Low temperature plasma-enhanced atomic layer deposition of metal oxide thin films

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Many reported atomic layer deposition (ALD) processes are carried out at elevated temperatures (>150°C), which can be problematic for temperature-sensitive substrates. Plasma-enhanced ALD routes may provide a solution, as the ALD temperature window can, in theory, be extended to lower deposition temperatures due to the reactive nature of the plasma. As such, the plasma-enhanced ALD of Al₂O₃, TiO₂, and Ta₂O₅ has been investigated at 25–400°C using [Al(CH₃)₃], [Ti(OOiPr)₃], [Ti(Cp*Me)(OiPr)₃], [TiCl₄(OMe)₃], and [Ta(NMe₅)₃] as precursors. An O₂ plasma was employed as the oxygen source in each case. We have demonstrated metal oxide thin-film deposition at temperatures as low as room temperature and compared the results with corresponding thermal ALD routes to the same materials. The composition of the films was determined by Rutherford backscattering spectroscopy. Analysis of the growth per cycle data and the metal atoms deposited per cycle revealed that the growth per cycle does not always accurately indicate whether or not true ALD processes in particular, showed that the number of Al atoms deposited per cycle was consistently high down to room temperature for the plasma-enhanced process but dropped for the thermal process at substrate temperatures lower than 250°C.© 2010 The Electrochemical Society. [DOI: 10.1149/1.3428705] All rights reserved.

Experimental
The experiments were carried out on three remote plasma ALD reactors. The home-built ALD-I reactor and the commercially built Oxford Instruments FlexAL reactor are described in detail elsewhere. The Oxford Instruments OpAL apparatus, an open-load system, was employed for the deposition of Al₂O₃ and operates in a similar manner to the FlexAL, although without a turbo pump. The base pressure was ~1 mTorr for the OpAL and ~10⁻³ mTorr for the ALD-I and FlexAL, and typical operating pressures were 100–

Atomic layer deposition (ALD), a method of ultrathin-film deposition by alternate dosing of gaseous precursors, gives dense, pure, and highly conformal films with excellent step coverage. Each ALD process is considered to have a temperature window, which is governed by the reactivity and stability of the precursors and surface functional groups. The ALD temperature window typically spans 200–400°C for the majority of processes, although many studies on metal oxides have investigated the range 100–600°C. It is often assumed that, within the temperature window, a submonolayer of material is deposited during each cycle and that the growth per cycle remains constant with varying substrate temperature (Fig. 1a). However, in several cases it is possible to see a small reduction in the growth per cycle with increasing temperature due to a small loss of reactive surface groups. Outside the temperature window, the growth per cycle can change dramatically. At lower temperatures, excess condensation of the precursors can result in a rapid increase in growth (A), for example, when the substrate temperature is lower than the bubbler temperature required to obtain an adequate vapor pressure. Also at lower temperatures, there may be insufficient thermal energy for a chemical reaction to occur, resulting in slower growth (B). At higher temperatures, decomposition of the precursors (chemical vapor deposition) can occur, leading to an increase in growth, which is not self-limiting (C), or, if the film material is volatile it may evaporate, thereby reducing the growth (D). However, as previously mentioned, a change in growth per cycle does not always accurately indicate whether or not true ALD is occurring, exemplified by the gradual loss of surface groups with increasing substrate temperature in Fig. 1b.

Generally, the ALD window (spanning 150–400°C) for most metal oxide processes has proved sufficient for many applications requiring ultrathin films. However, for emerging applications employing temperature-sensitive substrates, even temperatures as low as 200°C can be problematic, for example, in polymers or small organic molecules, whose structure can be affected at such temperatures. Applications that require such low temperatures include organic molecules, whose structure can be affected at such temperatures; as 200°C can be problematic, for example, in polymers or small organic molecules, whose structure can be affected at such temperatures. Applications that require such low temperatures include or–

The experiments were carried out on three remote plasma ALD reactors. The home-built ALD-I reactor and the commercially built Oxford Instruments FlexAL reactor are described in detail elsewhere. The Oxford Instruments OpAL apparatus, an open-load system, was employed for the deposition of Al₂O₃ and operates in a similar manner to the FlexAL, although without a turbo pump. The base pressure was ~1 mTorr for the OpAL and ~10⁻³ mTorr for the ALD-I and FlexAL, and typical operating pressures were 100–
are compared with our previous work using ALD-I. 27 The com-

