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Plasma and Thermal ALD of Al$_2$O$_3$ in a Commercial 200 mm ALD Reactor

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The deposition of Al$_2$O$_3$ by remote plasma atomic layer deposition (ALD) in the Oxford Instruments FlexAL reactor was studied and compared with results from thermal ALD in the same reactor. Trimethylaluminium [Al(CH$_3$)$_3$] was used as the metal precursor and O$_2$ plasma and H$_2$O were used as oxidizing agents for the plasma and thermal processes, respectively. For remote plasma ALD with a total cycle time of 4 s, the growth per cycle decreased monotonically with substrate temperature, from 1.7 Å/cycle at 25°C to 1.0 Å/cycle at 300°C. This growth per cycle was consistently higher than that obtained for thermal ALD. For the latter a maximum growth per cycle of ~1.0 Å/cycle was found at 200°C. The film properties investigated were nearly independent of oxidant source for temperatures between 100 and 300°C with a slightly higher mass density for the remote plasma ALD Al$_2$O$_3$ films. Films deposited at 200 and 300°C were stoichiometric with a mass density of 3.0 g/cm$^3$ and low C (<1 atom %) and H (<3 atom %) contents. At lower substrate temperatures, oxygen-rich films were obtained with a lower mass density and higher H-content. Remote plasma ALD produced uniform Al$_2$O$_3$ films with nonuniformities of less than ±2% over 200 mm diam substrates. Excellent conformity was obtained for films deposited in macropores with an aspect ratio of ~8 (2.0–2.5 μm diam). Preliminary results on electrical properties of remote plasma deposited films showed high dielectric constants of 7.8 and 8.9 for as-deposited and forming gas annealed Al$_2$O$_3$, respectively.

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Al$_2$O$_3$ is of interest for a wide range of applications because of its unique material properties. The most commonly investigated application is as a dielectric layer, for example as a gate oxide in complementary metal oxide semiconductor (CMOS) or as a capacitor dielectric in dynamic random access memory (DRAM). Al$_2$O$_3$ is considered for these applications as it combines a high dielectric constant (k ~ 9) with a high band gap (~9 eV). These properties make Al$_2$O$_3$ an interesting material as a dielectric in high density trench capacitors, e.g., for radio-frequency (rf) decoupling capacitors integrated in silicon. Additionally, Al$_2$O$_3$ attracts interest in emerging technologies involving organic electrical devices and photovoltaics, e.g., as transparent, high-density moisture permeation barrier for organic light emitting devices (OLEDs) and as a surface passivation layer on high-efficiency crystalline silicon solar cells. Furthermore, Al$_2$O$_3$ has excellent mechanical properties and can be used as a wear resistant coating, for example, microelectromechanical systems (MEMS).

Critical for all these applications is to have a deposition technique that is capable of producing high-quality films with low pinhole density and good conformity on substrates with demanding topologies, and which offers precise thickness control even over large-area substrates. Atomic layer deposition (ALD) of Al$_2$O$_3$ is a method that has shown great potential to meet these demands. This chemical vapor deposition (CVD) method is cyclic and based on two separately executed half reactions that are self-limiting: (i) chemisorption of the metal precursor and (ii) oxidation of the metal and removal of the organic surface groups. Thermal ALD of amorphous Al$_2$O$_3$ using trimethylaluminium [Al(CH$_3$)$_3$] as the metal precursor and H$_2$O as the oxidant has already been widely investigated and can be considered as a model system for ALD. In this process, Al(CH$_3$)$_3$ chemisorbs to surface hydroxyl groups by splitting off gaseous CH$_4$. After reaching saturation, residual Al(CH$_3$)$_3$ and reaction products are removed by purging and/or pumping. Subsequently, the –CH$_3$ ligands of the chemisorbed Al(CH$_3$)$_3$ species are removed by a reaction with H$_2$O leading to an additional submonolayer of Al$_2$O$_3$ while also regenerating the surface –OH groups.

To widen the ALD process window, O$_2$ plasmas and O$_3$ have recently been considered as alternative oxidants. Particularly O$_2$ plasmas are very effective oxidants that can easily remove organic ligands by O-radical driven combustion-like surface reactions. Therefore, the plasma-based process generally yields more process flexibility, including the potential of depositing higher quality materials at lower substrate temperatures while also allowing the use of the difficult-to-purge H$_2$O. The plasma assisted processes can be divided in three categories: (i) direct plasma ALD where the substrates are positioned on an electrode used for plasma creation, (ii) remote plasma ALD, where plasma creation takes place remotely from the substrate but with all plasma species still present at the position of the substrate, and (iii) radical-enhanced ALD where the plasma is created far from the substrate such that ions and electrons from the plasma do not reach the substrate at all. For direct plasma ALD plasma damage can occur due to high ion energies, while for radical-enhanced ALD ion damage is completely absent at the cost of a lower reactivity due to reduced fluxes of reactive species. Remote plasma ALD combines a high reactivity with a low ion energy, typically below the threshold energy for plasma damage.

