Picosun SUNALE™ ALD process tools for nanoscale coatings – seamless transition from R&D to industrial production

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ABSTRACT

Atomic layer deposition (ALD) is a chemical vapor processing method with which highly conformal, uniform, defect and pinhole free ultrathin films can be coated even on the most challenging nanoscale architectures such as high aspect ratio trenches, through silicon vias and highly tortuous through-porous networks. ALD is already widely in use in e.g. electronics, optics and sensor industries but it is rapidly gaining foothold also inside the renewable energy and clean and sustainable technology community. Picosun is a Finnish, globally operating ALD equipment manufacturer whose exclusive, pioneering expertise in the field reaches back to the invention of the ALD technology itself and whose ALD systems are used by high profile industries and top level research organizations across four continents.

Keywords: atomic layer deposition, upscalability, nanocoatings, industrial manufacturing

1 INTRODUCTION

Atomic layer deposition (ALD), originally known as atomic layer epitaxy (ALE) was invented in Finland in the early '70's by D. Sc. (Tech.) Tuomo Suntola. One of the technique's first applications was manufacturing of electro-luminescent displays though nowadays this thin film coating method utilizing chemical vapors has become a necessity especially in various fields of electronics, optics, optoelectronics and sensor industries. Newer but very potential future application areas are also renewable energy production and clean and sustainable technologies such as solar energy, fuel cells, hydrogen storage, batteries and supercapacitors, water purification and novel, fully recyclable packaging materials [1-16].

2 PRINCIPLES AND ADVANTAGES OF ALD

Atomic layer deposition is based on sequential and self-saturating surface-controlled chemisorption reactions. The gaseous precursor chemicals are introduced to the surface in alternate pulse-purge sequences, where inert gas purge wipes excess precursor off the surface before the next precursor is pulsed into the deposition chamber. This way the film growth proceeds by attaching fractions of a monolayer on the surfaces building up atomic layers that cover evenly and uniformly everything inside the deposition chamber, even the most challenging 3D nanoscale architectures such as ultra-high aspect ratio trenches or highly tortuous through-porous structures. Figure 1 visualizes the film growth steps of Al_2O_3 thin film from trimethylaluminium (TMA) and water vapor used as precursors and Figure 2 presents examples of high quality ALD coatings in deep nanoscale trenches.

In addition to uniformity, conformality and defect and pinhole free quality of the ALD films, the other advantages of the method are its gentle nature – ALD does not result in surface damage like ion bombardment based coating methods such as sputtering might do – and relatively small consumption of chemicals compared to the coated surface area. Due to the surface-controlled successive sub-monolayer growth, there is no need to pump large concentrations of precursor gases into the deposition chamber in order to grow thicker films because the excess would only be flushed away by the purge gas. Naturally, this is also the reason why ALD has sometimes been criticized as a slow method. This can be overcome, however, by specifically designed, automated and/or clustered batch reactors capable of coating e.g. several hundreds of solar cell silicon wafers in one run.

Suitable materials to be coated with ALD are basically all that can withstand some heat and which do not contain easily vaporizable ingredients that could evaporate during the ALD process and contaminate the insides of the deposition chamber. High heat tolerance is not necessarily needed either – typically the ALD processes take place in 200 – 400 ^{o}C but with novel, innovative solutions such as "ion-free" remote plasma source ALD films can be grown even at less than 100 ^{o}C temperatures. This means that even sensitive and fragile substrates such as papers and/or thin plastic foils can be treated with ALD.

