Analysis of the Advantages and Emerging Applications of ALD Technology in Semiconductor Manufacturing

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Abstract. Atomic layer deposition (ALD) technology, based on self-limiting surface reaction mechanisms, can precisely control film growth at the atomic scale and has gradually become a key process in semiconductor manufacturing. This article starts from the basic theory of ALD, compares its differences with traditional chemical vapor deposition (CVD), and focuses on discussing its practical applications in advanced semiconductor processes. The research finds that ALD performs outstandingly in high dielectric constant gate dielectrics (such as HfO_2), ultra-high aspect ratio metal interconnect barrier layers, and flexible electronic packaging, especially in conformal coating of complex three-dimensional structures where it is irreplaceable. Although ALD has shortcomings such as low deposition rate and high cost of precursors, its precise control ability at the nanoscale provides important technical support for the development of next-generation semiconductor devices. In the future, by optimizing process efficiency and material compatibility, ALD is expected to further expand its application scenarios in microelectronics and emerging technologies.

Keywords: Atomic Layer Deposition (ALD), Self-limiting Surface Reactions, High-k Gate Dielectrics, Diffusion Barrier Layers, Conformal Coating of High-Aspect-Ratio Structures.

1 Introduction

Finnish scientists in the 1970s first proposed Atomic Layer Deposition (ALD) technology. Its unique self-limiting surface reaction mechanism enables thin-film growth with atomic-level precision. In the following decades, ALD technology has undergone continuous theoretical improvement and process optimization. Especially after the mid-1990s, with the continuous miniaturization of semiconductor device sizes and the increasing demand for nanomaterial preparation, ALD technology has gradually become one of the key technologies in the semiconductor manufacturing field due to its excellent thin-film uniformity and precise thickness control ability. Compared with tradi-

S. Zhang (ed.), *Proceedings of the 2025 International Conference on Electronics, Electrical and Grid Technology (ICEEGT 2025)*, Advances in Engineering Research 292,
https://doi.org/10.2991/978-94-6463-986-5_16

tional Chemical Vapor Deposition (CVD) or Physical Vapor Deposition (PVD) technologies, although ALD has certain disadvantages in deposition rate, its advantages in the preparation of ultra - thin films (<10 nm) are becoming increasingly prominent, making it particularly suitable for advanced semiconductor processes with high precision and high consistency.

In the 21st century, the application scope of ALD technology has been further expanded, showing great potential in semiconductor manufacturing. For example, in key processes such as high-dielectric-constant (High-K) gate dielectric layers, metal interconnection diffusion barrier layers, and water-oxygen barrier layers for flexible electronic devices, ALD technology has become an irreplaceable solution. In addition, with the increasing complexity of semiconductor device structures, the combination of ALD with other thin-film deposition technologies (such as the collaborative process of ALD and CVD) provides more possibilities for the preparation of new-type semiconductor devices, further promoting the development of next-generation integrated circuits.

This paper aims to systematically analyze the advantages and disadvantages of ALD technology in semiconductor manufacturing and focus on its core advantage of precisely controlling the deposition thickness. At the same time, from aspects such as high - dielectric - constant gate dielectric layers and metal interconnection diffusion barrier layers, it explores the emerging applications of ALD technology in advanced semiconductor processes and its possible future applications, with the hope of providing theoretical references for the optimization and industrialization of ALD technology in the future [1-4].

2 Fundamentals of ALD Technology

ALD technology originated in the 1970s and was initially termed Atomic Layer Epitaxy (ALE), primarily used for depositing ZnS thin films in flat-panel displays. Subsequently, researchers developed a wide range of ALE processes for depositing various oxides, nitrides, and metals. Since most materials deposited by this method do not grow epitaxially on substrates but instead form conformal coatings, the term Atomic Layer Deposition (ALD) gradually replaced ALE. Research in ALD spans precursor design, development of novel materials (including oxides, nitrides, metals, doped compounds, and multicomponent materials), and innovative processes (such as planar substrates, complex 3D substrates, and powder surface ALD), enabling its expanding application across diverse fields.

