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by Fred Roozeboom (f.roozeboom@tue.nl ; fred@roozeboom.nl)

Atomic Layer Processing: basics, materials, processes and applications

Fred Roozeboom[1,2]

[1] Eindhoven University of Technology, Dept. of Applied Physics, The Netherlands

[2] TNO, Eindhoven, The Netherlands ; e-mail: *f.roozeboom@tue.nl*

Atomic Layer Deposition (ALD) is an emerging technique to deposit films with (sub-)monolayer thickness control and superior material quality for a wide variety of applications and substrate materials. Characteristic is the use of sequential self-limiting surface half-reactions (see www.phys.tue.nl/ALD/movies) to achieve uniform and conformal films even on demanding 3D topology, It is this asset that has already made conventional, *thermal* ALD accepted by the high-end nano-electronics and hard disk storage industry to produce critically thin and uniform HfO_2 and Al_2O_3 layers [1,2].

The introduction of plasma- and radical-enhanced ALD has further widened the process windows for various new materials and temperature sensitive substrates. In addition, maskless patterning by area-selective deposition has been introduced, where growth only occurs on substrate regions that have been activated or de-activated by exposing the substrate surface locally to microplasma, e-beam or laser (pre-)treatment [3].

Molecular Layer Deposition (MLD) is a close relative of the ALD technique. Where ALD is limited to inorganic coatings (oxides, sulphides, nitrides and metals), the wider choice of precursor chemistries in MLD enables to synthesize engineered coatings with 'tailor-made' properties. These coatings consist of both inorganic and organic building blocks fused together with atomic-level precision. As an example, we will discuss the growth of hybrid materials like "alucone" using trimethyl aluminum and glycol as precursors [1].

This way, an extensive material toolbox has become available, encompassing nanometer-scale functional films synthesized from inorganic to organic, to hybrid chemicals for application in electronics, displays, energy conversion and storage, MEMS/NEMS, nanoparticle photonics and catalysis, biological, antimicrobial, etc.

With the introduction of *spatial*, atmospheric pressure ALD [4], the technique is also becoming attractive for large-area and flexible substrate applications. The concept is based on the spatial separation of the half-reactions, instead of temporal, combined with gas-bearing technology. The reactor design contains separate zones exposing the precursor chemical vapors one by one to a substrate that moves underneath the reactant inlets at close proximity (~100 µm distance). Between and around these reaction zones, shields of inert gas separate the precursor flows. In addition, these gas shields act as gas bearings, facilitating virtually frictionless movement of a substrate through the reactor [5,6]. The major advantages of spatial vs. temporal ALD are the increased industrial-scale deposition rate and substrate size, combined with processing at atmospheric pressure. This way, spatial ALD has found or is foinding industrial application in photovoltaic, rechargeable battery and display device manufacturing, either in *roll-to-roll* or in *sheet-to-sheet* production.

In CMOS technology the scaling beyond 10 nm feature size is now requiring atomic-level technology breakthroughs beyond the resolution of advanced EUV lithography and the limits of conventional plasma etching. The scaling of future 3D FinFET and vertical NAND flash technology with narrower fins, lines and gap features created and filled at acceptable cost is only possible by state-of-the-art spacer-defined patterning, and processing mixes of atomic level cleaning, deposition and etching (ALE, also known as *reverse ALD*).

This tutorial will start with a short introduction on thin-film technology (history, trends in materials and dimension control). The topics treated next will be: materials used, nucleation, growth modes (thermal and plasma), selectivity in patterned growth, and reactor designs used for conventional and spatial processing. Finally, if time permits, a short outlook on Atomic Layer Processing will be given, based on the comparison between ALD and ALE principles [7,8], i.e. *layer-by-layer* growth or removal.

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