

A Comprehensive Review on Deposition Techniques for Functional Thin Films

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Abstract

Thin films have become a critical element in the design and development of advanced functional materials because of their remarkable versatility, high efficiency, and ability to be easily integrated into a wide variety of devices. These films are used in a broad range of industries, from electronics to energy, owing to their ability to improve the performance of components by providing tailored electrical, optical, and mechanical properties. The deposition of thin films plays a pivotal role in their fabrication, as the method used directly affects the resulting film's quality, structure, and functionality. A variety of deposition techniques are employed to fabricate these films, each with its unique principles, advantages, and limitations. This article attempts to provide a thorough examination of the many deposition procedures, covering both established and new approaches. It provides an in-depth exploration of methods such as physical vapor deposition (PVD), chemical vapor deposition (CVD), and sputtering, as well as novel approaches like atomic layer deposition (ALD) and laser ablation. The paper delves into the fundamental principles behind these techniques, examining how they contribute to the creation of thin films with specific properties. In addition, the review outlines the advantages and challenges associated with each method, such as deposition rate, uniformity, and material compatibility. The applications of functional thin films are also explored, highlighting their use in photovoltaic cells, sensors, semiconductor devices, and energy storage technologies. This review ultimately aims to provide a thorough understanding of the current state of thin film deposition techniques, while also offering insights into the future trends and potential advancements that could further enhance their efficiency and applicability across various fields.

Keywords: Thin Films, Deposition Techniques, Physical Vapor Deposition (PVD), Chemical Vapor Deposition (CVD), Atomic Layer Deposition (ALD), Functional Materials

INTRODUCTION

Functional thin films are materials with unique properties that arise from their reduced dimensions, typically ranging from nanometers to micrometers. Numerous sectors, such as electronics, optics, sensors, coatings, and energy storage devices, depend heavily on these films. Their physical properties, such as conductivity, magnetism, optical characteristics, and mechanical strength, can be significantly altered due to the thin nature of the material. The ability to control these properties makes functional thin films essential for modern technology. To create these materials, various deposition techniques are employed, each offering distinct advantages depending on the desired material characteristics and application. The ultimate characteristics of the thin film, including its shape, homogeneity, thickness, and adherence to

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surfaces, are greatly influenced by the deposition technique chosen. Therefore, understanding the principles, advantages, and limitations of these techniques is vital for researchers and engineers involved in the development and application of thin films. The purpose of this article is to present a thorough analysis of the many deposition methods that are employed to create functional thin films. Physical deposition and chemical deposition are the two main categories into which these techniques are usually divided. [1-3] The qualities of the resulting thin film may be precisely controlled thanks to the several processes in each category, each of which has unique uses and working mechanisms. Figure 1

Material is physically transferred from a source to a substrate via physical deposition procedures, typically in a vacuum environment. Sputtering is a popular physical deposition technique that uses high-energy particles to remove atoms from a target material. After that, these atoms create a thin film by condensing on a substrate. Evaporation, which entails heating a substance until it vaporizes and then letting the vapor fall onto a substrate, is another popular technique. These techniques are perfect for creating films that are highly consistent and pure, which makes them appropriate for use in optics and electronics.

However, in order to deposit material onto a substrate, chemical deposition techniques rely on chemical processes. One of the most popular methods is chemical vapor deposition (CVD), in which a thin coating is created when gaseous precursors combine with a heated substrate. CVD allows for the precise control of film composition and thickness, making it highly effective for producing films used in semiconductors and coatings. Another important chemical deposition technique is **sol-gel processing**, which involves the use of liquid solutions that undergo chemical reactions to form solid films. This method is often used for coating applications and offers the advantage of low-temperature processing [4].

Depending on the intended use, both chemical and physical deposition methods offer benefits and limitations. For example, while sputtering and evaporation can achieve high-quality films with excellent control over thickness and uniformity, they may not be suitable for complex material compositions. Conversely, chemical deposition techniques like CVD allow for greater versatility in terms of material types, but they may require more complex equipment and higher processing temperatures.

The choice of deposition technique is not only dependent on the material to be deposited but also on the desired properties of the thin film and the specific application. For example, thin films used in photovoltaics and energy storage devices must exhibit high uniformity and specific electrical characteristics, which can be achieved using methods like sputtering or CVD. On the other hand, films for decorative or functional coatings may prioritize aesthetic qualities and corrosion resistance, which may require different deposition methods [5] Figure 2.

