Thin Film Preparation Approaches: A Review

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Abstract
The purpose of this review study is to provide a critical evaluation of the available thin film deposition approaches. In this paper, some revolutionary and prevalent thin film processes are discussed. Each approach is discussed in terms of its benefits and drawbacks. Thin film technology (TFT) has revolutionized multiple fields, enabling the development of compact and high-performance electronic devices, such as transistors, gas sensor, optical sensor and solar cells. It also plays a crucial role in optical coatings for lenses, mirrors, and displays, enhancing their performance and durability. Additionally, thin films find applications in sensors, protective coatings, and flexible electronics, and other applications. TFT encompasses the study of film growth mechanisms, material properties, and the development of innovative deposition processes. Researchers and engineers in this field continually strive to enhance the performance, efficiency, and cost-effectiveness of thin film-based technologies to meet the ever-evolving demands of modern technology and industry. Thin films can be deposited onto substrates such as glass and alumina using various deposition techniques, including physical vapor deposition (PVD), electro-deposition, spray pyrolysis technique (SPT), chemical vapor deposition (CVD), and atomic layer deposition (ALD) and spin coating technique.

Keywords: Thin film technology, deposition processes, substrates, spin coating technique, efficiency.

I. Introduction

Modern society is filled with thin films, and many of the innovations that we use on every day are also reliant on thin film technology. In several stages of the fabrication process for solid-state devices, thin-film deposition approaches are required. It is crucial to choose compatible deposition methods that do not conflict with the device's existing structural elements [1]. A key factor in choosing an effective method is the process integration, which must take into account thermal effects, chemical and metallurgical compatibility, as well as functional needs and constraints. In order to satisfy the needs for particular device requirements, the deposition procedures must provide a high level of adaptability [1, 2].

Thin films are layers of material that range in thickness from a few nanometers to a few micrometers. Controlled material synthesis using a deposition procedure is the key step in many thin film applications. Touch screens, computers, mobile phones, tablets, electrical circuits, photovoltaic, power generation, and many more things are examples of regular things that employ TFT. At the present time, there are numerous approaches for producing thin films. Top-down (physical) and bottom-up (chemical) approaches are two major approaches used for the preparation of thin films. The current review paper's objectives are to study thin film deposition approaches, factors affecting the deposition approach, thin film characteristics, and applications. Identifying the benefits and limitations of thin film preparation techniques [1-5]. Due to the preservation of finite resources, creation of nanostructured coatings and nanocomposites, ecological considerations, a decrease in effluent output and electrical consumption, enhanced functionality of existing products, resolution of previously unsolved engineering problems, and development of completely new and pioneering products, thin films have a tremendous amount of future potential [5, 6]. Metal oxide semiconductors (MOS) based thin-film have received much attention for different applications like solar cell, gas sensor, photocatalyst, biosensor, battery electrodes and others due to their high sensitivity, good chemical resistance, large surface area, more sensitivity, easy surface immobilizations of bioreceptors, and easy fabrication [7, 8].

The current research articles present the various synthesis as well as preparation approaches for thin films. The advantages and limitations of the thin film preparation approach are also elaborated on in this paper.

II. Types of thin film preparation approaches

Thin film preparation approaches broadly divided into two type such as physical and chemical as illustrated in Figure 1 [9-13].

