What is limiting low-temperature atomic layer deposition of Al2O3? A vibrational sum-frequency generation study

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of the lower GPC for the H2O-based process is the lack of reactivity of the co-reactant at low temperatures. However, the precise ALD surface chemistry related to this lower reactivity is unclear. So far, the aforementioned diagnostic techniques have not been able to resolve this issue and therefore a different approach is needed.

In this work, the surface chemistry of ALD Al2O3 is investigated with the technique of broadband sum-frequency generation (BB-SFG). BB-SFG is a state-of-the-art nonlinear optical technique used predominantly in surface science which is used here to study ALD chemistry. BB-SFG is inherently interface selective with a sub-monolayer sensitivity for –CH3 groups and with fairly short acquisition times (120 s for a sensitivity better than 10% of a –CH3 monolayer). One of the key features of BB-SFG is that the measured signals are directly correlated to the absolute surface density, revealing more information than the so-called differential techniques (such as FTIR) from which only changes in surface coverage can be extracted. By its very nature, the surface selectivity of BB-SFG leads to the simultaneous detection of species which are changing after an ALD half-cycle and species which are persistent over the ALD half-cycles. In this letter, it will be shown that these persistent surface species play a key role in ALD of Al2O3 at low temperatures. Water is not reactive enough at low temperatures to remove all the –CH3 groups from the surface; even when saturation conditions are reached, a significant amount of –CH3 groups persist on the surface. These persistent –CH3 groups limit the uptake of TMA in the next half-cycle causing the reduction in GPC. The reduction in the areal density of the Al atoms deposited per cycle is found to be directly proportional to the persistent –CH3 coverage.

ALD of Al2O3 was studied with BB-SFG in a setup designed and built for this purpose. The setup consisted of a vacuum chamber equipped with two turbo-molecular pumps (base pressure below 10−7 mbar) and fast ALD valves to dose the vapor drawn reactants. A pump down step of ~140 s reaching a pressure below 10−6 mbar was performed after dosing the reactants. The sample was heated radiatively from the back side and the temperature of the sample was controlled with a thermocouple glued to the substrate within 5 mm of the spot measured with BB-SFG. The sample itself was a free-standing 2 in. Si(100) wafer with a 90 nm SiO2 film on top for optical enhancement purposes of the BB-SFG signal. The sample was mounted such that BB-SFG could be performed in reflection mode. The laser system used for the experiments produced a ~90 fs pulsed IR (3.3 μm) beam and visible (800 nm) beam with a repetition rate of 1 kHz. A band-pass filter was used to reduce the bandwidth of the visible pulse to ~1 nm. Both the IR and visible beams (pulse energy ~5 μJ each) were focused on the sample in a non-collinear geometry. The spectra shown in this work were acquired with an integration time of 120 s to reach a noise level of <1% for typical signals. Except for dark-field subtraction and the removal of features due to cosmic rays, the data are presented as-obtained.

The surface chemistry occurring during both ALD half-cycles was monitored with BB-SFG by probing the spectral region of the C-H stretching modes. The C-H stretching mode of –CH3 was detected at ~2950 cm−1 after precursor exposure, similar to what is typically observed with FTIR for chemisorbed TMA. The mode is in the same range as, for example, –CH3 groups of self-assembled monolayers (SAM) when probing them with BB-SFG. Subsequently, the –OH covered surface was exposed to a pulse of TMA by activating the ALD valve for 20 ms. As expected from Eq. (1a), the spectrum recorded after the TMA exposure shows the spectral feature indicative of the C-H stretching mode of –CH3 groups on the surface. A subsequent 20 ms pulse yields only a slight increase in peak height indicating a small additional uptake of TMA. Ensuing TMA pulses do not show any change in –CH3 coverage, implying that saturation has already been reached. When continuing with the H2O half-cycle after the TMA half-cycle, the first 20 ms H2O exposure results in a significant decrease in the amount of –CH3 on the surface as can be seen in Fig. 2(b). Subsequent pulses of water remove –CH3 groups from the surface until all –CH3 groups have disappeared. To recapitulate, the surface chemistry at 200°C is described by Eq. (1) which is reflected by the uptake and removal of –CH3 for the TMA and water half-cycle, respectively. This happens in a self-limiting fashion as is characteristic for ALD.

