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A Study on Performance Comparison and Application Scenarios of PVD, CVD and ALD Thin-Film Deposition Processes

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Abstract. Semiconductor thin films are the core functional structures of microelectronic and optoelectronic devices. The thickness, uniformity, and density of the thin film directly determine the performance, lifespan, and stability of the device. With the continuous miniaturization and three-dimensionalization of semiconductor devices, traditional deposition processes are struggling to meet the high-precision coating requirements of high aspect ratio micro/nano structures. Therefore, precise process selection has become crucial in semiconductor manufacturing. This paper focuses on three mainstream thin film deposition processes: Physical Vapor Deposition (PVD), Chemical Vapor Deposition (CVD), and Atomic Layer Deposition (ALD). It systematically elucidates the core working principles of these three processes, conducting a horizontal comparison from multiple dimensions, including deposition mechanism, thickness control accuracy, step coverage capability, film quality, and production cost. The paper analyzes the advantages and disadvantages of each process and clarifies the process selection logic in the context of semiconductor device fabrication. Research shows that there is no absolute superiority or inferiority among the three processes, each possesses differentiated application adaptability. PVD is suitable for low-cost planar thin film mass production, CVD balances efficiency and versatility, and ALD dominates the coating of high-end precision micro/nano devices. This paper also summarizes the technical bottlenecks of existing processes and clarifies the industry development trends of low-temperature processing, high-precision low-cost processing, and process integration.

Keywords: Physical vapor deposition, Chemical vapor deposition, Atomic layer deposition, Thin film deposition process

1. Introduction

The electronic information industry is developing rapidly, and semiconductor technology, as the core foundation of the industry, is widely used in many fields such as new energy, intelligent sensing, and optoelectronic communication. Nanoscale functional thin films exist in the core structures of various microelectronic and optoelectronic devices, and the quality of thin film preparation is a key factor restricting the performance upgrade of devices. Thin film deposition technology is the core process

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for solid-state thin film preparation, among which PVD, CVD, and ALD are the three most widely used technologies in industry and laboratories [1, 2] . Currently, academic research focuses on the optimization and improvement of single processes, lacking multi-dimensional and systematic comparative analysis of the three types of processes, making it difficult to meet the process selection requirements of complex micro- and nano-devices [3, 4] . Based on this, this paper systematically reviews the principles and characteristics of the three deposition processes, comprehensively compares the differences in process performance and applications, and identifies technical shortcomings and development directions. This research can provide theoretical reference for process selection and technology optimization in semiconductor thin film preparation, and also provide technical guidance for the research and manufacturing of advanced micro- and nano-devices, possessing significant engineering application value and academic significance.

2. Basic principles of three types of thin film deposition processes

Physical vapor deposition (PVD) is a vacuum deposition technology that relies on purely physical processes to form films, without any chemical reactions. Currently, commonly used PVD processes mainly include magnetron sputtering and vacuum evaporation. Magnetron sputtering, due to its good film density, strong adhesion, and wide material compatibility, has become the mainstream process for preparing semiconductor metal electrode films. Overall, PVD has a simple operation process, operates at relatively low temperatures, and does not cause high-temperature damage to the substrate device, making it suitable for preparing films from various materials such as metals, alloys, and some oxides. However, limited by the linear transport deposition characteristics, PVD is a typical line-of-sight deposition process, particles can only accumulate along a straight line, making it unable to deeply fill complex three-dimensional structures such as micro- and nano-grooves and vias. This has become a major limitation of this technology in the fabrication of advanced miniaturized devices. The premise of this technology is a high vacuum environment. By inputting external energy, the solid target material is bombarded or heated so that the atoms and molecules on the surface of the target material can obtain enough energy to break away from the original crystal structure, transform into gaseous particles and diffuse to the substrate surface, and finally gradually accumulate and condense on the substrate to form a continuous thin film [5] .