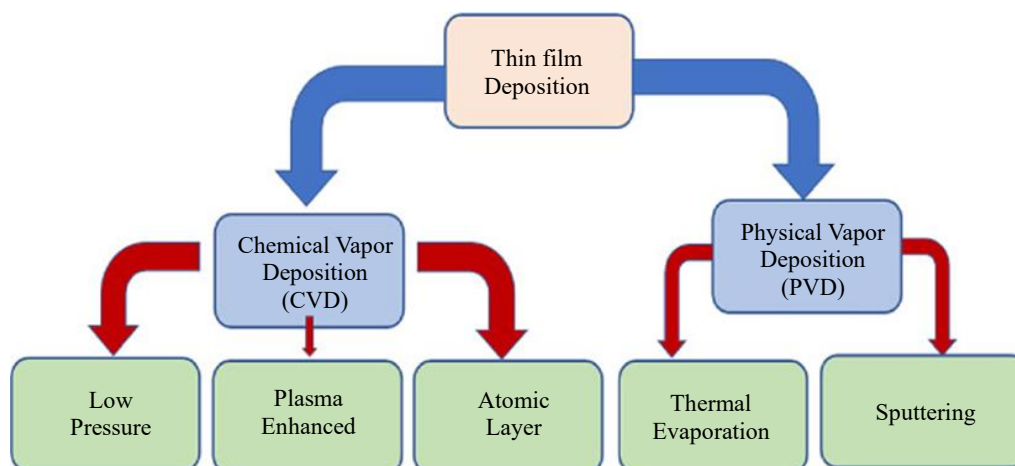


Figure 1. Thin film deposition.

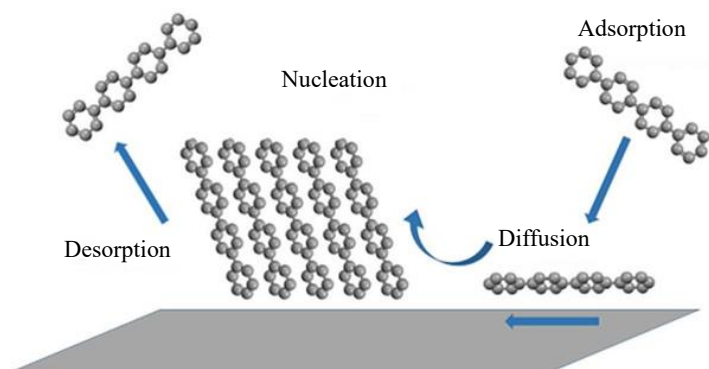


Figure 2. Technique of deposition process.

2. DEPOSITION TECHNIQUES FOR THIN FILMS

The two main categories of thin-film deposition methods are chemical vapor deposition (CVD) and physical vapor deposition (PVD). In addition to these traditional methods, several emerging techniques like Atomic Layer Deposition (ALD), Sol-Gel, and Pulsed Laser Deposition (PLD) have also been gaining attention for their unique capabilities. These deposition processes are critical for a wide range of applications in various industries, from optoelectronics to energy storage. Each technique offers distinct advantages and challenges based on the material properties, required film quality, and specific application needs [6-10].

2.1 Physical Vapor Deposition (PVD)

PVD is a process that uses condensation from a vaporized phase to deposit material onto a substrate. Usually, the source material is heated or bombarded to produce the vaporized substance. Under PVD, there are two primary sub-techniques:

- *Evaporation*: The substance is heated in a vacuum until it vaporizes in this procedure. A thin layer is created on the substrate when the vapor condenses.
- *Sputtering*: This method bombards a target material with intense ions, causing atoms to be expelled and deposited into the substrate.

Advantages

- PVD is renowned for creating highly pure films because of the vacuum environment.
- Metals, oxides, and nitrides are among the many materials that can be deposited using it.
- It can be used to deposit a wide range of materials, including metals, oxides, and nitrides.

Challenges

- Certain materials may have low deposition rates, limiting the process's efficiency.
- High vacuum systems are often necessary, which can be expensive and complex.

Applications

PVD is widely used in industries such as optoelectronics, sensor technologies, and coating applications, including corrosion-resistant layers for various components.

2.2 Chemical Vapor Deposition (CVD)

CVD involves a chemical reaction that takes place in a gaseous environment, resulting in the formation of solid material that is deposited onto a substrate. Various types of CVD methods are available, each optimized for specific requirements:

- *Low-Pressure CVD (LPCVD)*: This method operates under low-pressure conditions, which can enhance the quality and uniformity of the films.
- *Plasma-Enhanced CVD (PECVD)*: PECVD uses plasma to excite the gas phase reactants, enabling the deposition of films at relatively low temperatures compared to traditional CVD methods.

Advantages

- CVD techniques provide high-quality films with excellent uniformity.
- PECVD allows for the deposition of films at lower temperatures, which is beneficial for materials sensitive to heat.

Challenges

- CVD often requires complex and precise gas chemistries.
- Some CVD methods can be energy-intensive, leading to higher operational costs.

Applications

CVD processes are integral to fields such as microelectronics (especially for semiconductors), photovoltaics, and the creation of durable protective coatings for various applications.

2.3 Atomic Layer Deposition (ALD)

One atomic layer at a time, thin films can be deposited using ALD, a specialized type of CVD. This level of precision gives ALD remarkable control over the thickness and uniformity of films, especially on intricate and complex substrates.

Advantages

- ALD enables atomic-scale control of film thickness, providing highly accurate and uniform coatings.
- It is especially effective for depositing films on complex three-dimensional surfaces, such as porous or high-aspect-ratio structures.

Challenges

- High-throughput applications may be limited by ALD's typically slower deposition rates.
- The technique is often limited to specific types of materials that can form stable chemical reactions during the deposition process.