In order to reveal how the sample temperature influences the surface chemistry during steady-state film growth, the experiments have been carried out at temperatures ranging between 100°C and 300°C. A set of saturation plots was obtained for each temperature yielding the dependence of the –CH3 coverage on the precursor and co-reactant dose as shown in Fig. 3. In this figure, the BB-SFG spectra were normalized for each temperature to the –CH3 coverage obtained after a saturated TMA exposure. The reason is that the acquisition of the spectra for these experiments was relatively time consuming and necessary day-to-day adjustments of the
laser system influenced the optical alignment, preventing a direct comparison of absolute intensities between measurements at different temperatures. As can be seen from the figure, the saturation of the TMA half-cycle is fast and the dose for which saturation is achieved is independent of temperature. For low temperatures, the initial –CH3 coverage is not equal to zero and both –OH and –CH3 groups coexist on the surface at the beginning of the TMA half-cycle. This –CH3 can be traced back to the reactivity of the H2O co-reactant as can be seen in Fig. 3(b). This figure shows that water is reactive towards the –CH3 groups at high temperatures and quickly removes all the –CH3. However, for lower temperatures, the reaction slows down. Furthermore, below 200 °C, there are –CH3 groups which are no longer reactive towards H2O and these –CH3 groups therefore persist on the surface. In other words, the half-cycle saturates while there are still –CH3 groups present on the surface. An additional check with two extra-long H2O exposures of 400 and 800 ms at 150 °C (not shown) did not yield an additional decrease of the –CH3 signal. This implies that during thermal ALD of Al2O3 at low temperatures, there is a significant amount of –CH3 present on the surface at the beginning of the TMA half-cycle.

To obtain more quantitative information on the influence of the temperature on the ALD process, a less time consuming experiment was carried out such that the –CH3 coverages for different temperatures could be compared with each other. Instead of recording saturation curves, spectra were only recorded after a saturated half-cycle. Figure 4 shows the BB-SFG spectra of the C-H stretch mode after the TMA and H2O half-cycles. Again, at high temperatures, the –CH3 surface groups added to the surface during the TMA half-cycle are completely removed in the water half cycle, while at lower temperatures –CH3 groups persist. Moreover, the influence of temperature induced dehydroxylation is observed in the –CH3 coverage after a saturated TMA. Due to dehydroxylation, fewer reactive sites are available for TMA chemisorption at high temperature than at low temperature, hence the –CH3 coverage shows a decrease with temperature.

The trend in growth per cycle shown in Fig. 1 can be reproduced using the data in Fig. 4. The density of Al atoms deposited per cycle is proportional to the TMA uptake in the TMA half-cycle. The TMA uptake is directly related to the change in –CH3 coverage if the number of –CH3 ligands, n, which remain attached to the Al atom after chemisorption, is temperature independent. QCM studies showed that this is indeed the case over the temperature range investigated here. For the thermal ALD process, the TMA uptake will be limited by the persistent –CH3 groups in the H2O half-cycle. Therefore, the TMA uptake should be proportional to the difference in –CH3 coverage between the TMA and H2O half-cycles. The increase in –CH3 coverage caused by the TMA exposure was determined from Fig. 4, and the predicted GPC from this change in –CH3 coverage was plotted in Fig. 1. The validity of this procedure can be evaluated by also predicting the GPC of the plasma process. For the plasma process, there should be no persistent groups due to the high reactivity of the O2 plasma. In this case, the change in –CH3 coverage is equal to the –CH3 coverage after TMA exposure. This result is also plotted in Fig. 1 on the same scale as the data set for thermal ALD. Both data sets indeed show a good agreement with GPC determined by RBS. The agreement between the measured and predicted GPC for ALD of Al2O3 using TMA and H2O corroborates therefore that the persistent –CH3 groups are the limiting factor in the Al2O3 ALD process at low temperatures.