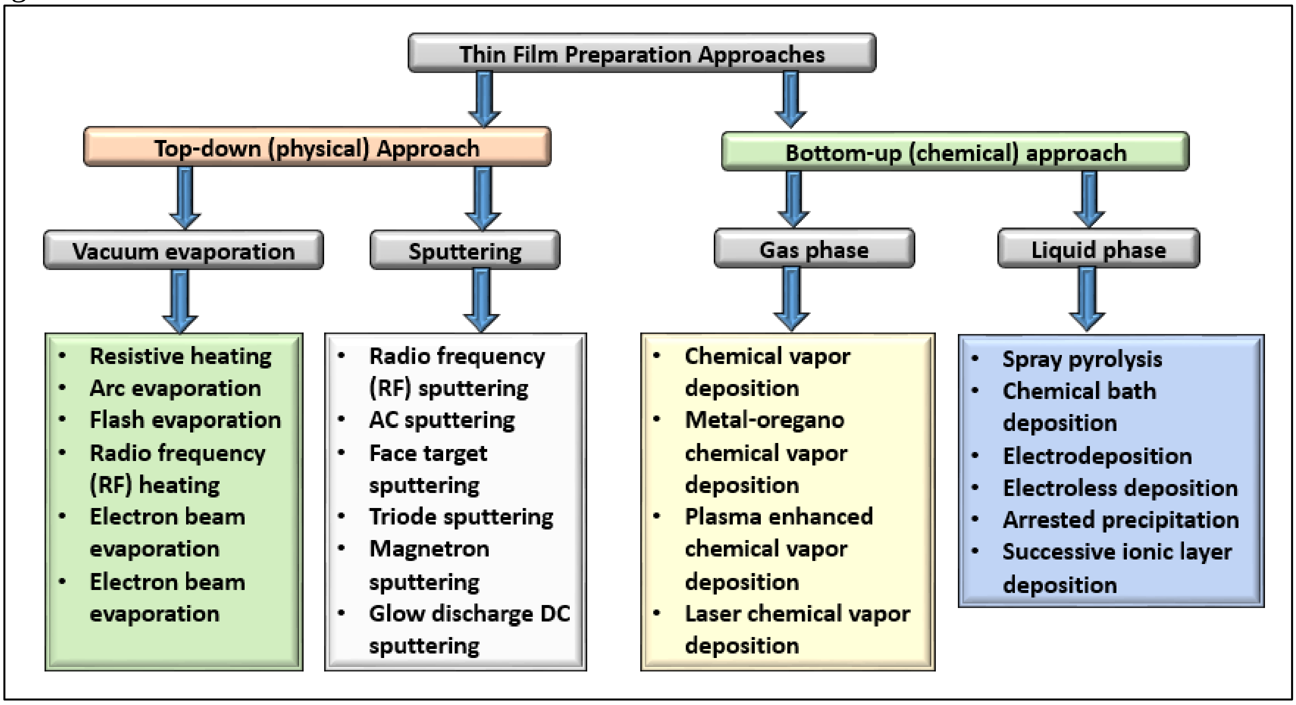

Figure 1: Types of thin film preparation approaches

1. **Physical Vapor Deposition (PVD):** PVD techniques involve the physical removal of material from a solid source followed by its deposition onto a substrate. Common PVD methods include evaporation and sputtering. PVD is a valuable thin film deposition technique known for its precision, high-purity films, and strong adhesion. However, it has limitations related to its line-of-sight deposition, vacuum requirements, and complexity for certain applications [13]. It is a vaporization coating process that involves the atomic-scale transfer of material in a vacuum. There are four steps in the procedure: (i) the material to be deposited is evaporated using a high energy source, such as an electron beam or ions, which removes atoms from the surface; (ii) the vapor is transported to the substrate to be coated; (iii) during the transport stage, a reaction occurs between the metal atoms and the proper reactive gas; and (iv) the coating is then deposited on the substrate surface [13, 14]. Figure 2 showing the schematic of physical vapor deposition system.

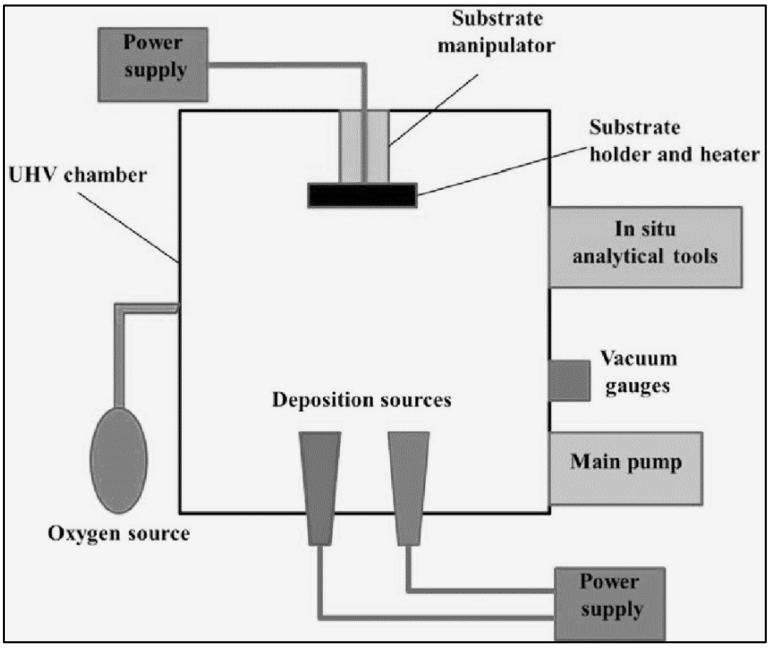

Figure 2: Schematic of physical vapor deposition system.

1.1 Advantages of PVD:

- **Thickness Control:** PVD offers excellent control over film thickness, making it suitable for producing thin films with precise thicknesses, often at the atomic or nanometer scale.
- **High Purity:** PVD processes can produce high-purity films because they involve the physical removal of material from a solid source. This is especially important for applications in microelectronics and optics where impurities can negatively impact device performance.
- **Uniformity:** PVD can provide uniform film deposition across a large area, ensuring consistent properties throughout the substrate. This uniformity is crucial for many applications, such as coatings for optical lenses or semiconductor devices.
- **Adhesion:** PVD films typically exhibit strong adhesion to the substrate due to the physical nature of the deposition process. This adhesion is essential for ensuring the long-term stability and performance of coated materials.
- **Wide Material Compatibility:** PVD can deposit a wide range of materials, including metals, semiconductors, ceramics, and alloys. This versatility makes it suitable for various applications in different industries.
- **Minimal Waste:** PVD is a relatively efficient process, with minimal material waste since it deposits only the material needed to form the thin film.
- **Customizable Properties:** By adjusting process parameters such as deposition rate, temperature, and pressure, researchers can tailor the properties of PVD films to meet specific requirements, such as hardness, optical properties, or electrical conductivity.

1.2 Limitations of PVD:

- **Line-of-Sight Deposition:** PVD is a line-of-sight technique, meaning it requires a direct line of sight between the source material and the substrate. This limitation can make it challenging to coat complex or three-dimensional substrates evenly.
- **Limited Film Thickness:** While PVD offers precise control over film thickness, it may not be suitable for depositing very thick films. The process is typically better suited for thin to moderate thicknesses.
- **High Vacuum Requirements:** PVD processes require a high vacuum environment, which can be energy-intensive and costly to maintain. This vacuum requirement can also limit the types of materials that can be used as source materials.
- **Substrate Temperature Sensitivity:** Some PVD techniques, such as sputtering, can subject the substrate to elevated temperatures. This can be a limitation for temperature-sensitive materials or substrates.

- **Complexity for Multilayer Structures:** Achieving precise multilayer structures with PVD can be complex and may require careful control of deposition parameters and multiple processing steps.
- **Limited Step Coverage:** Step coverage, or the ability to coat surfaces with significant topography differences, can be challenging with PVD. Gaps and crevices may not receive uniform film coverage.
- **Equipment Cost:** PVD equipment can be relatively expensive to purchase and maintain, which can be a barrier to entry for smaller research facilities or companies.

2. **Chemical Vapor Deposition (CVD):** CVD involves the chemical reaction of gaseous precursors to produce a thin film on a substrate. This can be done through various methods, including atmospheric pressure CVD (APCVD), low-pressure CVD (LPCVD), and plasma-enhanced CVD (PECVD). It is a versatile technique for depositing thin films and coatings onto various substrates. CVD is a powerful technique for depositing thin films and coatings with precise control over properties. However, it requires careful handling of precursors, often involves high temperatures, and can be complex and costly to implement. The CVD process stands out for its superior throwing power, which makes it possible to produce coatings with a uniform thickness and minimal porosity even on substrates with complex shapes. The capacity to do localized or selective deposition on patterned surfaces is another crucial aspect. Numerous thin film uses, such as epitaxial layers for nanotechnology, tribological and corrosion-resistant coatings, heat-resistant coatings, conductors, dielectrics, and conductive oxides, use CVD and related technologies. Figure 3 reveals schematic of chemical vapor deposition system.
3.