2.1 Technical Principles of ALD

The growth mechanism of ALD shares similarities with traditional Chemical Vapor Deposition (CVD). However, ALD employs alternating pulses of precursor gases during deposition, where each new atomic layer chemically reacts directly with the preceding layer, ensuring only a single atomic layer is deposited per cycle. Leveraging self-limiting surface reactions, ALD achieves highly conformal, pinhole-free thin films, particularly suitable for substrates with intricate 3D structures. By controlling the number of deposition cycles, precise thickness control of the film is realized [5-7].

A typical ALD cycle involves four sequential steps (as illustrated in Figure 1): the first precursor gas is introduced to the substrate, where it chemically adsorbs or reacts with the surface; unreacted precursor and by-products are then purged using inert gas; the second precursor is subsequently introduced to react with the adsorbed first precursor or its surface-modified species, forming the desired coating; finally, residual gases are thoroughly flushed from the reaction chamber with inert gas, completing one deposition cycle [8, 9].

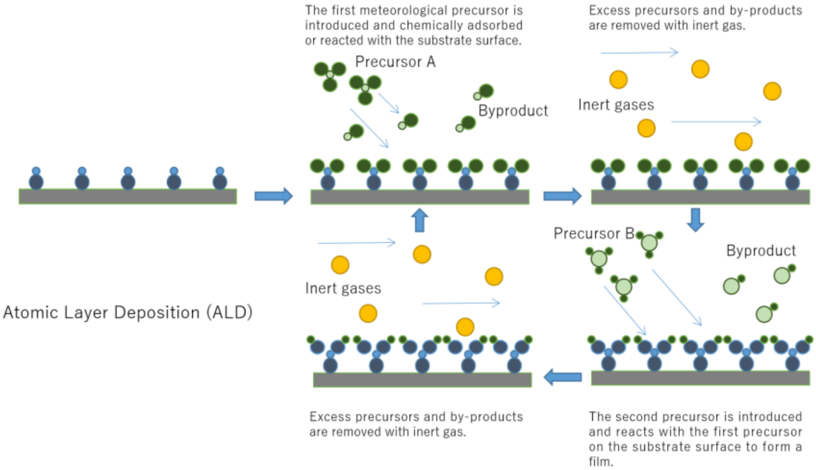

Fig. 1. Schematic diagram of the ALD technology process

2.2 Process Characteristics of ALD

Atomic Layer Deposition (ALD) is characterized by two core mechanisms: complementarity and self-limiting behavior. The complementarity requires synergistic alternating reactivity between the two reactants in a binary precursor system, where the chemical state of the substrate surface must regenerate active sites compatible with the subsequent precursor after each reaction step, ensuring continuity of the cyclic process. Simultaneously, the self-limiting nature guarantees that each reaction forms only a monolayer via chemical adsorption—once precursor molecules occupy all surface-active sites through chemical bonding, the reaction spontaneously terminates due to adsorption saturation. This precise self-regulation enables ALD to deposit uniform, dense films on substrates with complex morphologies, while achieving atomic-level thickness control through cycle repetition, demonstrating exceptional process reproducibility and stability. These two mechanisms synergistically form the physicochemical foundation for ALD's capability to achieve atomic-scale precision in thin-film growth [10, 11].

3 Comparison Between ALD and Conventional CVD

As core thin-film technologies in semiconductor manufacturing, ALD and CVD exhibit distinct process characteristics and application scenarios. ALD's uniqueness lies in its self-limiting surface reaction mechanism, where alternating precursor pulses and inert gas purging enable the deposition of a single atomic layer per cycle. This layer-by-layer growth ensures precise thickness control independent of gas flow dynamics. In contrast, CVD relies on continuous supply and decomposition of gaseous reactants, driven by thermal or plasma energy, to deposit solid products via homogeneous or heterogeneous reactions [12]. A detailed comparison is presented below.

3.1 Film Performance and Structural Control

Differences between ALD and CVD in film properties primarily manifest in conformality and crystallinity.

Conformality refers to the uniformity of film thickness across 3D structures. ALD outperforms CVD due to its sequential, self-limiting reactions, which ensure uniform coverage even on high-aspect-ratio surfaces. ALD excels in producing ultra-thin films (10 – 50 nm) with atomic-level precision. Conversely, CVD's continuous precursor flow leads to simultaneous surface reactions, often resulting in thickness non-uniformity and limited monolayer control [13]. Crystallinity, defined as the proportion of ordered crystalline regions in a material, is influenced by deposition conditions. ALD-grown metal oxides are typically polycrystalline or amorphous, requiring post-deposition annealing to enhance crystallinity. CVD's high-temperature processes, however, may induce lattice mismatch stress, causing film cracking or interfacial defects [14-17].