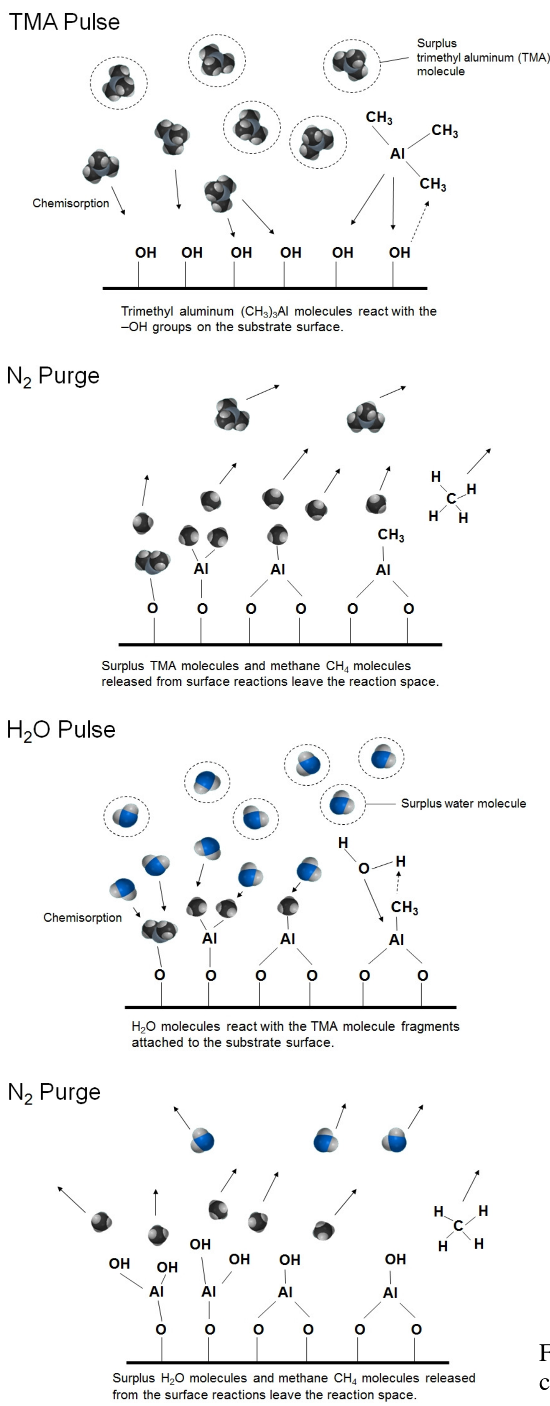

Figure 1: Reaction steps of Al_2O_3 film formation through ALD.