The underlying cause of the persistent –CH3 groups can be studied in more detail by considering the reaction kinetics. The kinetics of the reactions in Eq. (1) were determined from Fig. 3 by fitting the dependence of –CH3 coverages on the reactant exposure time with an exponential function. Briefly, the exponential time constant is equal to the reaction cross section multiplied with the (known) impinging flux of reactant species on the surface. Figure 5 shows the temperature dependence of the reaction cross...
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Intricate chemistry during the H$_2$O half-cycle especially at reaction probabilities, it can be concluded that the values of –OH or –CH$_3$ groups, respectively. The figure also shows the fraction of –CH$_3$ groups persisting after H$_2$O exposure as a function of temperature.

Section in both half-cycles and the related initial reaction probability (i.e., the reaction probability when the reactant TMA or H$_2$O interacts with a surface that is fully covered with –OH or –CH$_3$ groups, respectively). The figure also shows the fraction of persistent surface groups as a function of temperature obtained from the fits to the saturation plots (Fig. 5(c)). Considering the order of magnitude of the initial reaction probabilities, it can be concluded that the values of $10^{-3}$ for TMA and $10^{-4}$ for H$_2$O fall inside the range of values in the reported literature.\textsuperscript{15,16} However, those literature values vary over several orders of magnitude for different studies. The study of the reaction kinetics in this work, i.e., by directly measuring the surface coverage, is expected to yield very accurate results. The main uncertainty, the systematic error in the calculation of the reactant flux, introduces only a scaling factor and does not affect the trend in the data with temperature. Examining the temperature dependence in Fig. 5(a) more closely reveals that the reaction cross-section—and hence the initial reaction probability—during the TMA half-cycle, is independent of temperature. This confirms that chemisorption of TMA on the predominantly –OH terminated surface is a barrierless process which is not thermally activated. For the H$_2$O half-cycle, the reaction cross-section in Fig. 5(b) does depend on the temperature and the behavior is more complex. The increase in reactivity at high temperatures during the H$_2$O half-cycle suggests a thermally activated reaction for this half-cycle.

Although the reactions described by Eq. (1) suggest simple reaction kinetics, the data in Figs. 3 and 5 show a more intricate chemistry during the H$_2$O half-cycle especially at low temperatures: A pseudo first order reactions can describe the chemistry at high temperatures but it cannot describe the kinetics at low temperatures due to the presence of persistent surface groups. A possible explanation for the persistent surface groups can be found in the recent \textit{ab-initio} studies using density functional theory (DFT) performed by Shirazi and Elliott.\textsuperscript{17} They proposed that the so-called cooperative effects play an important role in the surface chemistry of ALD. For –CH$_3$ surface groups reacting with H$_2$O, they found a significantly higher activation barrier for isolated –CH$_3$ groups than for clusters of –CH$_3$. An independent DFT study from Weckman and Laasonen also reports a high activation barrier for isolated –CH$_3$ and cooperative effects for this ALD process.\textsuperscript{18} Such a cooperative effect could explain the persistence of –CH$_3$ groups at low temperatures and hence this work can be seen as experimental evidence of the cooperative effect.

In conclusion, we have addressed the question of what is causing the reduced GPC of thermal ALD of Al$_2$O$_3$ at low temperatures using the nonlinear optical technique of BSFG. It was found that water is not reactive enough to remove all –CH$_3$ groups at low temperatures, which leads to a significant amount of persistent –CH$_3$ groups. These persistent –CH$_3$ groups limit the TMA uptake and hence they limit the GPC. This was also corroborated by the fact that the predicted GPC, using the measured –CH$_3$ coverage as input, showed an excellent agreement with the GPC measured with RBS if the persistent groups were accounted for. These persistent –CH$_3$ groups are not incorporated in the film as is evidenced by the high-quality, virtually carbon-free material which is generally grown with the thermal ALD process at low temperatures.\textsuperscript{2,3} Furthermore, from the reaction kinetics, it was determined that for the TMA half-cycle the reaction cross-section is temperature independent indicating barrierless reaction. On the other hand, the temperature dependent reaction cross-section in the H$_2$O half-cycle indicates a thermally activated reaction. Finally, since the combination of H$_2$O as co-reactant and metal atoms with organic ligands as precursor are quite commonplace in other ALD chemistries, the presence of persistent surface groups reported in this work could play a role in other ALD processes.

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