Al2O3 was deposited using OpAL and FlexAL, TiO2 using FlexAL and ALD-I, and Ta2O5 using FlexAL. The Ta2O5 results on FlexAL are compared with our previous work using ALD-I. 27 The compounds [Al(CH3)3] (Sigma Aldrich), [Ti(O’Pr)3] (Sigma Aldrich), novel Cp-based ALD precursors [Ti(CpMe)2O(Pr)3] (donated by SAFC Hitech, Ltd.) and [TiCp’(OMe)3] (donated by Air Liquid), and [Ta(NMe2)3] (STREM Chemicals Ltd.), all having a purity of >99.9%, were employed as precursors 28 and were contained in stainless steel bubblers. Oxygen (purity >99.999%) was used to form the plasma, and argon (purity >99.999%) was employed as the purge gas. For the processes employing [Al(CH3)3], [TiCpMeO(’Pr)3], and [TiCp’(OMe)3], the oxygen flow was continuous throughout the entire process, but where [Ti(O’Pr)3] and [Ta(NMe2)3] were used, the flow was restricted to the plasma step. Water (VWR, GBR Rectapur grade, >99.999%) used in thermal ALD experiments was also held in a stainless steel bubbler at either ambient temperature (FlexAL) or 19°C (OpAL) to reduce the vapor pressure and prevent overdosing. The substrates were n-type Si(100) wafers, which were 100 mm in diameter for the FlexAL and OpAL reactors and ~40 × 40 mm for ALD-I. These wafers were covered with a thin native oxide (SiO2) layer and did not undergo any additional cleaning steps. The ALD conditions for each process are summarized in Table II. Film growth during the ALD process was monitored by in situ spectroscopic ellipsometry (SE), carried out using a J. A. Woollam Inc. M2000 rotating compensator ellipsometer. 21, 28 The atomic composition of the films was determined by Rutherford backscattering spectroscopy (RBS), except for the hydrogen concentration, which was obtained by elastic recoil detection (ERD) analysis. The detection limits for the RBS and ERD measurements are not the same for each set of measurements and were quoted where appropriate. The mass density of the films was calculated using a combination of the RBS and SE data.

### Results and Discussion

The plasma-enhanced ALD of Al2O3, TiO2, and Ta2O5 has been investigated at substrate temperatures down to 25°C. Every process was routinely monitored using in situ SE to determine the film thickness. The slope of the resulting thickness vs ALD cycles plot gave the growth per cycle for the process (an example for the depositions at 100°C is shown in Fig. 2). All ALD processes showed linear growth at every deposition temperature reported in this paper (with the exception of the TiO2 depositions from [Ti(O’Pr)3] at substrate temperatures >250°C), with no significant nucleation delay.

**Aluminum oxide.**—

Al2O3 has been a material of high interest with respect to ALD (see the review by Puurunen). 28 However, it is relatively recently that low substrate temperatures have been investigated. The growths per cycle of two of the most-reported thermal processes are compared with the plasma-enhanced route in Fig. 3. We deposited Al2O3 using both the plasma-enhanced and thermal processes on an Oxford Instruments FlexAL reactor 28 and OpAL reactor. The growth of the plasma-enhanced method showed a gradual decrease from 0.17 nm/cycle at 25°C to 0.11 nm/cycle at 300°C. The decrease was essentially linear, with the exception of the runs at 25 and 50°C, which were slightly higher. The corresponding thermal process showed a maximum value of 0.10 nm/cycle at 200–250°C. Our results for the thermal process differ from those of Groner et al., 8 where the growth was higher at ~0.13 nm/cycle. These two thermal processes were carried out in different reactors and were clearly optimized at different temperatures (where the peak of the data is). A possible reason for such a difference in growth per cycle is the water dose. Increasing the water dose (i.e., the mass of water per unit time) leads to an increase in growth per cycle without affecting the film composition. 29 As more surface hydroxyl groups are created with higher doses. So despite the difference in water dose time (20 ms for our work, 2 s for Groner et al.), it is likely that our water flow rate was lower, affecting a lower growth per cycle, because the water on the OpAL reactor was actively cooled to 19°C to avoid overdosing. The reduction

![Graph](image-url)

**Figure 1.** (Color online) A schematic representation of (a) an ideal ALD temperature window, where it is assumed that a sub-monolayer has been deposited per cycle and (b) a more commonly observed ALD window (especially for metal oxides), showing a slight reduction in growth per cycle with increasing temperature.