3.2 Process Economics and Equipment Compatibility

Deposition efficiency and cost: CVD demonstrates superior economic viability for large-area coatings due to its continuous reaction mechanism. For example, atmospheric-pressure CVD achieves deposition rates up to 500 nm/min for transparent conductive oxides in photovoltaics, with annual throughput exceeding 1 GW and unit costs below $0.1/W. ALD's self-limiting nature results in slower deposition rates, higher precursor costs (e.g., expensive metal-organic precursors for HfO_2), and lower production scalability.

Equipment complexity: CVD systems are relatively simple, utilizing low-cost precursors (e.g., $SiCl_4$, CH_4) and plasma-enhanced configurations to reduce operational barriers. ALD requires precise control of gas pulsing sequences and purge times, leading to higher equipment complexity and costs.

In summary, ALD dominates precision-driven fields like nanoelectronics and quantum devices due to its atomic-level thickness control and exceptional conformality, while CVD remains the preferred choice for high-throughput, cost-sensitive industrial applications.

4 Application of the ALD Process in Semiconductor Manufacturing

With the development of the semiconductor industry, the requirements for miniaturization and integration are getting higher and higher. The size of devices is constantly shrinking, and the etched grooves of transistors are also getting smaller. The coating technology is facing severe challenges. Chemical vapor deposition (CVD) and physical vapor deposition (PVD) find it difficult to meet the good step coverage requirements at extremely small dimensions. ALD technology, with its self-limiting growth and three-dimensional conformality characteristics, is suitable for various complex substrates and is widely used in advanced semiconductor thin film process technology. Some of the more popular applications are as follows.

4.1 High dielectric constant (High-K) gate dielectric layers (such as HfO_2)

In modern semiconductor devices, high dielectric constant (High-K) insulators play a core role and are widely used in key components such as capacitors, DRAM, decoupling filter capacitors, and isolation between the gate and channel of transistors. The dielectric constant (K) of oxide materials is significantly related to the bandgap width, with K values typically ranging from 0 to 60, reflecting the material's ability to store charge in an electric field; the bandgap width (2 - 10 eV) determines the material's conductivity, representing the energy difference between the valence band and the conduction band. Taking common oxides as examples, SiO_2, a commonly used insulating material in semiconductor manufacturing, has a large bandgap width; Al_2O_3, with its high hardness and good insulation, is often used in electronic packaging; MgO, as a high-temperature refractory material, is also applied in the insulating layers of electronic devices; CaO occasionally finds application in the electronics field; ZrO_2 has excellent chemical and electrical properties; TiO_2, due to its photocatalytic activity, is used in solar cells and other fields. Generally, as the K value increases, the bandgap width decreases, but due to the influence of crystal structure and chemical bond characteristics, there are deviations among different materials. In the application of High-K gate dielectric layer materials, Si_3N_4 and Al_2O_3 have relatively low dielectric constants; although TiO_2 has a dielectric constant as high as 80, its small bandgap width and significant interface defects with the substrate limit its application as a gate dielectric; while HfO_2 and ZrO_2, with their superior comprehensive performance, have become widely adopted gate dielectric layer materials in the industry

4.2 Metal interconnect diffusion barrier layers

In the interconnect process, a diffusion barrier layer is required to enhance the adhesion of aluminum-copper alloy interconnects to silicides, reduce the contact resistance and stress between interconnects and contact holes. In aluminum processes, the barrier layer metals are titanium (Ti) and titanium nitride (TiN), while for copper, they are tantalum (Ta) and tantalum nitride (TaN). When the aspect ratio of the internal trench in the device exceeds 100:1, atomic layer deposition (ALD) technology is used to deposit the diffusion barrier layer, which can achieve high step coverage, thin atomic layer thickness, and precise control of the film.

