Conformality of Al_2O_3 deposited by thermal, plasma-enhanced and ozone-based atomic layer deposition

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In principle, good conformality is one of the main advantages of ALD. However, the conformality of ALD should not be taken for granted and achieving conformal coatings in high aspect ratio (AR) structures requires careful optimization of process parameters. In this work, we have systematically studied the conformality of Al_2O_3 ALD films using TMA as precursor and H_2O, O_2 plasma or O_3 as oxidant. The conformality was quantified by measuring the deposited film thickness as a function of depth into macroscopic test structures [1]. Macroscopic holes were created by cutting a rectangle from a polytetrafluoroethylene (PTFE) film and then clamping this piece of PTFE between two planar SiO_2 substrates (fig.). A Woollam spectroscopic ellipsometer was used to measure the film thickness.

Gordon et al. developed an elegant model for the conditions needed to deposit conformal coatings in holes with a certain AR: the penetration depth of the ALD material increases with both the precursor pressure and the exposure time [2]. The theory was confirmed by our experiments using the thermal TMA/H_2O process. However, the drawback of using high H_2O exposures is the need for very long evacuation times, resulting in long deposition cycles.

O_2 plasma does not have that complication and has the added advantage of allowing for film growth in a lower temperature range and higher growth rates. However, comparison of the PE-ALD process for Al_2O_3 with the thermal TMA/H_2O process indicated that the conformality of the plasma based process is more limited due to the surface recombination of radicals during the plasma step. By prolonging the plasma exposure time the conformality could be improved, while increasing the O_2 gas pressure did not result in a significant increase of the penetration depth. This is explained by the fact that the gas pressure influences both the dissociation degree in the plasma and the transport of the radicals from the plasma source to the deposition chamber. For higher pressures, the radicals are more confined in the source. In addition, we attempted to interpret the shape of the observed coverage profiles for the remote PE-ALD of Al_2O_3 by means of Monte Carlo modeling and comparison with the PE-ALD process for CoO. There are indications that the H_2O produced during the plasma step in the PE-ALD process for Al_2O_3 may contribute to the observed conformality through a secondary thermal reaction.

A second oxidant that can be used as alternative for the difficult-to-evacuate H_2O is O_3. Compared to the thermal process, the O_3-based process requires much larger oxidant exposures to achieve saturation of the growth rate on a flat Si substrate. While we typically used a H_2O pressure of ~10^{-3} mbar, an O_3 (O_3/O_2 ~12%) pressure of ~10^{-1} mbar was needed. Using the saturated conditions for the TMA/O_3 process, we successfully deposited conformal coatings in ARs up to ~100. Further work is ongoing to characterize the conformality limit for the O_3-process.

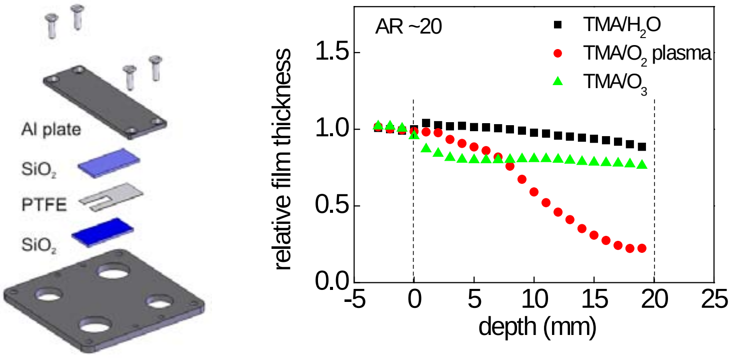

Figure: Schematic overview of the method used to construct macroscopic holes (left) and relative thickness (with respect to the thickness outside the hole) as a function of depth inside test structures for thermal, PE- and O_3-based ALD of Al_2O_3 (right).

[1] J. Dendooven et al., J. Electrochem. Soc., 156, P63 (2009).
[2] R. G. Gordon et al., Chem. Vap. Dep. 1**,** 73 (2003).