Table I. Examples of low temperature ALD of metal oxides deposited below 150°C.

<table>
<thead>
<tr>
<th>Material</th>
<th>Metal precursor</th>
<th>Oxidant</th>
<th>Lowest reported temperature (°C)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al2O3</td>
<td>[Al(CH3)3]</td>
<td>H2O</td>
<td>33</td>
<td>6</td>
</tr>
<tr>
<td>Al2O3</td>
<td>[Al(CH3)3]</td>
<td>O3</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>Al2O3</td>
<td>[Al(CH3)3]</td>
<td>O3 plasma</td>
<td>25, 14, 16, and 21–23</td>
<td></td>
</tr>
<tr>
<td>TiO2</td>
<td>TiCl4</td>
<td>H2O</td>
<td>100</td>
<td>18 and 19</td>
</tr>
<tr>
<td>TiO2</td>
<td>TiCl4</td>
<td>H2O</td>
<td>100</td>
<td>34</td>
</tr>
<tr>
<td>TiO2</td>
<td>[Ti(O’Pr)3]</td>
<td>H2O</td>
<td>150</td>
<td>35 and 36</td>
</tr>
<tr>
<td>TiO2</td>
<td>[Ti(O’Pr)3]</td>
<td>H2O</td>
<td>77</td>
<td>37</td>
</tr>
<tr>
<td>Ta2O5</td>
<td>TaCl3</td>
<td>H2O</td>
<td>80</td>
<td>42</td>
</tr>
<tr>
<td>Ta2O5</td>
<td>[Ta(NMe2)3]</td>
<td>H2O</td>
<td>150</td>
<td>45 and 46</td>
</tr>
<tr>
<td>Ta2O5</td>
<td>[Ta(NMe2)3]</td>
<td>O3 plasma</td>
<td>100</td>
<td>27</td>
</tr>
<tr>
<td>PtO2</td>
<td>[Pt(acac)2]</td>
<td>O3</td>
<td>120</td>
<td>24</td>
</tr>
<tr>
<td>ZnO</td>
<td>[Zn(CH2CH3)2]</td>
<td>H2O</td>
<td>60</td>
<td>7</td>
</tr>
<tr>
<td>ZnO</td>
<td>[Zn(CH2CH3)2]</td>
<td>H2O</td>
<td>25</td>
<td>8</td>
</tr>
</tbody>
</table>

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28 acac is acetylacetonate. CH(C=O)CH3; CpMe’ is monomethylcyclopentadienyl, C5H4CH2CH3; Cp’ is pentamethylcyclopentadienyl. C5H4CH2CH3; Me is methyl, CH3; and ’Pr is isopropyl, CH3(1)(2)(3)
Table II. The ALD process conditions for the metal oxides reported in this work. The purges for the ALD processes where [Ti(CpOMe)] were used only incorporated an argon flow for part of the duration. In these cases, the pumping and argon (Ar) times are given in the order they occurred during the purge. In all other cases, a continuous Ar flow was employed throughout the cycle. “Oxidant” refers to an O₂ plasma for plasma-enhanced ALD and water for thermal ALD. The conditions for the Ta₂O₅ process on the ALD-I reactor are reported elsewhere.³²

