Atomic layer deposition (ALD) is a thin film technology that enables new and highly competitive products. ALD is also a powerful resource for advanced nanotechnology research. ALD has commonly been seen as a slow, high value-added coating method, incapable of producing thick, several micrometers thick coatings, at least in an economical way. Quite contrary to this, however, ALD has no real difficulties in depositing thick films with affordable total cost of ownership. ALD is based on surface controlled thin film deposition. During ALD, the surface of the substrate is locally saturated, followed by an unreacted purge, resulting in a self-limiting, conformal, nanometer-thick coating. ALD is an enabling technology for new and improved products. It provides coatings and material features which either cannot be achieved cost-effectively with existing techniques, or they cannot be achieved at all. ALD, as a thin film coating method, offers:

- Precise control of the film thickness, at true nanometer scale.
- Pinhole-free films for e.g., superior barriers and surface passivation.
- Conformal coating of batches, large-area substrates and complex 3D objects, including porous bulk materials, as well as powders.
- Engineered and new functional materials and structures, such as nanolaminates.
- A highly repeatable and scalable process.

**Process and coating properties**

**Excellent adhesion:** Chemisorption of precursors with the surface provides excellent adhesion. Adhesion is further improved by the completely conformal nature of the coating.

**Saturation:** Self-terminating surface reactions enable automatic process control and eliminate the need for over-precise dosing and continuous operator attendance. The resulting coatings are inherently free from pinholes, making ALD especially suitable for surface passivation, barrier layers and insulators.

**Sequential:** Digital-like sequential growth provides for excellent accuracy without the need for extensive in situ feedback or operator attendance. This reduces coating tool complexity, improves tool reliability and lowers overhead costs.

**Surface-controlled reactions:** Surface reactions enable unconditionally conformal coatings, regardless of if the substrate is dense, porous, tubular, a powder or otherwise complex, e.g., exhibits deep trenches, gratings, nanotubes or -wires and other high aspect ratio features.

**Precise and repeatable:** Film growth thickness during a single ALD cycle is process specific, but typically about 1 Å (0.1 nm). Using process conditions in the full saturation regime gives very high repeatability.

**Thin, dense, and smooth:** ALD enables depositing layers less than one nanometer in thickness. Coatings as thin as 0.8 nm are currently used in certain industrial applications. ALD films are typically dense because the films are formed one molecular layer at a time; the coating material assembles tightly into the most favorable [stable] orientation.

**High capacity:** The surface-controlled growth feature allows for capacity expansion for both large batches and large surfaces.

**Plasma enhanced ALD:** ALD coating can also be modified by applying plasma to the deposition cycle, e.g., to enable coating with certain metals and low-temperature oxides and nitrides.

**Roll-to-Roll and Continuous ALD:** Roll-to-Roll coating opens the door for many new ALD applications in, e.g., the flexible electronics industry. Beneq, with the world’s first commercially available research platform for continuous ALD, is at the forefront of this development work.

**Technology basics**

ALD belongs to the group of chemical vapor deposition methods. It was initially developed for manufacturing nanolaminate insulators (Al2O3/TiO2) and zinc sulfide (ZnS) phosphor films for thin film electroluminescent (TFEL) displays. Beneq ALD systems are based on 25 years of experience from continuous 24/7 operation in demanding industrial applications, such as the aforementioned TFEL displays.

**Typical applications of ALD**

- **Engineered and new functional materials and structures,** such as nanolaminates.
- **Conformal coating of batches,** large-area substrates and complex 3D objects, including porous bulk materials, as well as powders.
- **Engineered and new functional materials and structures,** such as nanolaminates.
- **A highly repeatable and scalable process.**

**Typical process conditions:**

- **Pressure range:** 0.1–10 mbar (Torr, hPa) or atmospheric
- **Temperature:** typically, 50–500 °C

**ALD-deposited materials**

The most common materials deposited by ALD include (selection):

- **Oxides:** Al2O3, CaO, CuO, Cr2O3, Ga2O3, HfO2, La2O3, MgO, Nb2O5, SnO2, SiO2, Ta2O5, TiO2, V2O5, Y2O3, Yb2O3, ZrO2, Zr2O3, etc.
- **Nitrides:** AlN, GaN, TaN, Si3N4, etc.
- **Biomaterials:** Ca10(PO4)6(OH)2 (hydroxyapatite)
- **Polymer films:** PMDA–DAH, PMDA–ODA, etc.
- **Fluorides:** BaF2, CaF2, LaF3, MgF2, SrF2, etc.
- **Metals:** Ir, Pt, Pd, Ru, etc.
- **Sulfides:** ZnS, SrS, etc.
- **Others:** CaF2, LaF3, MgF2, SrF2, etc.
- **Biomaterials:** Ca3(PO4)2(OH)2 [hydroxyapatite]
- **Polymers:** PMDA–DAH, PMDA–DDA, etc.

Doping, nanolaminates and mixed structures: ALD enables a vast array of material combinations.

There are many more materials and processes available in ALD today. Beneq ALD specialists are at your service, if you have any inquiries.

**Summary**

Atomic layer deposition has for years played a major role in the established display and semiconductor industries. Today, lead by Beneq, ALD is being adapted to new and emerging industries, including photovoltaics, flexible electronics and new battery technologies.
Atomic layer deposition, ALD, is a thin film technology that enables new and highly competitive products. ALD is also a powerful resource for advanced nanotechnology research. Typical applications of ALD contain a requirement to manufacture very precise nanometer-thick, pinhole-free and totally conformal thin films on any shape and geometry. For today’s businesses, Beneq ALD offers the necessary tools to accelerate growth, by means of new and innovative applications, production equipment you can count on and affordable cost of ownership.