Chemical vapor deposition (CVD) is a process that relies on gas-phase chemical reactions to grow thin films, which is significantly different from the physical deposition mechanism of PVD. This process requires introducing a gaseous precursor containing the target element into a vacuum reaction chamber. Under conditions such as heating and plasma assistance, the gaseous precursor undergoes a series of chemical reactions on the substrate surface, including decomposition and combination. The resulting solid products adhere to the substrate surface and gradually accumulate to form a film, while byproducts are expelled from the chamber in gaseous form by the vacuum system. Compared to PVD, CVD has stronger gas-phase particle diffusion capabilities, is no longer limited to linear deposition, and exhibits significantly better step coverage than PVD, resulting in a higher deposition rate. This makes it suitable for large-scale, high-volume industrial production of semiconductor dielectric and functional thin films. However, most traditional CVD processes require high reaction temperatures, which can easily cause thermal damage to flexible substrates and precision micro/nano devices. Furthermore, the reaction process can easily generate trace impurities that can form structural defects within the film, affecting its electrical properties to some extent. Depending on the reaction conditions, CVD can be further divided into various branch processes such as atmospheric pressure chemical vapor deposition, low pressure chemical vapor deposition,

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and plasma-enhanced chemical vapor deposition. Different derivative processes can be adapted to different temperature requirements and thin film material preparation scenarios [6, 7] .

Atomic layer deposition (ALD) is a high-precision thin film growth technology developed on the basis of traditional chemical deposition, and it is also the cutting-edge core process for the fabrication of micro and nano devices [8] . The core feature of ALD is its self-limiting cyclic growth mechanism. The entire deposition process is divided into multiple independent pulse reaction cycles. Only one atomic-level thin film can be grown in a single cycle. By precisely controlling the number of cycles, the film thickness can be controlled at the nanoscale or even the atomic level. The specific workflow is as follows: First, the first type of precursor gas is introduced into the cavity so that it is uniformly adsorbed on all surfaces of the substrate, including complex structural areas such as trench sidewalls and bottom. After the adsorption is saturated, the excess gas is discharged. Then, the second type of reactive gas is introduced to react with the adsorbed layer to complete the growth of a single-layer thin film. Finally, the by-products are discharged again to complete a complete cycle. This special mechanism of layer-by-layer growth allows ALD to completely break through the structural limitations of traditional processes, possess excellent three-dimensional conformal coverage capabilities, and can perfectly adapt to the uniform coating requirements of high aspect ratio micro and nano structures. At the same time, the thin film prepared by this process has high density, few defects, excellent thickness uniformity, and excellent electrical and optical performance stability. However, due to the layer-by-layer growth mode, the deposition rate of ALD is much lower than that of PVD and CVD. The equipment cost and production time are higher, making it difficult to adapt to the mass production of ordinary thin films in large quantities. It is mostly used for the preparation of key ultra-thin films for high-end precision semiconductor devices [8] .

3. Multi-dimensional performance comparison of three types of thin film deposition processes

Different deposition mechanisms directly lead to significant differences in film thickness accuracy, microstructure, coverage performance, electrical properties, and production costs. To more systematically and comprehensively clarify the applicable scenarios of the three types of processes, this paper objectively compares and analyzes PVD, CVD, and ALD from five dimensions: deposition mechanism and process conditions, deposition rate and thickness control accuracy, step coverage and three-dimensional structure adaptability, film microstructure and electrical properties, and industrial cost and mass production adaptability.

In terms of deposition mechanism and environmental requirements, PVD is a purely physical phase transition process without any chemical reactions. The process relies on a high vacuum environment, using energy bombardment to detach solid target atoms from the surface, allowing them to deposit on the substrate surface in a straight-line manner. The overall process environment temperature is relatively low, preventing thermal damage to the substrate material. The process system is simple and highly controllable. CVD, on the other hand, is based on gas-phase chemical reactions. It requires the introduction of precursor gases into the chamber, where decomposition and synthesis reactions are completed on the substrate surface through thermal or plasma activation, ultimately generating a solid film. Compared to PVD, CVD has slightly lower vacuum requirements but is more sensitive to temperature, gas flow rate, and chamber pressure parameters, resulting in more process variables. Although ALD belongs to the chemical deposition system, its reaction mode is completely different from traditional CVD. ALD employs a segmented pulse, adsorption saturation, and reaction evacuation cyclic mechanism, with each round of reaction being an independent and self-limiting process. It has the highest requirements for process environmental

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stability, requiring strict control of pulse time and chamber cleanliness, therefore, the precision of process environmental parameters is far higher than the other two technologies.