<table>
<thead>
<tr>
<th>Variable</th>
<th>Al₂O₃</th>
<th>Al₂O₃</th>
<th>TiO₂</th>
<th>TiO₂</th>
<th>TiO₂</th>
<th>Ta₂O₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALD Reactor</td>
<td>Plasma-enhanced</td>
<td>Plasma-enhanced</td>
<td>Plasma-enhanced</td>
<td>Plasma-enhanced</td>
<td>Plasma-enhanced</td>
<td>Plasma-enhanced</td>
</tr>
<tr>
<td>Precursor</td>
<td>[Al(CH₃)]₂</td>
<td>[Al(CH₃)]₂</td>
<td>[Ti(O'Pr)_₂]</td>
<td>[Ti(CpOMe)]</td>
<td>[Ti(CpOMe)]</td>
<td>[Ta(NMe₂)]</td>
</tr>
<tr>
<td>Tₓsubstance</td>
<td>25–400°C</td>
<td>25–400°C</td>
<td>25–400°C</td>
<td>100–400°C</td>
<td>50–300°C</td>
<td>25–250°C</td>
</tr>
<tr>
<td>Tₓprecurser</td>
<td>~25°C</td>
<td>~25°C</td>
<td>45°C</td>
<td>70°C</td>
<td>110°C</td>
<td>65°C</td>
</tr>
<tr>
<td>Precursor dose</td>
<td>0.02 s</td>
<td>0.05 s</td>
<td>4 s</td>
<td>5 s</td>
<td>4 s</td>
<td>5 s</td>
</tr>
<tr>
<td>Precursor purge</td>
<td>3 s</td>
<td>10 s</td>
<td>4 s</td>
<td>4 s Ar</td>
<td>4 s Ar</td>
<td>5 s</td>
</tr>
<tr>
<td>Plasma power</td>
<td>400 W</td>
<td>—</td>
<td>400 W</td>
<td>100 W</td>
<td>100 W</td>
<td>200 W</td>
</tr>
<tr>
<td>Oxidant time</td>
<td>2 s</td>
<td>0.02 s</td>
<td>12 s</td>
<td>5 s</td>
<td>5 s</td>
<td>5 s</td>
</tr>
<tr>
<td>Oxidant purge</td>
<td>0.5 s</td>
<td>10 s</td>
<td>1.5 s</td>
<td>2 s pumping</td>
<td>4 s pumping</td>
<td>15 s</td>
</tr>
<tr>
<td>O₂ flow</td>
<td>60 sccm</td>
<td>—</td>
<td>60 sccm</td>
<td>7.5 mTorr</td>
<td>7.5 mTorr</td>
<td>50 sccm</td>
</tr>
<tr>
<td>Ar flow</td>
<td>20 sccm</td>
<td>200 sccm</td>
<td>30 sccm</td>
<td>15 mTorr</td>
<td>15 mTorr</td>
<td>100 sccm (purges), 150 sccm (pumps), 50 sccm (plasma)</td>
</tr>
</tbody>
</table>

Another important consideration is the oxidant purge time (Fig. 4). The post-plasma purge times required (0.5 s) were significantly lower than those required to purge water from the system in the thermal process (10 s for this work and 5–180 s for Groner et al.), which allows for a significantly reduced overall cycle time for the plasma-enhanced process. The thermal ALD process employing ozone as the oxidant reported by Kim et al.⁴⁰ gave the lowest growth per cycle above 100°C (~0.09 nm/cycle). Ozone is more reactive than water toward the surface methyl groups, forming hydroxyl, methoxy, formate, and carbonate surface groups in the process.³⁷,³² Therefore, Kim et al. suggested that the dramatic increase in growth per cycle observed at deposition temperatures below 100°C was attributed to the insufficient removal of the aforementioned oxygen-based surface groups in the steps subsequent to the oxidation because there was insufficient thermal energy with which to remove them.³⁷ Also in this case, the ozone purge was kept constant at 3 s at 33–100°C, where a longer purge at lower temperatures may have helped to reduce the impurities. In comparison, our plasma-enhanced ALD process with a shorter purge time (0.5 s), combined with the use of water for the plasma-enhanced process, allowed for a significantly reduced overall cycle time compared to the thermal process. The increase in film thickness with the number of ALD cycles as measured by in situ SE (deposition temperature = 100°C) is shown in Fig. 2. The increase was linear for each precursor: (a) [Al(CH₃)]₂, (b) [Ta(NMe₂)]₂, (c) [Ta(NMe₂)]₂ (FlexAL reactor), (d) [Ti(O'Pr)_₂], (e) [Ti(CpOMe)] and (f) [Ti(CpOMe)].
enhanced route gave a more consistent growth per cycle profile down to 25°C and provided the highest growths per cycle over 50–300°C with the shortest cycle times.