To date, the studies of plasma-assisted ALD of Al$_2$O$_3$ employed mostly direct plasma ALD reactors with the main focus the electrical properties of the material as well as the properties of the interface with the Si substrate (e.g., interfacial oxide formation). These aspects were also addressed in a comparison between remote plasma and thermal ALD by Choi et al. The growth characteristics and material properties obtained by radical enhanced ALD of Al$_2$O$_3$ were recently studied by Niskanen et al. In this paper, we report on the growth characteristics and material properties of remote plasma ALD Al$_2$O$_3$ while also making a comparison with the thermal ALD process of Al$_2$O$_3$. Both the remote plasma and thermal process were carried out in the new Oxford Instruments FlexAL ALD tool. The growth per cycle, material atomic composition, and uniformity are tested for a wide substrate temperature range while the conformality and the electrical properties of the Al$_2$O$_3$ are also addressed.

Experimental

ALD reactor and film synthesis.— Both the remote plasma and thermal ALD of Al$_2$O$_3$ was carried out in the FlexAL ALD tool recently developed by Oxford Instruments Plasma Technology. The
For Al$_2$O$_3$ ALD, trimethylaluminum [TMA, Al(CH$_3$)$_3$] (Akzo-Nobel, SSG grade) was vaporized at 25°C and a saturated dose was obtained by 20 ms vapor injection using fast switching ALD valves. For the plasma process, the oxidation step took place via a 400 W O$_2$ plasma at a pressure of 15 mTorr and ignited for a duration of typically 2 s. O$_2$ also served as a purge gas because O$_2$ does not react with Al(CH$_3$)$_3$. The O$_2$ flow was kept constant at 60 sccm during the entire cycle. A cycle time of 4 s was obtained by employing an Al(CH$_3$)$_3$ purge of 1.5 s and a post-plasma-purge of 0.5 s. For thermal ALD, H$_2$O was vaporized at 25°C and dosed in steps of at maximum 120 ms. If higher doses were required the 120 ms step was repeated with 0.5 s intermediate delays. A 110 sccm Ar flow at a pressure of 15 mTorr was used as purge gas and a pump-purge step (7 s evacuation and 5 s purging) was found most effective in removing residual H$_2$O from the reactor. Typical cycle times for the thermal ALD process were 16 s but it should be noted that no efforts were undertaken to optimize this cycle time. This can for example be done by increasing the residence time during water exposure and operating at higher pressure. The substrate temperature was varied between 25 and 300°C for remote plasma ALD. The lowest substrate temperature used for the thermal ALD process was 100°C to avoid extensive purge times necessary to remove H$_2$O at low temperatures. The reactor wall temperature was kept constant at 120°C, except for the remote plasma depositions at 25°C for which the wall was also kept at 25°C.

Film analysis and characterization.—Si p-type wafers with diameters up to 200 mm were used as substrates for characterization of the ALD process and film composition. The center thickness and refractive index of the Al$_2$O$_3$ films were monitored in situ by spectroscopic ellipsometry (SE) measurements (J.A. Woollam M-2000D, 193–1000 nm wavelength range) carried out between the ALD cycles. Ex situ measurements with the same ellipsometer were performed to measure the film thickness on any position of the wafer to obtain the nonuniformity of the films as defined by

$$d_{\text{average}} = \frac{d_{\text{max}} + d_{\text{min}}}{2}$$

where $d_{\text{max}}$, $d_{\text{min}}$, and $d_{\text{average}}$ are the maximum, minimum, and average thickness, respectively. The Al, O, and C-content of the film were determined by Rutherford backscattering spectrometry (RBS). Elastic recoil detection (ERD) was used to determine the H-content. A 2 MeV $^4$He$^+$ beam was applied in these measurements. The conformality of the remote plasma ALD process was examined for an 80 nm thick Al$_2$O$_3$ film deposited in 2–2.5 μm wide and ~19 μm deep silicon macropore structures. After sputtering a 2 nm platinum conductive layer for imaging purposes, high-resolution scanning electron microscopy (SEM) images using a FEI Nova NanoSEM 600 electron microscope revealed the conformality. For electrical characterization of the Al$_2$O$_3$ films, the Si substrates were HF-dipped (1% HF solution) prior to deposition to remove the native oxide. Aluminum electrodes (areas ranging from 0.02 to 1.2 mm$^2$) were sputtered on the Al$_2$O$_3$ films using a shadow mask.