In terms of industrial mass production efficiency and thickness accuracy, the three processes exhibit significant differences. CVD, relying on continuous gas-phase reactions, has the fastest film formation rate and the highest deposition efficiency, making it suitable for thin film preparation scenarios requiring rapid thickness increase and mass production. PVD has a moderate deposition rate, sufficient to meet the production needs of metal thin films of conventional thickness, with overall mass production efficiency second only to CVD. ALD, employing a "one atom per layer" deposition method, has the slowest deposition rate of the three processes, growing only about 0.1 nanometers of film per cycle, significantly increasing the time required to prepare thicker films. However, in terms of thickness accuracy, the advantages of the three are completely reversed. PVD can only achieve coarse control at the nanometer level, with relatively significant errors in film thickness uniformity, CVD is affected by gas flow distribution, resulting in greater thickness fluctuations, while ALD, relying on a self-limiting reaction, achieves highly uniform thickness in each growth cycle, enabling atomic-level precise thickness control, making it the only feasible process for preparing high-precision ultrathin thin films.

In terms of step coverage, PVD particles travel in a straight line, representing typical line-of-sight deposition. For high aspect ratio structures, particles cannot turn to enter the trenches and can only deposit on the plane and top of the structure, leaving the sidewalls and bottom films extremely thin or even completely exposed, resulting in the worst coverage. Therefore, PVD is basically only suitable for planar thin films and two-dimensional structure devices. CVD gas molecules have diffusion capabilities and can enter some shallow trenches, offering better coverage than PVD. However, in structures with greater depth and extremely small pore sizes, top accumulation and bottom thinning still occur, making complete uniform coating impossible. ALD precursor gases can be uniformly adsorbed and saturated on all exposed surfaces, unrestricted by structural angles, depths, or pores. Whether on sidewalls, bottoms, micropores, or nano-trenches, films of consistent thickness can be obtained. This is the fundamental reason why ALD has become a core process for advanced chip dielectric layers and high-precision device coating.

The density, defect quantity, purity, and internal stress of thin films directly affect the conductivity, insulation, and luminescence stability of semiconductor devices. PVD thin films have relatively coarse particles and contain a small number of pores and voids, resulting in generally low density and high surface roughness. Long-term use can easily lead to oxidation and increased leakage. CVD thin films generally have better crystal quality than PVD, with a denser structure. However, the high-temperature reaction process can easily generate impurities, causing lattice defects and negatively impacting carrier mobility. ALD films exhibit the highest density, fewest defects, and optimal purity. They also have uniform stress, good interface conditions, and extremely low leakage rates, with electrical stability far superior to traditional processes. They offer significant advantages in the fabrication of semiconductor core layers requiring high insulation, high uniformity, and high stability.

From the perspective of cost and mass production in practical industrial applications, PVD equipment has the best cost-performance ratio due to its simple structure, low maintenance cost, moderate energy consumption, and stable production speed. It is suitable for mass production of low-to-mid-end devices, metal electrodes, and ordinary coatings. CVD equipment has moderate cost and the largest capacity, making it suitable for large-scale production lines and the most widely used thin film process in the semiconductor industry. ALD equipment is expensive, has low production efficiency, and high consumable costs, making it unsuitable for mass production of ordinary thin

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films. However, its high precision and consistency are irreplaceable, so it is mostly used for the preparation of key thin films in high-end chips and precision optoelectronic devices.