In terms of film composition, the films deposited by both thermal and plasma-enhanced ALD in this work were over-stoichiometric at deposition temperatures below 200°C (Fig. 5a). The similar reduction in hydrogen content (Fig. 5b) with increasing substrate temperature suggests that this is due to the incorporation of hydroxyl groups in the film. In all cases, the carbon content was below the RBS detection limit (1 atom %); although thermal effusion measurements have suggested that a small quantity of carbon was present in the films deposited by this process. The mass density (Fig. 5c) was ~3.0 g cm⁻³ at deposition temperatures of 200°C and above for the plasma-enhanced process, which is close to the bulk value of Al₂O₃ (3.1 g cm⁻³). A gradual decrease was observed below 200°C to a minimum of 2.6 g cm⁻³ at 25°C. This decrease in mass density is likely to be the result of excess –OH in the film, which accounts for the higher than expected growths per cycle obtained below 100°C. The thermal water process showed no significant difference in terms of impurity content, and the mass density of the films over the temperature range was still within error, although slightly lower than that for the plasma-enhanced process. The thermal process with ozone gave over-stoichiometric films at all temperatures up to 300°C with up to 5 atom % carbon contamination.

The growth per cycle profiles are apparently all different, which, in part is caused by the varying mass densities. However, determination of the number of (metal) atoms deposited per cycle, obtained by dividing the atom density from RBS by the total number of ALD cycles, can show if this is the case. For example, if the number of atoms deposited per cycle does not vary significantly over a temperature range, any variation in growth per cycle is most likely due to the variation in mass density; however, if there is a difference in atoms deposited, other factors, such as chemical vapor deposition (CVD) or surface group loss, may be occurring. Figure 6 shows the growth per cycle data for the plasma-enhanced and thermal processes on both the FlexAL and OpAL reactors and the number of Al atoms deposited per cm² in a cycle. In terms of films deposited by plasma-enhanced ALD, there is no significant difference between the growths per cycle from either reactor; but for the thermal process, more atoms appear to have been deposited by the OpAL reactor. The OpAL reactor is not equipped with a turbo pump or load lock, so it may not be able to purge the water away as effectively as in the FlexAL reactor and the chamber vacuum has to be disrupted for sample loading. However, a greater difference in mass density would be expected for such a difference in Al atoms deposited per cycle where the growth per cycle remains the same. There is a clear gradient for Al atoms deposited per cycle with the plasma-enhanced process, showing the effect of dehydroxylation (loss of surface groups) with increasing substrate temperature. A similar gradient was observed for the growth per cycle, although this is enhanced at 25 and 50°C as a result of the decreased film density and increased OH concentration (as shown in Fig. 5). For the thermal processes, the effect of lower temperatures is clear; with the number of Al atoms deposited being half of that of the plasma-enhanced process at 100°C, suggesting that the rate of reaction is lower at these temperatures. The temperature at which the thermal process was optimized (i.e., the saturation of each ALD step was determined, which was

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**Figure 4.** (Color online) A comparison of the oxidant purges required for various Al₂O₃ ALD processes: the plasma-enhanced and thermal processes on OpAL, the thermal process with water (note the break in the scale), as reported by Groner et al., and the thermal process with ozone, as reported by Kim et al.

**Figure 5.** (Color online) The film characteristics of the Al₂O₃ films obtained on the OpAL reactor. (a) The [O]/[Al] ratio of the films (the line serves as a guide to the eye), (b) the hydrogen content of the films, and (c) the mass density of the films.
200°C in these cases) apparently gave the highest growth per cycle and the highest number of Al atoms deposited. At higher temperatures, the growth per cycle and atoms per cycle decrease in line with the plasma-enhanced process as a result of the loss of surface groups. In summary, the plasma-enhanced ALD of Al₂O₃ generally gives a higher growth per cycle at low temperatures than the corresponding thermal processes using water or ozone, although the temperature at which the thermal process is optimized and the water flow rate play an important role. The film compositions of the plasma-enhanced and thermal processes were comparable, with the concentration of −OH increasing with decreasing substrate temperature. Carbon was not detected in the films (RBS detection limit = 1 atom %). Analysis of the Al atoms deposited per cycle showed that the temperature window could easily be extended down to room temperature with fixed cycle settings for the plasma-enhanced ALD of Al₂O₃. For the thermal process, temperatures lower than the optimization temperature could be considered outside the temperature window; however, if saturation curves were determined for each deposition temperature and the water flow rate were increased, this could be overcome.