Both as-deposited and forming gas annealed films (30 min 425°C, 10% H$_2$-90% N$_2$) were characterized electrically. The dielectric constant and breakdown voltage of these test structures were determined by 10 kHz capacitance-voltage (C-V) and current-voltage (I-V) measurements with an HP4275A multifrequency LCR meter and an Agilent 4155B parameter analyzer.

Figure 1. (Color online) Al$_2$O$_3$ film thickness as a function of the number of cycles for both remote plasma ALD and thermal ALD. The thickness was determined by in situ spectroscopic ellipsometry and the growth per cycle was obtained from the linear fits shown in the figure. The substrate temperature was 200°C.

Growth per cycle and saturation behavior.—Figure 1 shows an in situ SE measurement of the Al$_2$O$_3$ film thickness as a function of the completed number of ALD cycles for both the remote plasma and the thermal ALD process. The substrate temperature was 200°C. As expected, the thickness increases linearly with the number of completed ALD cycles for both the remote plasma and the thermal ALD process. From these in situ thickness measurements the growth per cycle (GPC) can be determined from a linear fit of the data. Clearly, the growth per cycle is higher for remote plasma ALD than for thermal ALD, i.e., 1.2 Å/cycle for remote plasma ALD and 1.0 Å/cycle for thermal ALD.

The saturation behavior of the oxidation step was investigated for the remote plasma and thermal ALD by considering the GPC as a function of the O$_2$ plasma exposure time and H$_2$O dosing time. For remote plasma ALD, the results are shown in Fig. 2 for a substrate temperature of 200°C. The corresponding nonuniformity of the film thickness over a 150 mm wafer is also given. Figure 2 reveals that surface reactions saturate during the oxidation step when the O$_2$ plasma exposure time is greater than 1.0 s, with a saturated value of the GPC of 1.2 Å/cycle. For shorter plasma exposure times, the GPC is not saturated and the plasma step becomes a source of film nonuniformity. This can be explained by a shortage of oxidizing plasma species at these short plasma exposure times. In this subsaturated regime the growth rate is slightly higher in the center where the flux of plasma species is greatest. Note that if the surface reaction kinetics were slow, the flux of plasma species would be more isotropic within the reactor and a good uniformity would also be achieved at plasma exposure times shorter than required for saturation. For a plasma exposure of 2 s the growth per cycle was found to saturate over the whole substrate area for all substrate temperatures investigated between 25 and 300°C. The nonuniformity determined over 200 mm wafers decreased from 1.2% at 25°C to 0.5% at 300°C for this setting.

Figure 3 shows the GPC for the thermal process as a function of H$_2$O dosing time for substrate temperatures of 100 and 200°C. Different pump and purge steps have been used for the different data points shown in Fig. 3, which can explain the scatter between data points. Note that the H$_2$O dosing time required to obtain saturation...
is significantly longer than the Al(CH$_3$)$_3$ dosing time of 20 ms, even though the delivery details and vapor pressure are similar for both H$_2$O and Al(CH$_3$)$_3$ [saturated vapor pressure of H$_2$O and Al(CH$_3$)$_3$ are $\sim$24 and $\sim$16 Torr at 25°C, respectively]. The relatively long time required to achieve saturation of the surface reactions is probably due to slow kinetics of the H$_2$O half reaction,$^27$ which also explains the excellent uniformity of the thermal ALD process under all conditions studied. The nonuniformities were $<$1% as determined over 200 mm wafers. In addition, for shorter cycle times with reduced purging (and pumping) using high H$_2$O dosing times (>240 ms), a slightly decreased GPC was observed using the same Al(CH$_3$)$_3$ dose. Generally, one expects an increase in growth per cycle due to parasitic chemical vapor deposition (CVD) reactions when there is residual H$_2$O during Al(CH$_3$)$_3$ dosing. Yet, it is also possible that some Al(CH$_3$)$_3$ is consumed by parasitic CVD, at spots within the reactor that are more difficult to purge. In the remainder of this work a typical H$_2$O dosing time of 240 ms was used in the thermal ALD process of Al$_2$O$_3$. Under this condition, the GPC appears to be saturated while it also prevents the need for the very long purge times required when using longer H$_2$O dosing times.