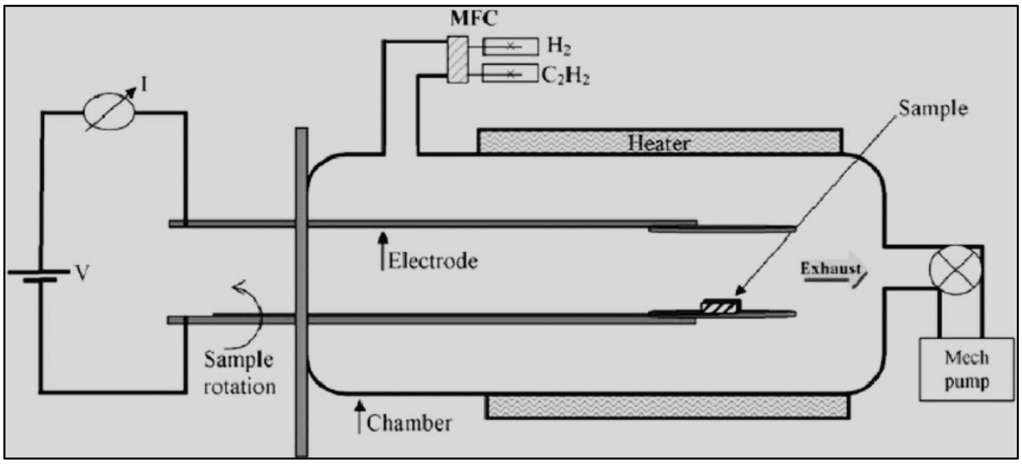

Figure 3: Schematic of chemical vapor deposition system.

2.1 Advantages of CVD:

- **Uniform and Conformal Coatings:** CVD can provide uniform and conformal coatings, meaning it can coat complex and three-dimensional structures evenly. This makes it suitable for coating irregularly shaped objects or creating thin films with uniform thickness over large areas.
- **Precise Control:** CVD allows for precise control over film thickness, composition, and other properties. This control is crucial in industries like microelectronics and optics, where exact specifications are essential.
- **High Purity:** CVD typically yields high-purity films since it relies on chemical reactions in a controlled environment. This is advantageous for applications where impurities can negatively affect performance.
- **Wide Material Compatibility:** CVD can deposit a broad range of materials, including metals, semiconductors, ceramics, and even complex compounds. This versatility makes it applicable to various industries and applications.
- **Customizable Properties:** By adjusting parameters like gas flow rates, temperature, and pressure, researchers can tailor the properties of CVD films to meet specific requirements, such as optical, electrical, or mechanical properties.

- **Atomic Layer Deposition (ALD):** A variant of CVD, known as ALD, allows for atomic-scale control over film thickness and composition. ALD is especially valuable in the semiconductor industry for precise device fabrication.

2.2 Limitations of CVD:

- **High-Temperature Requirement:** Many CVD processes require high temperatures to facilitate chemical reactions. This can limit the choice of substrates, as some materials may not withstand these temperatures. It can also hinder the coating of temperature-sensitive materials.
- **Precursor Handling:** Handling and storing chemical precursors can be hazardous and require careful safety measures. Some precursors may be toxic, flammable, or reactive, posing risks to operators and equipment.
- **Equipment Complexity:** CVD equipment can be complex and expensive to set up and maintain. It often necessitates a controlled environment with strict safety protocols.
- **Energy Consumption:** High-temperature CVD processes can be energy-intensive, increasing operational costs. This is a consideration for both research and industrial applications.
- **Substrate Size Limitations:** The size of the substrate that can be coated using CVD may be limited by the size of the reaction chamber. Large-scale coating of substrates can be challenging.
- **Limited Step Coverage:** Achieving uniform coatings in deep and narrow cavities or trenches can be challenging with CVD. This limitation is important in microfabrication and semiconductor manufacturing.
- **Slow Deposition Rates:** CVD can have relatively slow deposition rates compared to some other techniques, such as sputtering. This can be a limitation for high-throughput manufacturing.
- **Chemical Compatibility:** The choice of precursors and process conditions must be compatible with the substrate material. Incompatibility can result in damage or degradation of the substrate.

4. **Spin Coating technique:** Spin coating involves depositing a thin layer of liquid precursor onto a substrate and then spinning it at high speeds to achieve a uniform and thin film. Spin coating is a versatile and straightforward technique for depositing thin films with advantages such as uniformity, ease of use, and versatility in material selection. However, it may not be suitable for all applications, particularly those requiring precise control over very thick films or compatibility with non-liquid precursors. It is a commonly used technique for depositing thin films and coatings on a variety of substrates. The simplest technique for creating a film on a substrate is spin coating. Thin resist layers for photolithography are coated. The diluting of the substance to be deposited in a solvent is the first step in the spin-coating approach. After that, the solution is applied to the substrate's surface. The wafer is then spun quickly after that. Surface tension, solution viscosity, and spinning speed all affect how thick the film is. Spinning causes some of the solvent to evaporate, and subsequent baking at high temperatures removes some of it as well. Spin coating produces a surface that is largely flat. This method is frequently applied to planarization. Sol-gels can be deposited via spin coating. [17, 18].

3.1 Advantages of Spin Coating:

- **Uniform and Thin Films:** Spin coating can produce uniform and thin films with precise control over thickness. The spinning action spreads the liquid precursor evenly over the substrate, resulting in a uniform coating.
- **Ease of Use:** Spin coating is a relatively simple and cost-effective technique, making it accessible for both research and industrial applications. It does not require complex equipment or a high vacuum environment.
- **Wide Range of Materials:** Spin coating can be used with a wide range of materials, including polymers, photoresists, nanoparticles, and organic compounds. This versatility makes it suitable for various applications.
- **High Throughput:** Spin coating can be adapted for high-throughput applications, making it suitable for rapid prototyping and small-scale production.
- **Conformal Coatings:** Spin coating can provide conformal coatings, meaning it can coat complex and three-dimensional structures evenly. This is valuable in microfabrication and MEMS (Micro-Electro-Mechanical Systems) applications.

- **Customizable Properties:** By adjusting parameters such as spin speed, solution viscosity, and concentration, researchers can tailor the properties of spin-coated films to meet specific requirements.