Titanium dioxide.—TiO₂ is a well-studied ALD material, and a selection of the low temperature ALD studies is summarized in Fig. 7. For the plasma-enhanced ALD of TiO₂, we employed [Ti(OPr)₄], [Ti(CpMe₃)(OPr)₃], and [TiCp₃(OH)₃] as precursors. The heteroleptic mono Cp-based alkoxides are not sufficiently reactive with water during ALD, but they are reactive with ozone and an oxygen plasma. The growths per cycle for our plasma-enhanced processes were 0.05–0.06 nm/cycle, over the deposition temperature range 100–250°C. The growths per cycle using [Ti(CpMe₃)(OPr)₃] were slightly higher than those of the other two Ti precursors, as more Ti atoms were deposited per cycle for this precursor (Fig. 8a). Again, a gradual decrease in growth per cycle was observed with increasing substrate temperature for all of the Ti precursors, which can be attributed to increasing mass density. The loss of surface groups is not likely to be a significant factor for the Cp-based precursors, as the Ti atoms deposited per cycle were constant over the temperature range. At 25°C, the growth per cycle obtained using [Ti(OPr)₄] was higher than the expected trend, which is a result of the excess OH groups in the film, as for the Al₂O₃ process, where there is a distinct negative peak in the C₃, and O₂ 1s XPS regions (Fig. 8b). The data also complement the growths per cycle for the TiCl₄/water process at 150–175°C reported by Aarik et al. The number of Ti atoms deposited per cycle is shown in Fig. 8a. For the two Cp-based precursors, the Ti deposited was generally consistent across the temperature ranges studied, implying that these precursors are less affected by surface dehydroxylation than Al₂O₃ films, where there is a distinct negative peak in the C₃, and O₂ 1s XPS regions (Fig. 5b). The data also complement the growth per cycle values in Fig. 7, whereby [Ti(CpMe₃)(OPr)₃] deposited
Figure 8. (Color online) Compositional details of the TiO₂ films deposited by plasma-enhanced ALD. (a) The Ti atoms deposited per cycle, (b) the [O]/[Ti] ratio (the ratio for stoichiometric TiO₂ being represented by a dashed line), (c) the hydrogen content, and (d) the mass density of the films.

Tantalum oxide.— Ta₂O₅ is another thoroughly studied ALD material, particularly via thermal routes using halide-, alkoxide-, and amide-based precursors. However, films grown at <150°C are not so commonly known. We recently reported the low temperature plasma-enhanced ALD of Ta₂O₅ using [Ta(NMe₂)₃] on the ALD-1 reactor, 37 which gave a growth of ~0.08 nm/cycle over the temperature range 100–225°C (Fig. 9), which is comparable to the TaCl₅/H₂O process above 100°C. 36 All films were stoichiometric Ta₂O₅ with a [O]/[Ta] ratio of 2.5 and

more Ti atoms per cycle and afforded a higher growth per cycle, when compared with [TiCp³(OMe)₃]. In addition to the experimental inaccuracy of RBS, the [Ti(O’Pr)₃] is not so straightforward, as there is no real, clear-cut linear trend. The rise in Ti atoms deposited at 300°C can be attributed to the decomposition (CVD) of the precursor, as a significant amount of carbon (~17 atom %) was present in films deposited at that temperature. For depositions using [Ti(O’Pr)₃] at temperatures ≥250°C, crystallization was observed in the amorphous phase, resulting in higher growths per cycle. 26 At 250 and 300°C, the growth began in the amorphous phase at a lower growth per cycle, after which anatase TiO₂ was deposited at a much higher rate. The transitions were observed between 400–700 cycles at 250°C and above 200 cycles at 300°C. Where [Ti(Cp³Me)(O’Pr)₃] was the precursor, anatase TiO₂ was also observed at substrate temperatures ≥250°C, but this did not seem to have such a dramatic effect on the growth per cycle, suggesting that the Cp³Me group inhibits the anatase formation to some extent.