In the metal interconnect process of very large-scale integrated circuits, the diffusion barrier layer metal is crucial. It not only enhances the adhesion strength of aluminum-copper alloy interconnects to the silicide substrate, preventing interconnects from falling off, but also reduces the contact resistance between interconnects and contact holes, minimizing signal transmission loss and power consumption. Additionally, it alleviates structural stress and avoids damage caused by stress concentration. In aluminum interconnect processes, titanium (Ti) and titanium nitride (TiN) are commonly used barrier layer materials. The former can stably bond with the substrate, while the latter effectively blocks diffusion and reduces resistance. For copper interconnects, tantalum (Ta) and tantalum nitride (TaN) are often used as barrier layers. When the aspect ratio of the internal trench in the device exceeds 100:1, atomic layer deposition (ALD) technology becomes the preferred method for preparing diffusion barrier layers. This technology, based on self-limiting reactions, can achieve high step coverage in high aspect ratio structures, with thin film thickness and strong controllability, meeting the requirements of miniaturization and refinement for nanoscale devices.

4.3 Water and oxygen barrier layers

In the field of flexible electronics, as a key development direction for the next generation of display technology, the application of flexible organic polymer substrates is extremely common. However, the stability of such substrates is poor, and water vapor and oxygen can easily penetrate them, causing degradation of devices, oxidation of electrodes, and other failure issues, which seriously restrict the service life and performance of the devices. Atomic layer deposition (ALD) technology, with its unique self-limiting surface chemical reaction mechanism, can precisely deposit uniform, dense, and thickness-controllable water and oxygen barrier layer films on the substrate surface.

Numerous practical application cases have demonstrated the outstanding effectiveness of ALD technology. In flexible OLED display devices, by depositing aluminum oxide (Al_2O_3) or silicon dioxide (SiO_2) water and oxygen barrier layers through ALD technology, the service life of OLED devices can be significantly extended, enabling stable display in flexible wearable devices, flexible displays, and other products; in the field of flexible solar cells, the use of silicon nitride (SiN_x) barrier layers deposited by ALD not only effectively blocks water and oxygen erosion but also utilizes its optical properties to enhance the photoelectric conversion efficiency of the cells. These application cases indicate that the water and oxygen barrier layers deposited by ALD technology provide reliable protection for the long-term stable operation of flexible electronic devices and have become an important technical means to improve the environmental adaptability and reliability of flexible electronic devices.

5 Future Development Potential of ALD Technology

Atomic layer deposition (ALD) technology exhibits immense development potential in many aspects due to its unique advantages, such as atomic - level precision in thin - film thickness control, excellent conformality and uniformity, and the absence of pinholes. Taking the Al_2O_3 thin film as an example, the thin film prepared by ALD has a high dielectric constant, good chemical and thermal stability, and has broad application prospects in fields such as solar cells, microelectronic devices, and energetic materials. It is expected to replace traditional silicon materials and significantly improve device performance. Even today, when there is still great room for development in the technology of manufacturing Al_2O_3 thin films by ALD, solar cells manufactured using this technology can achieve a photoelectric conversion ratio of over 25%. In the future, as the ALD technology improves, this ratio will further increase [18-20]. However, the ALD technology currently still faces problems such as slow deposition rate, high substrate dependence, and impurities in low-temperature deposition, which limit its industrial application. In the future, with the breakthrough of these technical problems, the ALD technology will play a greater role in the fields of semiconductors and nanoelectronics. For example, it can be used to prepare ternary oxide nano-thin films (promoting the development of quantum computing), noble metal electrodes (such as key components in DRAM/FRAM), and high-K dielectric materials (improving chip performance). Its nanoscale precision has greatly improved these precision devices [21]. Despite the existing challenges, with its irreplaceable precision and material adaptability, the ALD technology will surely achieve revolutionary applications in more emerging fields and become one of the core technologies in future materials science and micro-nano manufacturing [22].

6 Conclusion

Atomic layer deposition (ALD) technology demonstrates irreplaceable advantages in key semiconductor processes such as high - dielectric - constant gate dielectrics (e.g., HfO_2), metal interconnection barrier layers with an aspect ratio of over 50:1 (TaN/TiN), and water - oxygen barrier layers for flexible electronics (Al_2O_3) due to its self - limiting surface reaction mechanism and atomic - level precision of layer - by - layer growth. In particular, it far exceeds the traditional CVD technology in terms of conformality and thickness control of complex three-dimensional structures. However, problems such as low deposition rate (<1 nm/min), high precursor cost, and impurities in low-temperature deposition (e.g., carbon residues) still restrict its industrial application. In the future, it is necessary to develop rapid ALD processes (such as spatially separated deposition), low - cost precursor replacement solutions, and modular integration of equipment to balance precision, efficiency, and cost, so as to promote the large - scale application of ALD in advanced manufacturing processes, quantum devices, and emerging flexible electronics fields.