3.2 Limitations of Spin Coating:

- **Limited Film Thickness Control:** While spin coating is excellent for producing thin films, it can be challenging to control the thickness accurately, especially for very thick films. Achieving sub-nanometer precision can be difficult.
- **Non-Uniformity on Large Substrates:** Spin coating may lead to non-uniform coatings on large substrates due to variations in centrifugal force across the substrate's surface. This can require additional processing steps to achieve uniformity.
- **Limited to Liquid Precursors:** Spin coating is primarily suitable for liquid or solution-based precursors. It is not well-suited for depositing solid materials or certain gases.
- **Solvent Compatibility:** The choice of solvent and its compatibility with the substrate must be considered. In some cases, solvents may damage or interact with the substrate.
- **Waste Generation:** Spin coating can generate a significant amount of waste in the form of excess precursor material that is not deposited on the substrate.
- **Not Suitable for High-Aspect Ratio Structures:** Spin coating is less effective for coating structures with high aspect ratios, such as deep trenches or fine lines, as the liquid may not penetrate these structures evenly.
- **Limited to Small to Medium-Sized Substrates:** Spin coating is best suited for relatively small to medium-sized substrates. Coating large or irregularly shaped substrates can be challenging.

5. **Chemical Bath Deposition (CBD):** CBD is a method that uses a chemical bath containing the precursors of the thin film material. The substrate is immersed in the bath, and the film forms through chemical reactions. It is a thin film deposition technique that relies on the chemical reaction of precursors in a bath solution to deposit materials onto a substrate. CBD is a cost-effective and versatile technique for depositing thin films, particularly when uniformity and conformal coatings are important. However, it may not be suitable for applications requiring precise control over film thickness or when high deposition rates are needed [19-21]. Schematic of chemical bath deposition system is illustrated in Figure 4.

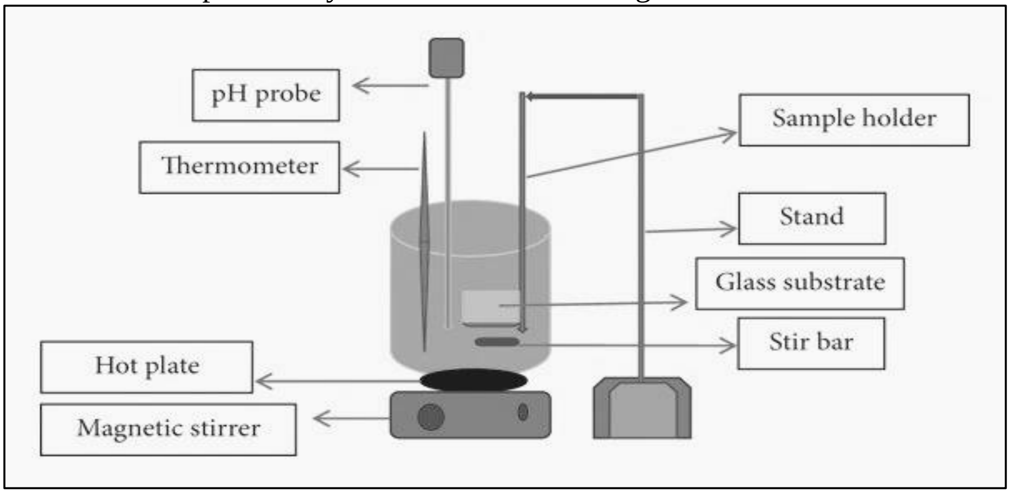

Figure 4: Schematic of chemical bath deposition system.

4.1 Advantages of Chemical Bath Deposition (CBD):

- **Low Equipment Costs:** CBD is relatively cost-effective compared to some other thin film deposition techniques, as it does not require complex or expensive equipment.
- **Conformal Coatings:** CBD can provide conformal coatings, meaning it can coat complex and irregularly shaped substrates uniformly. This makes it suitable for applications involving 3D structures.
- **Ease of Scale-Up:** CBD can be scaled up for large-scale production relatively easily, making it suitable for industrial applications.
- **Wide Material Compatibility:** CBD can be used to deposit a variety of materials, including semiconductors, oxides, and compound materials. It is versatile in this regard.

- **Low Temperature Deposition:** CBD typically operates at relatively low temperatures, which is advantageous for depositing materials onto temperature-sensitive substrates.
- **Self-Limiting Growth:** In some cases, CBD exhibits self-limiting growth, meaning that as the film thickness increases, the growth rate decreases. This can result in precise control over film thickness.

4.2 Limitations of Chemical Bath Deposition (CBD):

- **Limited Thickness Control:** While CBD offers some control over film thickness, it can be challenging to achieve precise control, especially for very thin or ultra-thick films.
- **Uniformity Challenges:** Achieving uniform coatings across large substrates or complex structures can be challenging with CBD. Variations in bath conditions, such as temperature and concentration, can lead to non-uniform films.
- **Slow Deposition Rates:** CBD generally has slower deposition rates compared to some other techniques like sputtering or chemical vapor deposition. This can be a limitation for high-throughput applications.
- **Waste Generation:** CBD can generate waste in the form of excess precursor solution, which may contain toxic or environmentally harmful components. Proper waste disposal and treatment are necessary.
- **Limited Film Properties:** The properties of CBD films may not always meet the specific requirements of certain applications, particularly when precise control over material properties is needed.
- **Chemical Handling and Safety:** CBD involves handling chemical precursors, some of which can be toxic or hazardous. Safety precautions and proper disposal are essential.
- **Film Porosity:** CBD films can sometimes be porous, which may not be suitable for applications requiring dense and impermeable coatings.
- **Precursor Decomposition:** Precursors used in CBD can degrade over time, leading to changes in film composition and quality.

6. **Atomic Layer Deposition (ALD):** ALD is a highly controlled and precise technique that deposits thin films one atomic layer at a time by alternating exposure to different precursor gases. It is a precise thin film deposition technique that allows for atomic-level control over film thickness and composition. It operates by sequentially exposing a substrate to alternating precursor gases. It may not be suitable for all scenarios due to its slower deposition rates, equipment complexity, and precursor handling requirements. Chemical gas phase thin film deposition based on consecutive, self-saturating surface reactions is known as atomic layer deposition [22, 23]. The substrate surface is gradually exposed to two or more precursor chemicals, each of which contains a different ingredient of the materials being deposited. Each precursor completely covers the surface, creating a monolayer of substance. Using an inert carrier gas, such as nitrogen, at a pressure of roughly 1 mbar is the foundation of the majority of commercial ALD deposition systems [24].