In terms of film composition, films deposited by plasma-enhanced ALD from all of our Ti precursors gave stoichiometric TiO₂ at 50°C and above (Fig. 8b). The film from [Ti(O’Pr)₃] at 25°C was over-stoichiometric, which, as with the [Al(Ch₃)₃]/water process, is the result of the incorporation of hydroxyl groups in the film, evident by the 8 atom % hydrogen present (Fig. 8c) and the lower mass density of the film (Fig. 8d). At other temperatures, the carbon and hydrogen concentrations were below their detection limits for RBS and ERD (1 and 5 atom %, respectively) where [Ti(O’Pr)₃] was the precursor. The stoichiometry of the films deposited by [Ti(Cp³Me)(O’Pr)₃] and [TiCp³(OMe)₃] were the same as those obtained using [Ti(O’Pr)₃] (and so the data overlap in Fig. 8b), and no carbon was detected at any temperature for the Cp-based precursors. Hydrogen was detected in the films from [TiCp³(OMe)₃] (2–3 atom %), and similar quantities are possibly present in the films from the other two precursors, as the detection limit in those experiments was higher. As such, it is difficult to directly compare the hydrogen content of our films with those of Ritala et al., 35 as they reported a hydrogen content of ~0.3 atom % (measured using nuclear reaction analysis with a 15N²⁺ beam), which is below the lowest detection limit (1 atom %) for ERD in our experiments. The films grown from TiCl₄ and water at 100°C were also stoichiometric but contained 1.2 atom % chlorine, which can lead to films with a high surface roughness, due to the aforementioned etching. 41 In terms of mass density (Fig. 8d), the films deposited, by all precursors had densities over the range 3.6–4.2 g cm⁻³, which is comparable to the bulk density of anatase TiO₂ (3.9 g cm⁻³). 36 The films from [Ti(O’Pr)₃] had the most variation in density owing to the larger experimental inaccuracy in the RBS experiments. The low density at 25°C was a result of –OH incorporation as mentioned previously, whereas the higher density of 4.18 g cm⁻³ at 300°C is likely to be a result of the crystallization. For the noncrystalline films below 200°C, the high density is a feature of the plasma-enhanced ALD method.

The plasma-enhanced ALD processes TiO₂ using [Ti(O’Pr)₃], [Ti(Cp³Me)(O’Pr)₃], and [TiCp³(OMe)₃] afford higher growths per cycle compared with the [Ti(O’Pr)₃] and water process. They were preferable to the TiCl₄/H₂O process, in that the possibility of the films containing chlorine is negligible. The films grown in this study were consistently stoichiometric down to 50°C.
contained hydrogen (Fig. 10c). No nitrogen or carbon was detected. The mass density varied from 7.8 g cm$^{-3}$ at 100°C to 8.1 g cm$^{-3}$ at 225°C, which is comparable to the bulk density value of Ta$_2$O$_5$ (8.24 g cm$^{-3}$). Maeng et al. previously carried out a comparison of the thermal and plasma-enhanced ALD of Ta$_2$O$_5$ from Ta(NMe$_2$)$_5$ using water and an oxygen plasma, respectively. The thermal process afforded comparable growths, $\sim$0.085 nm/cycle, to those obtained in our plasma-enhanced process at 200–300°C (Fig. 9). The growths per cycle for the thermal process increased at both the higher and lower substrate temperatures due to precursor decomposition CVD and condensation of water, respectively. The plasma-enhanced ALD of Ta$_2$O$_5$ using [Ta(NMe$_2$)$_5$] reported by Maeng and co-workers gave much higher growths per cycle of $\sim$0.12 nm. These films had an O/Ta ratio of 2.6, and no nitrogen or carbon incorporation was reported. The hydrogen content was not commented upon. The mass density reported, $\sim$7.75 g cm$^{-3}$ (94% of the bulk value of Ta$_2$O$_5$ although the precise substrate temperatures were not reported), was slightly lower than our previously reported values, but this difference cannot be the reason for such a significant difference in growth. It may be a result of the use of different ALD equipment, where the design of the reactor may affect the way in which precursors are introduced to the substrate. With the exception of our results, plasma-enhanced ALD using [Ta(NMe$_2$)$_5$] afforded higher growths per cycle than the TaCl$_5$/water process, although the [Ta(NMe$_2$)$_5$]/water process gave similar growths per cycle.