4. Limitations and development trends

The preceding comparison of the principles and performance of PVD, CVD, and ALD thin film deposition processes demonstrates that each technology has its advantages and disadvantages in industrial applications. No single process can simultaneously achieve high uniformity, high coverage, high production rate, and low cost. As semiconductor device manufacturing processes continue to shrink and chip structures become increasingly complex and three-dimensional, traditional thin film deposition processes are gradually revealing numerous unavoidable technical shortcomings and practical limitations in adapting to the demands of advanced manufacturing. A thorough analysis of the shortcomings of various processes and an assessment of technological evolution directions are of significant reference value for the selection and optimization of microelectronic thin film processes.

PVD equipment is simple, the process is stable, the preparation temperature is low, and the production cost is controllable, making it suitable for large-area, high-volume preparation of ordinary thin films. However, its line-of-sight deposition physical nature introduces inherent structural limitations. In current mainstream high aspect ratio trench, dense via, and sidewall stacked structures, the linear deposition mode of PVD particles cannot achieve three-dimensional coating, easily leading to problems such as top film accumulation, missing sidewall coatings, and insufficient bottom coverage. In addition, films prepared by magnetron sputtering generally have residual stress, which can easily induce film warping, peeling, and accelerated oxidation under long-term operation, affecting device stability and gradually limiting its application in next-generation high-precision, three-dimensional micro/nano devices.

Traditional CVD technology overcomes the shortcomings of PVD in terms of insufficient three-dimensional coverage, offering faster deposition rates and better mass production capabilities. It is currently one of the most widely used thin film fabrication technologies in the semiconductor industry. However, CVD processes are highly temperature-dependent. The growth of most dielectric and semiconductor thin films requires high-temperature environments of several hundred degrees Celsius. High-temperature heat treatment can easily cause negative impacts such as thermal deformation of the substrate material, diffusion of dopant elements, and damage to existing device structures, making it unsuitable for the fabrication needs of flexible electronics and low-temperature sensitive devices. Furthermore, the high randomness of gas-phase chemical reactions can easily generate trace amounts of carbon and oxygen impurities, leading to porosity and defects within the film, reducing its density and electrical stability, and hindering the performance improvement of high-end precision devices.

ALD technology currently offers the best film quality, highest thickness accuracy, and strongest three-dimensional conformal capabilities among the three processes, meeting the needs of ultrathin dielectric films and highly coated insulating films for advanced processes such as 7nm and 5nm. However, the biggest drawback of ALD technology is its extremely low production efficiency. Relying on a single-cycle, single-layer growth mode, the film thickness increase rate is far lower than that of PVD and CVD. To prepare thicker functional films, tens of thousands of pulse cycles are required, significantly lengthening the production cycle. Furthermore, ALD equipment is expensive, precursor consumables are costly, and chamber cleanliness requirements are stringent, resulting in high overall production costs. This makes it difficult to scale up production for low- to mid-range devices, limiting its application to small-scale preparation of core precision thin films.

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5. Conclusion

This paper compares three thin film deposition processes: PVD, CVD, and ALD. It discusses their working principles and evaluates them based on deposition mechanism, process conditions, production efficiency, film quality, and cost. The findings highlight that no process is universally superior, rather, each has specific advantages and limitations suited for different applications. PVD is noted for its low temperature and cost-effectiveness, ideal for large-scale production of metal films. CVD is recognized for its versatility and strong production capacity, making it common in the semiconductor industry. ALD stands out for its precision in thickness and conformal coverage, essential for advanced micro/nano devices and optoelectronics.

However, this study did not conduct practical verification of the combined application schemes of the three types of processes, nor did it perform quantitative analysis based on the fabrication parameters of specific devices. Furthermore, the research depth on novel improved processes and novel precursor materials is insufficient.

Future research should target three key areas: optimizing low-temperature composite deposition processes to create an efficient and cost-effective coating system, quantifying optimal preparation parameters and establishing a standardized process selection model, and developing novel precursor materials and deposition technologies to address challenges like low ALD efficiency and high-temperature damage in CVD, thereby enhancing thin film deposition technology for advanced semiconductor manufacturing.

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