5.1 Advantages of Atomic Layer Deposition (ALD):

- **Precise Thickness Control:** ALD offers exceptional control over film thickness at the atomic or nanometer level. This level of precision is essential for applications in microelectronics, optics, and nanotechnology.
- **Conformal Coatings:** ALD provides conformal coatings, ensuring that the film uniformly covers complex and three-dimensional structures. This is crucial for coating advanced semiconductor devices and MEMS (Micro-Electro-Mechanical Systems).
- **Uniformity:** ALD films are highly uniform, with consistent properties across the entire substrate. This uniformity is essential for maintaining device performance.
- **Film Purity:** ALD typically produces high-purity films since it relies on self-limiting surface reactions, minimizing impurities and defects in the film.
- **Wide Material Compatibility:** ALD can deposit a wide range of materials, including metals, semiconductors, dielectrics, and even complex compounds. This versatility makes it suitable for various applications.
- **High Aspect Ratio Structures:** ALD is effective for coating structures with high aspect ratios, such as deep trenches, fine lines, and nanopores, due to its self-limiting growth mechanism.

- **Conductivity Control:** ALD allows for precise control over material properties, including electrical conductivity, by selecting appropriate precursor materials.

5.2 Limitations of Atomic Layer Deposition (ALD):

- **Slow Deposition Rates:** ALD typically has slower deposition rates compared to some other techniques, making it less suitable for high-throughput manufacturing.
- **Complex Equipment:** ALD equipment can be complex, expensive, and may require a high vacuum environment, which can be a barrier for some research facilities or companies.
- **Precursor Handling:** ALD involves handling and storing chemical precursors, which can be hazardous, costly, and require careful safety measures.
- **Cycle Time:** ALD operates in cycles, with each cycle comprising exposure to one precursor gas followed by purging. This cycle time can lead to longer deposition times for thicker films.
- **Limited Film Thickness:** While ALD excels at producing thin films, it may not be the best choice for depositing very thick films efficiently.
- **Energy Consumption:** ALD can be energy-intensive, particularly when operating under vacuum conditions and at elevated temperatures.
- **Film Roughness:** In some cases, ALD films can exhibit roughness, which may require post-processing treatments to achieve the desired surface quality.
- **Precursor Compatibility:** The choice of precursor materials and their compatibility with the substrate must be considered. Incompatibility can lead to poor film quality or substrate damage.

7. Electrodeposition: Electrodeposition is a method that involves the use of an electric current to deposit material from a solution onto a substrate. It is also known as electroplating or electrodeposition, is a widely used technique for depositing metal and alloy thin films onto various substrates. A flexible, affordable approach of creating a wide range of two- and three-dimensional materials, such as coatings and films, is electrodeposition [25]. The underlying principles of electrochemical processes connected to the reduction or deposition of electroactive and concomitant species on the cathode surface serve as the foundation for the electrodeposition process. If one takes the electrochemical principles into consideration for the intended uses and applications, this would make the electrodeposition procedure more manageable [26, 27]. Due to its low operating and capital costs, high deposition rates, near ambient temperature functioning, and ability to modify the deposition conditions to customize the properties of materials, electrodeposition is the preferred method for creating nanoengineered thermoelectric materials [28].

Electrodeposition includes the following steps:

a) Electroplating – This method of coating metallic or non-metallic surfaces with metal prevents corrosion of the metals.

b) Electrometallization is a method for depositing a metal for aesthetic or protective purposes on a conducting base.

c) Electro typing is a technique used to set up typing, reproduce printing, and create medals, among other things.

d) Electro forming: This technique for reproducing items by electrodeposition increases their durability.

e) Electro facing: Using an electrodeposition procedure, a tougher metal is applied to metallic surfaces to boost their endurance.

Figure 5 display the schematic diagram of electrodeposition system.

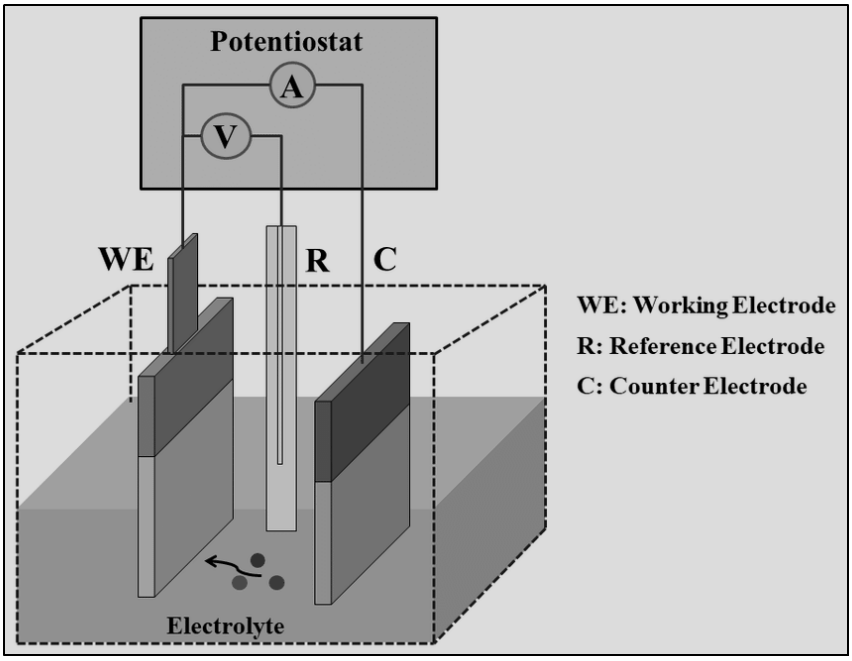

Figure 5: Schematic diagram of electrodeposition system.