To investigate the use of different reactors, the [Ta(NMe$_2$)$_5$] plasma-enhanced ALD process was transferred from the ALD-I to the FlexAL reactor, extending the investigation down to 25°C. The growths per cycle obtained bore more resemblance to the results of Maeng et al. than those obtained using ALD-I. The increase in growth per cycle at temperatures below 100°C was significant, which was again a result of the low mass density of the film as the number of Ta atoms deposited did not change dramatically over the temperature range (Fig. 10a and d). At 250°C, there was also an increase in growth per cycle, due to the decomposition of the [Ta(NMe$_2$)$_5$] precursor. This was consistent with the thermogravimetric analysis of the precursor in the literature, which showed the onset of decomposition at around 200°C. The effect of the CVD is clearly shown by the almost twofold increase in the Ta deposited at 250°C, and to a much lesser extent at 200°C.

Despite the similarity in the numbers of atoms being deposited per cycle between the ALD-I and FlexAL reactors, the film compo-

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**Figure 9.** (Color online) A comparison of growths per cycle for the ALD of Ta$_2$O$_5$ from [Ta(NMe$_2$)$_5$]. Shown here are the thermal process with water and the plasma-enhanced process, as reported by Maeng et al. and our plasma-enhanced processes on ALD-I and FlexAL. The TaCl$_5$/H$_2$O process is also shown for comparison. Lines serve as a guide to the eye.

**Figure 10.** (Color online) Compositional data for the Ta$_2$O$_5$ films deposited on the FlexAL and ALD-I reactors. (a) Ta atoms deposited per cycle (lines serve as a guide to the eye), (b) O/Ta ratio, the ratio of stoichiometric Ti$_2$O$_5$ is represented by a dashed line, (c) the hydrogen concentration, and (d) the mass densities of the films.
sitions were different (Fig. 10b-d). The films deposited on the ALD-I reactor had a density close to that of the bulk, were stoichiometric Ta₂O₅, and contained very low concentrations of hydrogen. At 50 and 100°C on the FlexAL reactor, the films were stoichiometric with an excess of oxygen (Fig. 10b). The films also contained significant concentrations of hydrogen (up to 35 atom %), which are very high when compared with the Al₂O₃, TiO₂, and other Ta₂O₅ processes. However, in common with these processes, the hydrogen concentration decreased with increasing substrate temperature. It is likely that there is a significant presence of OH groups in the film; therefore, it might just be coincidence that the film at 25°C was stoichiometric, as there was a significant presence of hydrogen and oxygen in that film. Carbon and nitrogen were not detected at any temperature (RBS detection limit = 5 atom % in each case). There was a positive correlation between substrate temperature and film density (Fig. 10d), but the densities were much lower than expected for a good ALD film, less than half the bulk value below 50°C. This comparison with the 94% of the bulk value reported by Maeng et al. [66] despite similar growths per cycle, probably due to the excess of hydroxyl groups. Why the film densities were low and hydroxyl groups were present in such high quantities and why the mass densities were so low, is still unclear. The differences observed between the two reactors could be a result of the composition of the polymers used, which interact with the NMe₂ ligands in different ways. However, such a difference in growth per cycle and film density has not been observed for other processes. A possible reason is that the ion flux and ion energies in the ALD-I system are generally higher than in the FlexAL reactor. The plasma composition in all reactors and the effects on film growth are currently under investigation.

Conclusions

We have deposited Al₂O₃, TiO₂, and Ta₂O₃ thin films using plasma-enhanced ALD and addressed the ability of plasma-enhanced ALD to deposit metal oxide thin films at temperatures as low as room temperature. Analysis of the metal atoms deposited per cycle and film density has not been observed for other processes. A possible reason is that the ion flux and ion energies in the ALD-I system are generally higher than in the FlexAL reactor. The plasma composition in all reactors and the effects on film growth are currently under investigation.

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