td>CpCo(CO3)</td>
<td>300–600 °C</td>
<td>–</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Co(TMHD)2</td>
<td>450–550 °C</td>
<td>–</td>
<td>17</td>
</tr>
</tbody>
</table>

Table II. Overview of ALD process parameters for the Co3O4 and Li2CO3 sub-cycles used in the super-cycle for the preparation of LiCoO2.

<table>
<thead>
<tr>
<th>Precursor/reactant</th>
<th>Dosing time</th>
<th>Pump purge time</th>
<th>Precursor temperature</th>
<th>Precursor line temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co3O4</td>
<td>CoCp2</td>
<td>2 s</td>
<td>3 s</td>
<td>80 °C</td>
</tr>
<tr>
<td></td>
<td>O2 plasma</td>
<td>5 s</td>
<td>0.5 s</td>
<td>–</td>
</tr>
<tr>
<td>Li2CO3</td>
<td>LiO'Bu</td>
<td>2 s</td>
<td>3 s</td>
<td>120 °C</td>
</tr>
<tr>
<td></td>
<td>O2 plasma</td>
<td>5 s</td>
<td>0.5 s</td>
<td>–</td>
</tr>
</tbody>
</table>

Cu plate was used as electrical conductor for the working electrode, while pure lithium foils were used as counter and reference electrodes. 1 Molar LiClO4 dissolved in Ethyl Carbonate (EC)/Diethyl Carbonate (DEC) was used as liquid electrolyte (Puriel, Techno, Semichem Co., Ltd, Korea). The cells were placed in a stainless steel holder that was thermostatically controlled at room temperature. Contaminants in the glove-box (water and oxygen) were monitored and controlled below 1 ppm. Galvanostatic cycling was performed with a M2300 galvanostat (Maccor, Tulsa, USA), applying a current density of 0.5 μA/cm2 between 3.0 and 4.1 V. The following definition is adopted throughout the manuscript: charging LiCoO2 refers to Li-ion extraction (or delithiation) and discharging to Li-ion insertion (or lithiation). Based on the electrode surface area, the layer thickness as determined by spectroscopic ellipsometry and the density determined by quantitative EBS measurements (Table III), the volumetric and gravimetric capacities were calculated.

Electrochemical analyzes.— The electrochemical analyzes were performed in three-electrode cylindrical electrochemical cells with an effective surface area of 2 cm2 (Fig. 1). The cells were made of Teflon with a volume of about 15 ml. The cells were assembled in an argon-filled glove-box. The Si/TiO2/Pt/LiCoO2 substrates are used as working electrode during the electrochemical measurement. Layer thicknesses are 5 and 20 nm for TiO2 and Pt respectively.
**Results and Discussion**

**ALD growth.**—To investigate the ALD process parameters, the self-limiting behavior of the ALD process was investigated for the CoCp₂ and LiO'Bu precursors using a Co:Li dosing ratio of 1:1 for the super-cycle as presented in Fig. 2. This means that one cycle of Co₃O₄ was alternated with one cycle of Li₂CO₃. The plasma exposure time was fixed at 5 seconds for both precursors. The Li precursor dosing time was varied while the Co dosing time remained constant at 2 s, which is the same dosing time used during the deposition of Co₃O₄. Saturation of the Li precursor occurs after about 2 s as can be seen in Fig. 3a. The same procedure was conducted for the Co precursor while the Li dosing time was kept constant at 2 s. Proper saturation is also observed in the Co case (Fig. 3b). Note that the growth rates under saturated conditions are slightly different in Fig. 3a and 3b. This can most likely be attributed to the different film thicknesses employed when generating Fig. 3a and 3b. The growth rate was found the change slightly with film thicknesses (see Fig. 4). Dosing times of 2 s for both precursors were therefore fixed for all deposition experiments described.

Applying a Co:Li dosing ratio of 1:1 lead to a slightly higher growth rate than expected on the basis of the individual growth rates for Co₃O₄ (0.05 nm/cycle) and Li₂CO₃ (0.08 nm/cycle). This could be due to the high growth rate of pure Li₂CO₃ as compared to pure Co₃O₄, but

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**Table III. Material properties and electrochemical results for LiCoO₂ thin films prepared for various Co/Li dosing ratios. Compositions are measured by EBS. The Co/Li dosing ratio (x) for the ALD process is defined as the number of Co₃O₄ sub-cycles divided by the number of Li₂CO₃ sub-cycles. For the lithium concentration an average is taken of the EBS and NRA measurements. Typical experimental errors are: Co (3%), Li (5%), O (5%) and C (7%).**