6.1 Advantages of Electrodeposition:

- **Uniform and Conformal Coatings:** Electrodeposition can produce uniform and conformal coatings over complex and irregularly shaped substrates, making it suitable for applications with 3D structures.
- **Precise Control over Film Thickness:** Electrodeposition allows for precise control over film thickness by adjusting the deposition time and current density. This level of control is essential for meeting specific thickness requirements.
- **High Adhesion:** Electrodeposited films typically exhibit strong adhesion to the substrate, ensuring long-term stability and performance.
- **Wide Range of Materials:** Electrodeposition can be used to deposit a broad range of materials, including metals, alloys, and some semiconductor materials.
- **Cost-Effective:** Electrodeposition is often a cost-effective method compared to some other thin film deposition techniques, especially for applications that require metal coatings.
- **High Throughput:** Electrodeposition can be scaled up for high-throughput applications, making it suitable for industrial manufacturing processes.
- **Control over Alloy Composition:** Electrodeposition can be used to precisely control the composition of alloy films by adjusting the composition of the electroplating bath.

6.2 Limitations of Electrodeposition:

- **Limited to Conductive Materials:** Electrodeposition is primarily used for depositing conductive materials, so it may not be suitable for applications requiring insulating or semiconducting films.
- **Limited to Aqueous Solutions:** Most electrodeposition processes use aqueous solutions, which may not be compatible with all materials or substrates.
- **Surface Finish:** The surface finish of electrodeposited films may not always meet the desired requirements, and post-processing steps may be necessary to achieve the desired surface quality.
- **Electrolyte Compatibility:** The choice of electrolyte and its compatibility with the substrate must be considered, as some electrolytes can react with or damage certain materials.
- **Energy Consumption:** Electrodeposition can be energy-intensive, especially for thick coatings or large-scale production.
- **Waste Generation:** Electrodeposition can generate waste in the form of excess solution, which may contain toxic or environmentally harmful components. Proper waste disposal and treatment are necessary.
- **Limited to Metal and Alloy Films:** Electrodeposition is primarily used for depositing metals and metal alloys. It may not be suitable for applications requiring complex compound films.

- **Complexity of Bath Composition:** Achieving the desired film properties can require careful control over the composition of the electroplating bath, including the concentration of additives and other chemical components.

8. **Molecular Beam Epitaxy (MBE):**

In order to generate very high quality, single crystal multilayers of III-V semiconductors, the 1960s-era Bell laboratories technique known as "molecular beam epitaxy" (MBE) is frequently utilized in the field of semiconductor research. In the MBE approach, epitaxial layers are developed on a heated substrate that is held in an extremely high vacuum by the impingement of atomic or molecule beams. The components of the beam "stick" to the substrate, forming a layer with the same lattice as the substrate [29, 30]. The different sticking coefficients of the different elements that make up the epitaxial layers can be taken into account by controlling the beam intensity separately. MBE is a technique used to grow high-quality crystalline thin films by depositing atoms or molecules in a vacuum through precisely controlled beams. It is a sophisticated thin film deposition technique used to create precise and high-quality crystalline structures. It operates in a high-vacuum environment and involves the deposition of individual atoms or molecules onto a substrate [31, 32].

7.1 Advantages of Molecular Beam Epitaxy (MBE):

- **Precise Control over Film Thickness:** MBE allows for precise control at the atomic or molecular level, making it ideal for applications that require extremely accurate film thickness and composition control.
- **High Purity Films:** The high vacuum environment in MBE prevents contamination and ensures the deposition of ultra-pure films with minimal impurities or defects. This is crucial for applications in microelectronics and quantum technologies.
- **Atomically Sharp Interfaces:** MBE can create atomically sharp interfaces between different materials, enabling the design of complex layered structures and heterostructures with unique properties.
- **Wide Material Compatibility:** MBE can deposit a wide range of materials, including metals, semiconductors, superconductors, and magnetic materials, allowing for the growth of diverse thin film structures.
- **Low Deposition Rates:** MBE is a low-deposition-rate technique, which can be advantageous for applications that require controlled growth of thin films with atomic precision.
- **Temperature Control:** Researchers can precisely control substrate temperatures during deposition, enabling the growth of materials with specific crystalline structures and properties.
- **Layer-by-Layer Growth:** MBE facilitates layer-by-layer epitaxial growth, which is vital for creating high-quality semiconductor and photonic devices with controlled band structures.
- **High-Quality Crystalline Films:** MBE produces high-quality, single-crystal films, which are essential for many electronic and optoelectronic devices.

7.2 Limitations of Molecular Beam Epitaxy (MBE):

- **Complex Equipment:** MBE systems are complex, expensive, and require a high-vacuum environment, making them less accessible for smaller research facilities and universities.
- **Slow Deposition Rates:** Due to the precise control and low deposition rates, MBE is not suitable for high-throughput industrial production.
- **Material Wastage:** MBE can result in material wastage since it deposits one atom or molecule at a time, which may not be practical for large-scale manufacturing.
- **Material Compatibility:** Not all materials are compatible with MBE. Some materials may evaporate or decompose at the high temperatures and vacuum levels required for the process.
- **Substrate Size Limitations:** MBE systems typically have size limitations for the substrates they can accommodate, limiting the scale of the films that can be grown.
- **High Energy Consumption:** The high vacuum and temperature requirements of MBE can lead to elevated energy consumption, which may be a consideration for long-term operation.
- **Complex Growth Recipes:** Achieving the desired film properties often requires complex growth recipes and optimization, which can be time-consuming and challenging.
- **Maintenance:** MBE systems require regular maintenance and a high level of technical expertise to operate effectively.

9. **Spray Pyrolysis:** In this approach, a precursor solution is sprayed onto a heated substrate, and the solvent evaporates, leaving behind a thin film. Spray pyrolysis is a thin film deposition technique that involves spraying a precursor solution onto a heated substrate, where the solvent evaporates, leaving behind a thin film [33, 34]. This method is commonly used for depositing a variety of materials, including oxides, semiconductors, and organic compounds. Due to its enticing characteristics, including their low production costs, flexibility in substrate choice, and potential for vast area deployment, spray pyrolysis process has recently gained growing attention. Due to their potential technical utility and the scientific interest in their properties, several materials have been produced as thin films. In the hunt for the most dependable and affordable method of creating thin films, a number of strategies have been investigated [35-37]. The schematic diagram of spray pyrolysis method is reveal in Figure 6.