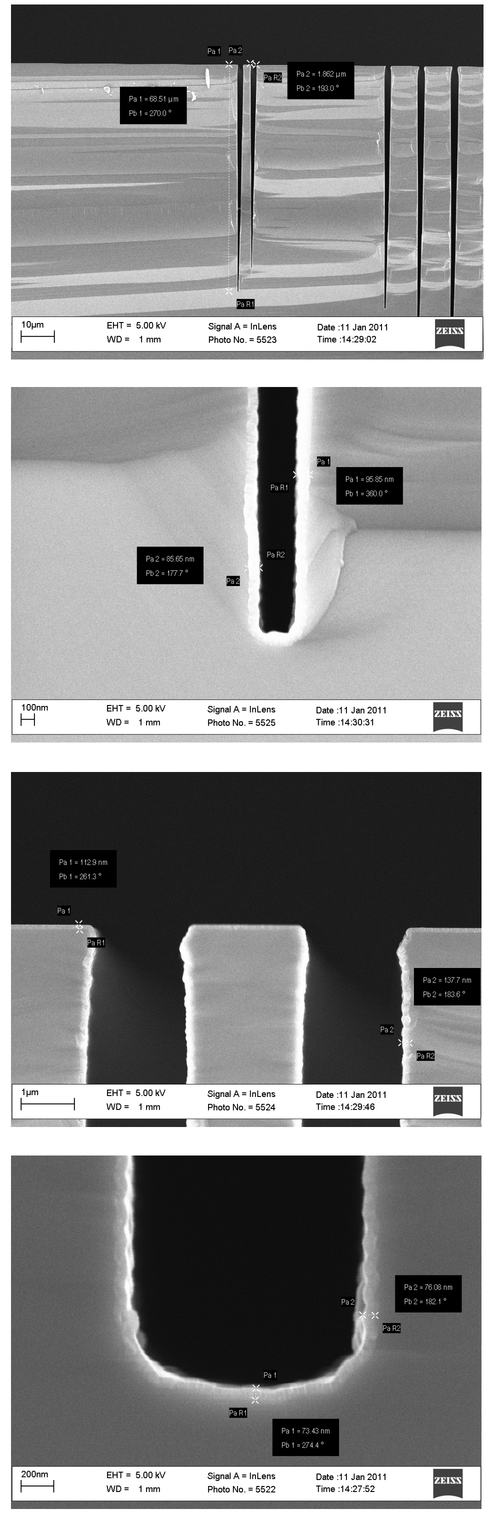

Figure 2: SEM-pictures of highly uniform and conformal metal nitride thin film in trenches (trench aspect ratio 40:1, film thickness ca. 70 nm). Film

was deposited with Picosun SUNALE™ R-200 reactor.

3 ALD PRECURSORS, DEPOSITABLE MATERIALS AND STRUCTURES

The selection of precursor chemicals ranges from gases to liquids and solids, the last of which can be vaporized with a specifically designed, heatable dispenser. Basic requirements for an ALD precursor are high reactivity, thermal stability and sufficient vapor pressure. The most typical precursor chemicals are organometallic compounds such as trimethylaluminium (TMA) or diethylzinc (DEZ), though also metal halides and metalorganics work well as precursors. Vapor of deionized water is the most often used oxidizer though in some reactions more reactive species such as ozone or plasma (typically oxygen, nitrogen or hydrogen) is used. The typical growth speed of ALD films varies on the range 0.2 – 1.4 Å per cycle depending on the deposited material – cycle meaning here the double pulse-purge procedure as depicted in Figure 1.

Amorphous or polycrystalline inorganic materials that can be deposited with ALD comprise metal oxides, nitrides, sulfides, fluorides, pure metals (including noble ones), mixed oxides, even multilayer or graded layer nanolaminates, binary, ternary and doped compounds – the variety ranges from dielectrics to semiconductors and purely metallic thin films. Single crystal materials are rarities. Dielectric oxides such as Al_2O_3 are still the most often used ALD films, however, due to their large demand in electronics industries.

Table 1: Film thickness uniformity data of an Al_2O_3 batch process (25 wafers) for production. Non-uniformity: 1σ, STD, 9 points in each 4” Si wafer (Picosun customer data).

	Specification	*Measured data*
Within wafer	< 1 %	0.6 %
Within batch	< 2 %	1.0 %
Batch to batch	< 2 %	0.3 %

Table 2: Excellent film uniformities achieved with various ALD materials. Data measured by Picosun and its R&D customers in single wafer processes.

Material	*Deposition temperature (°C)*	*Film thick-ness (nm)*	*Film thickness non-uniformity %; 1σ*
Al_2O_3	300	47.2	0.21
Plasma-Al_2O_3	120	55.8	1.78
HfO_2	250	30.6	1.96
TiO_2	300	117.0	0.6
TiN	400	25.5	1.57
ZnO	300	28.1	0.94
Pt	300	39.3	3.41

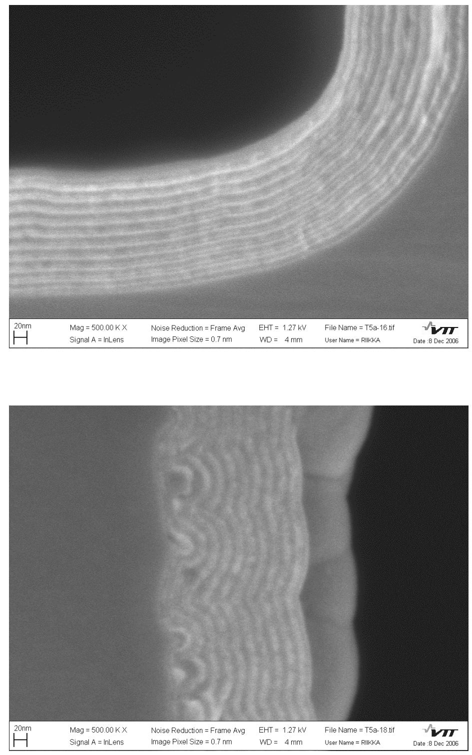

Figure 3: Al_2O_3-TiO_2 multilayer nanolaminate on trench structure. Images by courtesy of VTT Technical Research Centre of Finland.