<table>
<thead>
<tr>
<th>Co/Li dosing ratio (x)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ALD process</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Super-cycles</td>
<td>300</td>
<td>200</td>
<td>200</td>
<td>169</td>
</tr>
<tr>
<td>Cycles (total)</td>
<td>900</td>
<td>800</td>
<td>1000</td>
<td>1014</td>
</tr>
<tr>
<td>Thickness (nm) (± 0.5 nm)</td>
<td>54</td>
<td>48</td>
<td>60</td>
<td>61</td>
</tr>
<tr>
<td><strong>Composition</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Co (10¹⁵ atom/cm²)</td>
<td>45.3</td>
<td>51.6</td>
<td>79.0</td>
<td>83.6</td>
</tr>
<tr>
<td>Li (10¹⁵ atom/cm²)</td>
<td>149</td>
<td>98.7</td>
<td>91.6</td>
<td>101</td>
</tr>
<tr>
<td>O (10¹⁵ atom/cm²)</td>
<td>353</td>
<td>210</td>
<td>266</td>
<td>315</td>
</tr>
<tr>
<td>C (10¹⁵ atom/cm²)</td>
<td>86</td>
<td>41</td>
<td>30</td>
<td>37</td>
</tr>
<tr>
<td>Average O/Co ratio</td>
<td>0.30</td>
<td>0.52</td>
<td>0.86</td>
<td>0.83</td>
</tr>
<tr>
<td>Average Li/Co ratio</td>
<td>7.9</td>
<td>4.1</td>
<td>3.5</td>
<td>3.8</td>
</tr>
<tr>
<td><strong>Composition</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Li₁.₃Co₁.₀7₉₉</td>
<td>3.2</td>
<td>2.6</td>
<td>2.8</td>
<td>3.0</td>
</tr>
<tr>
<td>Li₁.₉Co₀.₁₄</td>
<td>12.1</td>
<td>–</td>
<td>27.0</td>
<td>–</td>
</tr>
<tr>
<td>Li₁.₂Co₀.₁₅</td>
<td></td>
<td>28</td>
<td>–</td>
<td>62</td>
</tr>
<tr>
<td>Li₁.₅Co₀.₈</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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**Figure 2.** Schematic representation of an ALD super-cycle consisting of the two individual ALD processes for Co₃O₄ and Li₂CO₃. A cycles of the Co₃O₄ process are combined with B cycles of the Li₂CO₃ process. The film-substrate stack is also shown.

**Figure 3.** Saturation curves for remote plasma ALD of LiCoO₂ at 325°C (a) Growth rate as a function of LiO'Bu dosing time, while the CoCp₂ dosing time and the plasma exposure time are kept constant at 2 s and 5 s respectively. (b) Growth rate as a function of CoCp₂ dosing time, while the LiO'Bu dosing time and the plasma exposure time are kept constant at 2 s and 5 s respectively. The lines serve as guides to the eye.
the growth of Li$_2$CO$_3$ could also be catalyzed by the presence of cobalt atoms. Fig. 4 shows that the thickness was almost linearly dependent on the number of ALD cycles at a dosing ratio of Co:Li = 4:1 with an overall growth rate of $\sim 0.06$ nm/cycle. It is not expected that a change in Co:Li dosing ratio will significantly affect the saturation behavior for both precursors in the Co$_3$O$_4$ and Li$_2$CO$_3$ cycles.

Fig. 5 shows the in situ measured dielectric function $\varepsilon_2$ for photon energies between 1.24 and 6.5 eV of the as-deposited Co$_3$O$_4$, Li$_2$CO$_3$ and LiCoO$_2$. A clear difference is found between the three films. The dielectric function of Co$_3$O$_4$ has been described in an earlier publication. Unfortunately, from the literature not much is known about the dielectric functions of Li$_2$CO$_3$ and LiCoO$_2$. In order to distinguish between Co$_3$O$_4$, Li$_2$CO$_3$ and LiCoO$_2$ the films of the latter two materials have also been investigate. Fig. 5 clearly shows that Li$_2$CO$_3$ hardly contributes to the LiCoO$_2$ signal and that a typical spectrum for LiCoO$_2$ is obtained.

Material properties.— Knowledge of the overall film composition is essential in order to evaluate ALD-deposited LiCoO$_2$ thin films, especially to properly evaluate the electrochemical results. EBS and NRA are excellent techniques to determine the atomic composition of compounds and can thus be used to reveal the ratio between lithium, cobalt and oxygen in the films (Fig. 6). These analyzes show that materials prepared with a Co:Li dosing ratio $x$ of 4 and higher have more or less the same atomic ratios (Table III). In addition, a Co:Li dosing ratio larger than 4:1 seems to increase the deposition rate of the lithium sub-cycle in the ALD process slightly (Fig. 6), while the deposition rate during the cobalt sub-cycle is unaffected and continues to increase linearly with $x$. This effect is not yet fully understood, but limits the ALD process from obtaining the desired Co/Li ratio in the film as determined by Nuclear reaction analysis (NRA) and Elastic backscattering spectroscopy (EBS). For the Co/Li dosing ratio the amount of Li cycles per super-cycle is kept constant at 1.