Figure 4 shows the GPC of the remote plasma ALD process measured as a function of substrate temperature between 25 and 300°C. For remote plasma ALD, the GPC decreases monotonically with increasing substrate temperature from 1.7 Å/cycle at 25°C to 1.0 Å/cycle at 300°C. This agrees well with values obtained in our home-built remote plasma reactor as reported previously.$^9$ Studies using direct plasma ALD report GPCs that are slightly higher than reported here, i.e., 1.75 Å/cycle at 100°C down to 1.0 Å/cycle at 350°C.$^{15,16}$ Remarkably, the GPC values reported for radical assisted ALD of Al$_2$O$_3$ were as high as 3.2 Å/cycle.$^{17}$ For thermal ALD the GPC is 1.0 and 0.9 Å/cycle for 200 and 300°C, respectively, which corresponds well to the literature values within the error margins.$^{12,16,27,29}$ For temperatures lower than 200°C, there is some scatter in the literature values and our GPC of 0.8 Å/cycle at 100°C is for example relatively low compared to the maximum value of 1.3 Å/cycle reported by Groner et al.$^{16}$ Although not apparent from Fig. 3, we found that it was difficult to reach saturation for the H$_2$O dose at 100°C. This difficulty might explain relatively low GPC at 100°C found in this study and might also explain the relatively wide spread in the literature values.

The decrease of the GPC of Al$_2$O$_3$, at increasing substrate temperature for remote plasma and thermal ALD (for substrate temperatures >200°C) is in line with observations reported in the literature for thermal ALD$^{12,16,27,29}$ and plasma assisted ALD.$^{15,17}$ This decrease is generally attributed to thermally activated recombination reactions of surface hydroxyl groups (–OH), the so-called dehydroxylation.$^{12,30}$ Assuming that the reactive Al$_2$O$_3$ surface sites created during O$_2$ plasma exposure are also hydroxyl groups,$^{16}$ these dehydroxylation reactions can also explain the decrease of the GPC for the remote plasma ALD case. Furthermore, note that the GPC for the remote plasma ALD process exceeded in all cases the GPC for thermal ALD. Especially at lower temperatures, this effect becomes very apparent. A similar result was reported by Lim et al.$^{16}$ who compared direct plasma ALD with thermal ALD of Al$_2$O$_3$. It appears that the O$_2$ plasma is more effective as oxidant than H$_2$O, especially at low substrate temperatures. At higher temperatures the discrepancy becomes relatively small. This suggests that the GPC becomes dictated by the stability of the hydroxyl groups at the surface at these temperatures.

**Film composition**—Figure 5 shows the RBS and ERD results for the remote plasma and thermal ALD films. The mass density, depicted in Fig. 5a was calculated from the atomic areal densities and the film thickness determined by SE. The mass density for remote plasma ALD increases from 2.6 ± 0.1 g cm$^{-3}$ at 25°C to 3.0 ± 0.1 g cm$^{-3}$ for temperatures higher than 200°C. The densities obtained with thermal ALD were comparable but always slightly lower than the remote plasma ALD values. Figure 5b shows that the ratio of oxygen to aluminum [O]/[Al] in the Al$_2$O$_3$ films were very similar for the remote plasma ALD and thermal ALD process. Films deposited at temperatures of 200°C and higher were stoichiometric ([O]/[Al] = 1.5) whereas the films were oxy-
The results reported here show good agreement with the properties of the \( \text{Al}_2\text{O}_3 \) films obtained in our home-built remote plasma ALD reactor under saturated conditions.\(^3\) Compositional data on radical-enhanced ALD yielded also similar trends but the films were more oxygen rich \([O]/[\text{Al}] = 1.81\) at 100°C and contained also more carbon, \(2.3 \text{ atom}\% \) at 100°C.\(^7\) Other studies on plasma assisted ALD of \( \text{Al}_2\text{O}_3 \) did not focus on film composition. For thermal ALD, the densities of the \( \text{Al}_2\text{O}_3 \) films agree with values obtained by Groner et al.,\(^26\) however the H content found in the present study is somewhat lower \(7.9 \text{ atom}\% \) instead of 14 atom% at 100°C. Furthermore, the refractive index of 1.64 ± 0.02 that we found for films deposited at temperatures higher than 100°C by spectroscopic ellipsometry agrees well with other thermal ALD studies.\(^27,28\) From the aforementioned results, it can be concluded that the remote plasma process yields higher growth per cycle values at reduced cycle times than thermal ALD. The material properties of remote plasma are very similar and at least as good as that of thermal ALD for substrate temperatures beyond 100°C. For low substrate temperatures, the discrepancy between remote plasma ALD and thermal ALD becomes more apparent. At low temperatures, remote plasma ALD provides the option to deposit \( \text{Al}_2\text{O}_3 \) with fair to good material properties at high growth rates, i.e., with a high growth per cycle and short cycle times.