4 PICOSUN – THE ALD COMPANY

Picosun Oy was founded in 2003 but the company’s origins date back to the development of the ALD technology itself in Finland in the early seventies. Both the inventor of the ALD method, D. Sc. (tech.) Tuomo Suntola, as well as CTO Mr. Sven Lindfors, who has been designing novel, innovative ALD reactors since 1975, are Picosun Board Members and still participate actively in the running of the company. Thus, it can be said that today, Picosun represents continuity to almost four decades in ALD equipment design and manufacturing. Knowing that focusing on a clear and coherent product range best serves customers’ interests, Picosun concentrates solely and exclusively on ALD. The company’s core team consists of academically trained ALD experts, combining together over 200 person years of ALD system development and contributing to over 100 patents in the field. The company has been growing very fast during the past few years, it has redistributors in ca. 30 countries and its ALD systems have been installed in top level research institutions and high profile industries on four continents.

5 PICOSUN PRODUCT LINES

Picosun's ALD systems can be divided to two "families": SUNALE™ R-series, which is designed mainly for research, development and small scale pilot production purposes, and SUNALE™ P-series, which main customers are industries with need for large scale batch production. The uniqueness of Picosun's reactor design is represented in these two product lines: due to the similar base design and structure which is developed specifically aiming at easy scalability, versatility and customizability, the results achieved and techniques developed with the R-series R&D reactors can be easily transferred to mass production with the P-series equipment. The range of coatable substrates varies from the standard Si wafers up to 300 mm diameter and 3D objects to powders and particles, for which specific sample holders and precursor feed and flow control systems have been designed. With P-series batch reactors, several hundreds of wafers can be processed per day.

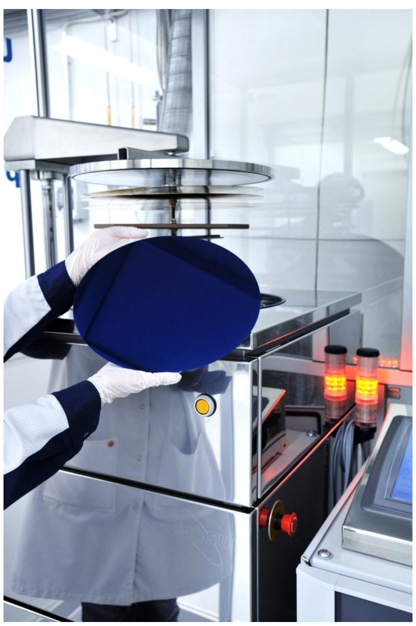

Figure 4: Uniform thin films on large substrates with Picosun's SUNALE™ P-series reactor.

Picosun's ALD reactors can be fully automatized, they can be integrated to vacuum line and/or glove box systems, equipped with remote plasma source, and clustered together into a versatile, multifunction production unit (which, if necessary, can be further combined with other process modules) capable of depositing several different materials simultaneously at high speed and quality fulfilling even the strictest industrial production requirements.

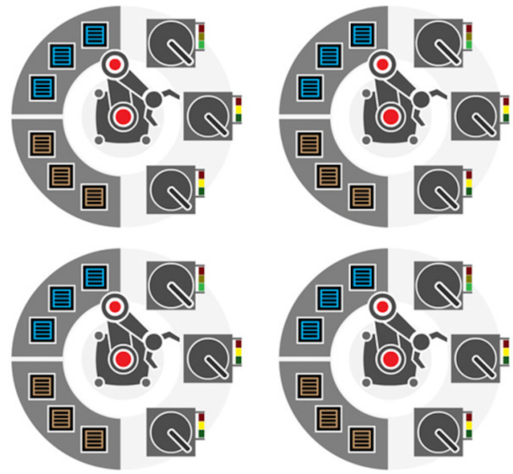

Figure 5: Illustration of clustering several SUNALE™ P-series batch reactors together and operating with an industrial robot.

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