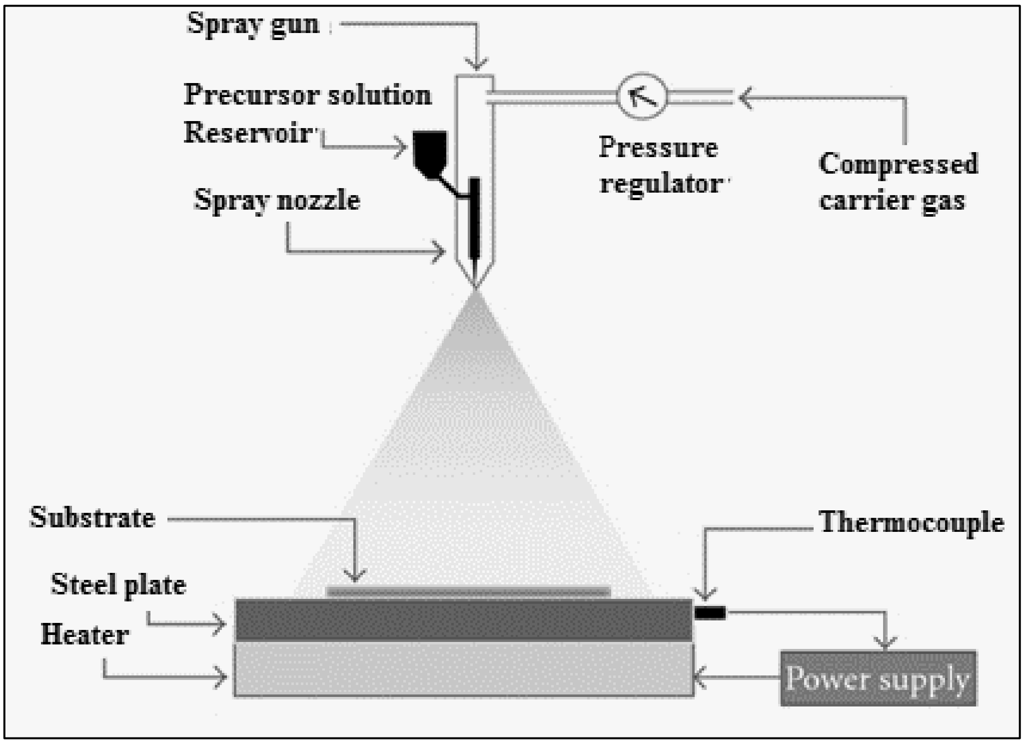

Figure 6: Schematic diagram of spray pyrolysis method

8.1 Advantages of Spray Pyrolysis:

- **Cost-Effective:** Spray pyrolysis is a relatively simple and cost-effective technique compared to some other thin film deposition methods. It does not require complex equipment or a high vacuum environment.
- **Large Area Deposition:** Spray pyrolysis can be used to coat large substrate areas evenly, making it suitable for applications that require uniform coatings over extensive surfaces.
- **Conformal Coatings:** It can produce conformal coatings on complex and 3D structures, ensuring uniformity across irregularly shaped substrates.
- **Versatility in Materials:** Spray pyrolysis is compatible with a wide range of precursor solutions, allowing for the deposition of various materials, including oxides, sulfides, and organic compounds.
- **Customizable Properties:** Researchers can tailor the properties of the deposited films by adjusting precursor concentrations, substrate temperatures, and deposition conditions.
- **Low Temperature Processing:** Many spray pyrolysis processes operate at relatively low temperatures, making it suitable for depositing materials on temperature-sensitive substrates.

8.2 Limitations of Spray Pyrolysis:

- **Limited Thickness Control:** Precise control over film thickness can be challenging with spray pyrolysis, especially for very thin or ultra-thick films. Achieving sub-nanometer precision is difficult.
- **Limited Material Compatibility:** While spray pyrolysis is versatile, it may not be suitable for all materials, especially those that require precise compositional control at the atomic level.

- **Substrate Surface Quality:** The quality of the substrate surface and its preparation can significantly impact the quality of the deposited films. Surface defects or contamination can lead to issues in the film.
- **Slow Deposition Rates:** Spray pyrolysis typically has slower deposition rates compared to some other techniques, which can be a limitation for high-throughput applications.
- **Solvent Compatibility:** The choice of solvent in the precursor solution and its compatibility with the substrate must be considered. In some cases, solvents may damage or interact with the substrate.
- **Complex Film Structures:** Achieving complex multilayer structures with precise control can be challenging with spray pyrolysis.

III. Applications of thin films

Thin films have a wide range of uses and have proven crucial to many industrial and scientific activities over time. The films are between several tenths of a nanometer and a few micrometers thick. A crucial field of study and application is thin films. Applications of thin films can be categorized under the following broad categories, including fuel cells, gas sensor, energy storage, optical science, optoelectronics, chemical engineering, sensors, and electrochemistry. The different types of applications of thin film are illustrated in Figure 7.