Authors Contribution. All the authors contributed equally and their names were listed in alphabetical order..

References

1. eefocus_3901714, What are the similarities and differences between ALD (Atomic Layer Deposition) and CVD. (2025) https://www.eefocus.com/e/1739862.html
2. Shenzhen Yuansu Technology Co., Ltd., Plasma Enhanced System. (2025) https://www.superald.com/
3. D. Shanshan, S. Changyong, Y. Lizhen et al., Research status and development trends of Al2O3 thin film preparation by atomic layer deposition. Vacuum 58, 13–20 (2021)
4. W. Hehe, H. Gang, D. Bin et al., Development status and application prospects of atomic layer deposition technology. J. Vac. Sci. Technol. 34, 413–420 (2014)
5. T. Suntola, Atomic layer epitaxy. Mater. Sci. Rep. 4, 261–312 (1989)
6. S. M. George, Atomic layer deposition: an overview. Chem. Rev. 110, 111–131 (2010)
7. M. Knez, K. Nielsch, L. Niinistö, Synthesis and surface engineering of complex nanostructures by atomic layer deposition. Adv. Mater. 19, 3425–3438 (2007)
8. R. L. Puurunen, Surface chemistry of atomic layer deposition: A case study for the trimethylaluminum/water process. J. Appl. Phys. 97, 121301 (2005)
9. A. C. Jones, M. L. Hitchman (Eds.), Chemical Vapour Deposition: Precursors, Processes and Applications. Royal Society of Chemistry, Cambridge, UK (2009)
10. Kintek Solution, What is the difference between ALD and CVD? Precision and versatility in thin film deposition, (2023-05-20) https://zh.kindle-tech.com/faqs/how-is-ald-different-from-cvd
11. Z. Yang, Research on the Preparation Technology of Al2O3 Thin Film by ALD on Organic Films. Changchun University of Science and Technology (2024)
12. V. Miikkulainen, M. Leskelä, M. Ritala et al., Crystallinity of inorganic films grown by atomic layer deposition: Overview and general trends. J. Appl. Phys. 113, 021301 (2013)
13. M. Leskelä, M. Ritala, Atomic layer deposition (ALD): from precursors to thin film structures. Thin Solid Films 409, 138–146 (2002)
14. Q. Zhang, M. Chen, P. Fan et al., Research on the influencing factors of crystallinity of PETG polyester film. Plast. Packag. 34(5), (2024)
15. Y. Han, Research on the Preparation of HfO2 Nanofilms by ALD and the Accurate Measurement of Their Thickness. China University of Petroleum (2022)
16. H. Lu, Research on Atomic Layer Deposition of High Dielectric Constant Gate Dielectric. Fudan University (2006)
17. J. Shen, Research on Polyimide Substrates for Large-Area Transparent Flexible Optoelectronic Devices. Huazhong University of Science and Technology (2018)
18. Z. Li, Research on the Performance of Al2O3 Thin Films Deposited by Atomic Layer Deposition on Pre-Bent Substrates at Low Temperature and Their Application in Flexible Packaging. Jilin University (2022)
19. S. Ming, Y. Guo, Y. Xia, Development of Atomic Layer Deposition Technology and Its Application in Perovskite Solar Cells. In: Proceedings of the Second National Conference on Solar Cell Materials and Devices. Jiaxing Kemin Electronic Equipment Technology Co., Ltd.; Research Center for Microelectronics Instruments and Equipment, Institute of Microelectronics, Chinese Academy of Sciences (2022)
20. S. Ming, Y. Guo, Y. Xia, Development of atomic layer deposition technology and its application in perovskite solar cells. In: Proceedings of the Second National Conference on Solar

Cell Materials and Devices. Jiaxing Kemin Electronic Equipment Technology Co., Ltd. (2022)

21. J. Yang, Preparation of Novel Two-Dimensional Semiconductor Material Bi2O2Se and Research on the Photoelectric Properties of Its Heterostructures. East China Normal University (2023)
22. B. Zhao, J. Liu, Atomic layer/molecular layer deposition technology and its application in advanced semiconductor processes. Mater. Rev. 38(20), 59–70 (2024)