Applications

ALD is particularly important in the semiconductor industry for the fabrication of transistors, in energy storage technologies such as batteries and supercapacitors, and in catalysis applications where precise material control is necessary.

2.4 Sol-Gel Process

A liquid sol (a colloidal suspension) is transformed into a gel using the sol-gel process, a low-temperature technique that, when heated, becomes a thin film. This process is particularly useful for producing organic-inorganic hybrid films and is widely used in industries requiring cost-effective deposition techniques.

Advantages

- Comparing the sol-gel process to other thin film deposition procedures, it is comparatively less expensive.
- **It is perfect for applications like flexible electronics since it can be used to deposit films on flexible substrates. Challenges:**
- One of the key limitations is the ability to control the film's density and structure, which can lead to inconsistencies in the final product.
- The process is restricted to materials that can form sols, limiting the range of materials that can be used.

Applications

The sol-gel process is often used in the creation of photovoltaic cells, sensors, and protective coatings for various types of surfaces.

2.5 Pulsed Laser Deposition (PLD)

PLD is a process that involves ablation of a target material with a powerful laser, followed by its thin-film deposition onto a substrate. The material can be in various phases, including metals, ceramics, and oxides. PLD is often preferred for materials that are difficult to deposit using traditional methods like PVD or CVD.

Advantages

- PLD allows for high deposition rates, which makes it suitable for large-scale production.
- It is capable of depositing a wide range of materials, including complex compounds, ceramics, and oxides.

Challenges

- The equipment used for PLD can be expensive, making the initial investment quite high.
- Achieving uniformity in the deposited films can be challenging, especially when working with large areas or intricate substrates.

Applications

PLD is used in the deposition of thin films for superconducting materials, magnetic devices, and thin-film batteries, all of which require specific material properties.

3. COMPARISON OF DEPOSITION TECHNIQUES

Every deposition technique has unique benefits and drawbacks. The choice of an appropriate deposition technique is influenced by a variety of factors, including the type of material being deposited, the substrate material, desired film thickness, and the specific application for which the thin film is intended. These factors play a crucial role in determining the best method for a given task [10-12].

- **PVD (Physical Vapor Deposition)** is widely favored for its versatility and the purity of the thin films it produces. This technique is particularly effective for fabricating metal films and coatings, which are often used in industries such as electronics, optics, and aerospace. PVD allows for excellent control over the material properties, such as composition and film thickness, making it ideal for applications where precision is critical [13].
- **CVD (Chemical Vapor Deposition)** methods are known for their ability to produce high-quality films with excellent adhesion to a variety of substrates. These properties make CVD ideal for applications in the semiconductor industry, as well as in the fabrication of photovoltaic devices, where uniformity and strong bonding are essential for optimal performance. CVD can also be used to create complex thin-film materials that may not be possible with other techniques.
- **ALD (Atomic Layer Deposition)** is a highly specialized deposition method that provides unmatched atomic-scale control over layer thickness. This level of precision makes ALD the preferred choice for applications that require ultra-thin films with atomic-layer accuracy. It is frequently utilized in the semiconductor sector and in the manufacturing of cutting-edge materials like catalysts and high-k dielectrics, where performance depends on accurate layer deposition [14].
- **Sol-Gel** is a highly cost-effective method for large-scale production of thin films, especially for applications in industries like optics, coatings, and energy. It works especially effectively for applications that need to cover a lot of ground quickly. But compared to other approaches, the variety of materials that can be used using this process is more constrained. Sol-Gel films may not always offer the same level of uniformity and precision as those produced by PVD or CVD, but they excel in cost-effectiveness and scalability.

- **PLD (Pulsed Laser Deposition)** is a high-energy deposition technique that can produce thin films with unique material properties, such as high crystallinity. However, it faces challenges when it comes to uniformity, especially in large-area deposition. PLD is well-suited for research applications and for producing thin films of complex materials that require a high degree of precision. Despite its strengths, the uniformity of PLD films may be inconsistent, especially when applied to large-scale production [15].

CONCLUSION

Deposition techniques are an essential aspect of the fabrication process for high-performance functional thin films, which are integral to a wide range of technological applications. These films, which are typically just a few nanometers to micrometers thick, require precise control during deposition to ensure their quality, uniformity, and functionality. Various deposition techniques, including sputtering, chemical vapor deposition (CVD), and physical vapor deposition (PVD), each have unique benefits based on the materials and intended purpose. However, each technique also comes with certain limitations, including challenges in scaling up, ensuring uniform thickness, or optimizing material properties. As industries like electronics, energy, and biotechnology continue to evolve, there is an increasing demand for thin films with enhanced performance, durability, and efficiency.

Advancements in deposition technologies are critical to meeting these demands. Ongoing research efforts are focused on improving the precision and reliability of current techniques, as well as developing innovative approaches to overcome existing challenges. The creation of hybrid deposition techniques, which combine the advantages of several approaches to provide better results, is one field that shows a lot of promise. These hybrid approaches offer the potential to create functional thin films that are not only high-quality but also cost-effective and scalable for large-scale production. The future of functional thin films lies in the continuous improvement of deposition methods to meet the ever-growing demands of modern industries.

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