Conformality and electrical properties.— For the application of the \( \text{Al}_2\text{O}_3 \) films as dielectric material in demanding three-dimensional topologies, both the electrical properties and the conformality of the films deposited in high-aspect ratio structures are important. Figure 6 shows a high-resolution SEM image of a remote plasma \( \text{Al}_2\text{O}_3 \)-film deposited in 700 cycles at a substrate temperature of 200°C in a macropore structure with an aspect ratio of \(8:1\). Arrays of such macropores are used for the synthesis of metal oxide semiconductor (MOS) “trench” capacitors that serve as rf decoupling capacitors integrated in silicon.\(^3\) The thickness of the film measured with spectroscopic ellipsometry on the top surface of the wafer was 83 nm. The thicknesses measured with high-resolution SEM at the bottom and sidewall of the macropores was \(80 \pm 3\) nm. The remote plasma is therefore able to deposit \( \text{Al}_2\text{O}_3 \) with fair to good material properties at high growth rates, i.e., with a high growth per cycle and short cycle times.

Preliminary results of the electrical characterization of \( \text{Al}_2\text{O}_3 \) films deposited by remote plasma ALD on planar substrates at a substrate temperature of 200°C are shown in Fig. 7. In this figure, the equivalent oxide thickness (EOT) values calculated from the
O$_2$ plasma was characterized and compared to the well-established permittivity, the dielectric constant can be determined as $\varepsilon_r$. ALD films are slightly higher than those of the thermal ALD process of Al$_2$O$_3$ employing H$_2$O as the oxidant. This comparison was carried out for films deposited in the same commercial 200 mm reactor. The growth per cycle, saturation of the surface and substrate temperatures below 300°C, the dielectric constants reported were 7.6 or 7.8 and according with those obtained in the literature for plasma ALD at 200°C. Dielectric constants obtained for thermal ALD of Al$_2$O$_3$ have been summarized by Groner et al. 32 For deposition temperatures below 300°C, the dielectric constants reported were 7.6 or 7.8 for the as-deposited and annealed Al$_2$O$_3$, respectively. The offset of the linear fit can be most probably attributed to the presence of an interfacial SiO$_2$ layer. Other ALD studies also reported on such an interfacial layer 33 and we found a 1.2 nm thick SiO$_2$ interfacial layer for Al$_2$O$_3$ deposited in our home-built remote plasma ALD reactor. 10 Investigation of the formation of this interfacial oxide layer is outside the scope of the present study and no effort was undertaken to minimize its thickness. Furthermore, the breakdown voltage was investigated by current density measurements using the same samples. The catastrophic breakdown field, defined as the field where the current reaches the compliance setting (i.e., 100 mA) of the parameter analyzer, was determined to be 9.7 ± 0.5 MV/cm for as-deposited films and 8.4 ± 0.5 MV/cm for the postdeposition annealed films. The dielectric constants obtained in these studies are in good agreement with those obtained in the literature for plasma ALD of Al$_2$O$_3$ have been summarized by Groner et al. 32 For deposition temperatures below 300°C, the dielectric constants reported were 7.6 or lower. The breakdown field reported here is relatively high but cannot easily be compared to values reported in the literature due to the use of different definitions for breakdown. Although these results are promising, more investigations are required to get full insight into the electrical properties of the Al$_2$O$_3$, also under other operating conditions.

Conclusions

The remote plasma ALD process of Al$_2$O$_3$ from Al(CH$_3$)$_3$ and O$_2$ plasma was characterized and compared to the well-established thermal ALD process of Al$_2$O$_3$ employing H$_2$O as the oxidant. This comparison was carried out for films deposited in the same commercial 200 mm reactor. The growth per cycle, saturation of the surface reactions, and material properties were investigated for substrate temperatures between 25 and 300°C. It was demonstrated that uniform high-quality films can be obtained for substrate temperatures above 100°C. For these temperatures, the mass densities of the remote plasma ALD films are slightly higher than those of the thermally deposited films. Remote plasma ALD also yields fair material properties below 100°C at a relatively high growth per cycle and short cycle times. Conformal films in high-aspect ratio structures were achieved using remote plasma ALD and preliminary results on electrical characterization reveal that the Al$_2$O$_3$ show good dielectric performance.

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