Atomic layer deposition, ALD, is a thin film technology that enables new and highly competitive products. ALD is also a powerful resource for advanced nanotechnology research.

Typical applications of ALD contain a requirement to manufacture very precise nanometer-thick, pinhole-free and totally conformal thin films on any shape and geometry. For today’s businesses, Beneq ALD offers the necessary tools to accelerate growth, by means of new and innovative applications, production equipment you can count on and affordable cost of ownership.

Introduction

ALD belongs to the group of chemical vapor deposition methods. It was initially developed for manufacturing nanolaminate insulators (Al2O3/TiO2) and zinc sulfide (ZnS) phosphor films for thin film electroluminescent (TFEL) displays. These displays started in the mid-1980’s, mainly thanks to ALD. Engineering and new functional materials and structures, such as nanolaminates.

Typical ALD cycle is shown in Figure 1.

Technology basics

ALD is an enabling technology for new and improved products. It provides coatings and material features which either cannot be achieved cost–efficiently with existing techniques, or they cannot be achieved at all. ALD, as a thin film coating method, offers:

- Precise control of the film thickness, at true nanometer scale.
- Pinhole-free films for, e.g., superior barriers and surface passivation.
- Conformal coating of batches, large-area substrates and complex 3D objects, including porous bulk materials, as well as powders.
- Engineered and new functional materials and structures, such as nanolaminates.
- A highly repeatable and scalable process.

Typical process conditions:

- Pressure range: 0.1–10 mbar (Torr, hPa) or at atmospheric pressure.
- Temperature: typically, 50–500 °C

Figure 1. Typical ALD growth cycle when depositing aluminum oxide (Al2O3) film. The cycle is repeated until the desired film thickness is achieved.

Schematic of ALD cycle for depositing aluminum oxide (Al2O3) with trimethyl aluminum (TMA) and water:

1. Pulse 1, TMA is fed in vapor phase to the reaction chamber where its molecules react and adhere to the substrate surface. All surface sites are occupied and the surface is fully saturated.
2. Purge 1, which “rinses” the substrate and chamber from superfluous precursor and reaction by-products.
3. Pulse 2, water [H2O] is fed in vapor phase and reacts with the surface molecules and develops into a solid Al2O3 layer. Any gaseous by-products leave the surface.
4. Purge 2, Same as Purge 1.
5. The ALD cycle is repeated until the required film thickness is achieved.

Process and coating properties

Excellent adhesion: Chemisorption of precursors with the surface provides excellent adhesion. Adhesion is further improved by the completely conformal nature of the coating.

Saturation: Self-terminating surface reactions enable automatic processing and eliminate the need for over-precise dosing and continuous operator attendance. The resulting coatings are inherently free from pinholes, making ALD especially suitable for surface passivation, barrier layers and insulators.

Sequential: Digital-like sequential growth provides for excellent accuracy without the need for extensive in situ feedback or operator attendance. This reduces coating tool complexity, improves tool reliability and lowers overhead costs.

Surface-controlled reactions: Surface reactions enable unconditionally conformal coatings, regardless of if the substrate is dense, porous, tubular, a powder or otherwise complex, e.g., exhibits deep trenches, gratings, nanotubes or -wines and other high aspect ratio features.

Precise and repeatable: Film growth thickness during a single ALD cycle is process specific, but typically about 1 Å (0.1 nm). Using process conditions in the full saturation regime gives very high repeatability.

Thin, dense, and smooth: ALD enables depositing layers less than one nanometer in thickness. Coatings as thin as 0.8 nm are currently used in certain industrial applications. ALD films are typically dense because the films are formed one molecular layer at a time; the coating material assembles tightly into the most favorable (stable) orientation.

High capacity: The surface-controlled growth feature allows for capacity expansion for both large batches and large surfaces.

Plasma enhanced ALD: ALD coating can also be modified by applying plasma to the deposition cycle, e.g., to enable coating with certain metals and low-temperature oxides and nitriles.

Roll-to-Roll and Continuous ALD: Roll-to-Roll coating opens the door for many new ALD applications in, e.g., the flexible electronics industry. Beneq, with the world’s first commercially available research platform for continuous ALD, is at the forefront of this development work.

ALD-deposited materials

The most common materials deposited by ALD include (selection):

- Dielectrics: Al2O3, CaO, CuO, Er2O3, Ga2O3, HfO2, La2O3, MgO, Nb2O5, Sc2O3, SiO2, Ta2O5, TiO2, V2O5, Y2O3, ZrO2, Zr2O, etc.
- Nitrides: AlN, GaN, InN, TiN, TaN, TaN, etc.
- Carbides: TaC, TiC, etc.
- Metals: Ir, Pt, Rh, Ru, etc.
- Sulfides: ZnS, SnS, etc.
- Fluorides: CaF2, LaF3, MgF2, SrF2, etc.
- Biomaterials: Ca,[PO4]3(OH), (hydroxyapatite)

Polymer: PMDA-DAH, PMDA-DDA, etc.

Doping, nanolaminates and mixed structures: ALD enables a vast array of material combinations.

There are many more materials and processes available in ALD today. Beneq ALD specialists are at your service, if you have any inquiries.

Summary

Atomic layer deposition has for years played a major role in the established display and semiconductor industries. Today, lead by Beneq, ALD is being adapted to new and emerging industries, including photovoltaics, flexible electronics and new battery technologies.