As-deposited samples were investigated by GI-XRD and Raman spectroscopy and subsequently annealed at 700 °C for 6 minutes before being measured again with the same techniques. Fig. 7 shows that a large diffraction peak becomes visible after annealing at a 2θ angle of 19°, which has also been reported in the literature for metal organic (MO) CVD deposited LiCoO$_2$ at various temperatures. This peak can be assigned to either the (111) reflection of Co$_3$O$_4$ or the (003) reflection of LiCoO$_2$. As both cobalt oxide and lithium cobalt oxide can be present in the deposited thin films it is not possible to unambiguously determine the origin of the diffraction peak and the nature of the film from XRD. Therefore Raman spectroscopy has been used to further investigate these films. Figure 8 shows that the high temperature (HT) hexagonal phase of LiCoO$_2$ is observed with two typical phonon modes at 486 and 596 cm$^{-1}$ which becomes even more defined after annealing. The Raman spectra reveal no significant fraction of Co$_3$O$_4$ in the films as this would lead to a distinct peak at 693 cm$^{-1}$.

Electrochemical analyzes.— It is well-known that a heat-treatment of about 700 °C is required to obtain the electrochemically active, crystalline, LiCoO$_2$. The annealed LiCoO$_2$ films were electrochemically characterized in the experimental three-electrode battery set-up using
Figure 8. Raman measurements for LiCoO$_2$ annealed at 700°C for 6 minutes compared to as-deposited LiCoO$_2$ and the theoretical spectrum of Co$_3$O$_4$. The used Co:Li dosing ratio was 2:1 ($x = 2$).

A remote plasma ALD process for the preparation of LiCoO$_2$ thin films was developed using the combination of CoCp$_2$ as cobalt precursor, LiO’Bu as lithium precursor and a O$_2$ plasma as the oxidant source. To the best of our knowledge this paper provides the first evidence that electrochemically active LiCoO$_2$ can be deposited by ALD. It was shown that LiCoO$_2$ films could be deposited by ALD with the Li/Co ratio depending on the Co:Li dosing ratio. Moreover elastic backscattering spectrometry was shown to be an accurate method to analyze the Li-content in this type of films, which simplifies the analysis significantly. After heat-treatment the high temperature phase of LiCoO$_2$ was obtained as shown by XRD and Raman measurements.

constant current (dis)charge cycling. The charge transfer reaction of the LiCoO$_2$ electrode can be represented by

$$\text{LiCoO}_2 \rightleftharpoons \text{Li}_{1-z}\text{CoO}_2 + z\text{Li}^+ + ze^- \quad (z \leq 0.5) \quad [1]$$

where $z \leq 0.5$. Extracting more than 0.5 lithium atoms per formula unit would irreversibly change the crystal structure of LiCoO$_2$, making the electrode (partly) electrochemically inactive. All electrode films investigated showed electrochemical activity. However, the storage capacity was clearly found to be dependent on the ALD dosing ratio.

Fig. 9a shows the (dis)charge behavior of the LiCoO$_2$ electrode for the Co:Li dosing ratio $x$ of 4 which revealed the highest storage capacity. By taking the derivative of the storage capacity with respect to the electrode potential (Fig. 9b), the plateaus in Fig. 9a are transformed into either broad or sharp peaks dependent on the slope of the voltage curves. A clear charge transfer reaction is now visible at 3.9 V as expected for LiCoO$_2$. Also a 12% capacity loss between the charge and discharge reactions is found (Fig. 9a). A similar effect has been reported before and this has been attributed to irreversible side reactions (e.g. oxidation of the liquid electrolyte, the formation of the less electrochemically active spinel LiCo$_2$O$_4$ phase or mechanical strain-induced degradation of the LiCoO$_2$ film, but also the (electro)chemical stability of the impurities found in ALD LiCoO$_2$ with respect to the liquid electrolyte could play a role.

The electrochemical storage capacity is, however, lower than the theoretically expected for LiCoO$_2$ (155 mAh/g), but remained fairly stable upon cycling as shown in Fig. 9c. Over 60% of the maximum theoretical storage capacity has been obtained with the ALD deposited ($x = 4$) thin film electrode (Fig. 9c). This lower capacity can be explained by the presence of Li$_2$CO$_3$ within the thin film as indicated by the increased oxygen over cobalt (O/Co) and decreased cobalt over lithium (Co/Li) ratios and the presence of carbon (Table III). Moreover Table III shows an abundance of lithium and oxygen which could also indicate the formation of inactive Li$_2$O during the ALD process. These two effects may contribute to the reduced capacity compared to the theoretical maximum. Referring to Table III it is clear that the impurity level of the $x = 2$ material is significantly higher than the $x = 4$ material. This is in line with the reduced capacity of the $x = 2$ material compared to $x = 4$. It is expected that further process optimization will yield a higher chemical purity and improved storage capacity.

Conclusions

A remote plasma ALD process for the preparation of LiCoO$_2$ thin films was developed using the combination of CoCp$_2$ as cobalt precursor, LiO’Bu as lithium precursor and a O$_2$ plasma as the oxidant
Electrochemical charge/discharge cycling experiments showed good reversible electrochemical performance with a significant fraction (60%) of active material for the annealed LiCoO$_2$ films, revealing that ALD is a promising method to deposit active lithium-containing electrode materials.

**Acknowledgments**

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**References**