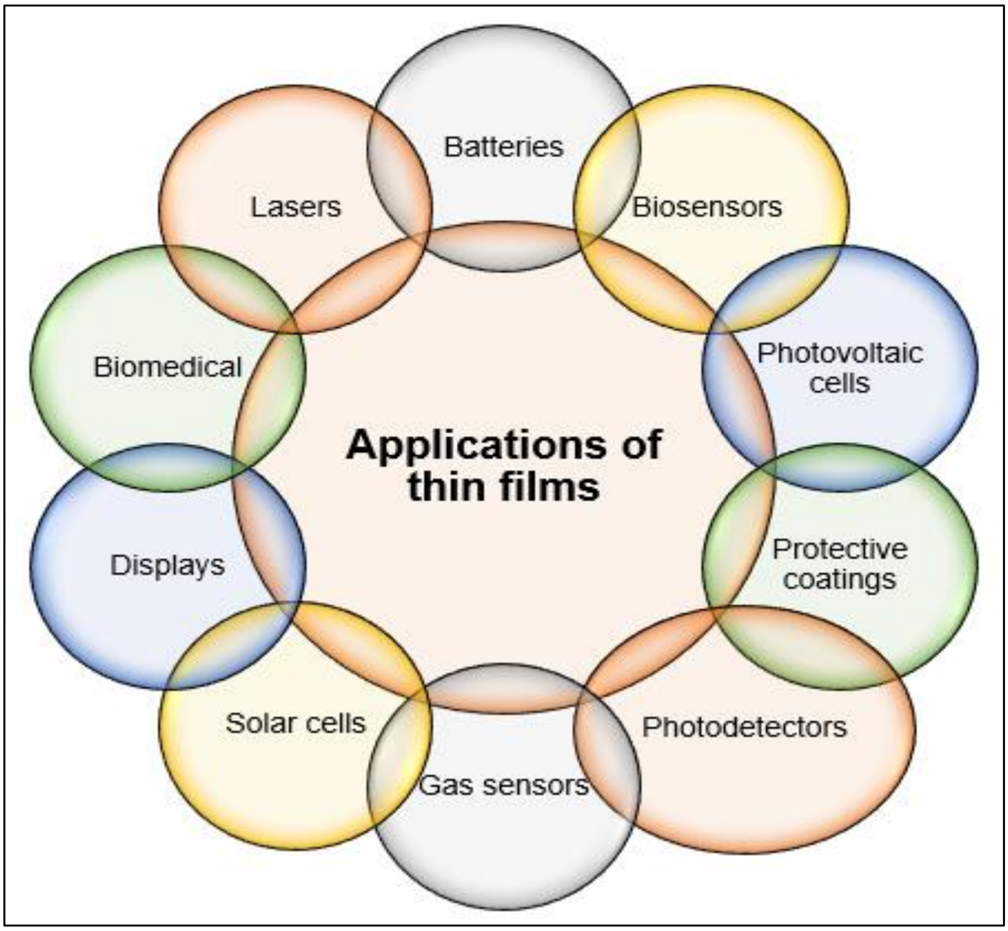

Figure 7: Applications of thin film

Few applications of thin films:

1. **Microelectronics and Nanoelectronics:** Thin films are fundamental to the semiconductor industry, enabling the fabrication of integrated circuits, transistors, and memory devices with high performance and miniaturization.
2. **Optics and Photonics:** Thin films play a pivotal role in optical coatings, antireflection coatings, and optical filters, enhancing the performance of lenses, mirrors, and optical devices.

3. **Solar Cells and Photovoltaics:** Thin film solar cells, such as amorphous silicon and cadmium telluride, have the potential to revolutionize renewable energy production due to their cost-effectiveness and efficiency.
4. **Sensors and Detectors:** Thin films are integral components in various sensors, including gas sensors, biosensors, and chemical sensors, offering high sensitivity and selectivity.
5. **Medical Devices and Biomaterials:** Thin films are used in medical implants, drug delivery systems, and tissue engineering, facilitating advancements in healthcare and regenerative medicine.
6. **Microfluidics and Lab-on-a-Chip:** Thin films are critical in microfluidic devices and lab-on-a-chip systems, enabling precise manipulation of fluids for applications in diagnostics and analytical chemistry.
7. **Protective Coatings and Corrosion Resistance:** Thin films are applied as protective coatings to prevent corrosion and wear on surfaces, extending the lifespan of various materials.
8. **Data Storage:** Thin films are used in hard disk drives, providing the magnetic recording media necessary for data storage.

Conclusion:

A review of thin film preparation approaches reveals a diverse and dynamic field of research and development with significant scientific and technological implications. The numerous approaches to thin films and their advantages and limits are explained in brief in this article. This article also covered the applications of thin films in different domains. Thin film preparation techniques have evolved significantly, offering precise control over film properties and enabling a wide range of applications in electronics, optics, energy, healthcare, and beyond. The continued research and development in this field promise to drive innovation and shape various industries in the future.

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References

1. Chaudhari, M.N., Ahirrao, R.B. and Sanabhau, D.B., 2021. Thin film Deposition Methods: A Critical Review. *International Journal for Research in Applied Science & Engineering*, *9*, pp.5215-5232.
2. Budida, J. and Srinivasan, K., 2023. Review of thin film deposition and techniques. *Materials Today: Proceedings*.
3. Mehla, S., Das, J., Jampaiah, D., Periasamy, S., Nafady, A. and Bhargava, S.K., 2019. Recent advances in preparation methods for catalytic thin films and coatings. *Catalysis Science & Technology*, *9*(14), pp.3582-3602.
4. Özakar, R.S. and Özakar, E., 2021. Current overview of oral thin films. *Turkish journal of pharmaceutical sciences*, *18*(1), p.111.
5. Hardwick, D.A., 1987. The mechanical properties of thin films: a review. *Thin solid films*, *154*(1-2), pp.109-124.
6. Abegunde, O.O., Akinlabi, E.T., Oladijo, O.P., Akinlabi, S. and Ude, A.U., 2019. Overview of thin film deposition techniques. *AIMS Materials Science*, *6*(2), pp.174-199.
7. Wang, H., 2011. Progress in thin film solar cells based on. *International journal of Photoenergy*, *2011*.
8. Reichelt, K. and Jiang, X., 1990. The preparation of thin films by physical vapour deposition methods. *Thin solid films*, *191*(1), pp.91-126.
9. Rim, Y.S., 2020. Review of metal oxide semiconductors-based thin-film transistors for point-of-care sensor applications. *Journal of Information Display*, *21*(4), pp.203-210.
10. Pevzner, S., Regev, O. and Yerushalmi-Rozen, R., 1999. Thin films of mesoporous silica: preparation and characterization. *Current opinion in colloid & interface science*, *4*(6), pp.420-427.
11. Mathew, X., Thompson, G.W., Singh, V.P., McClure, J.C., Velumani, S., Mathews, N.R. and Sebastian, P.J., 2003. Development of CdTe thin films on flexible substrates—a review. *Solar Energy Materials and Solar Cells*, *76*(3), pp.293-303.
12. Li, W.J., Tu, M., Cao, R. and Fischer, R.A., 2016. Metal–organic framework thin films: electrochemical fabrication techniques and corresponding applications & perspectives. *Journal of Materials Chemistry A*, *4*(32), pp.12356-12369.

13. Baptista, A., Silva, F., Porteiro, J., Míguez, J. and Pinto, G., 2018. Sputtering physical vapour deposition (PVD) coatings: A critical review on process improvement and market trend demands. *Coatings*, *8*(11), p.402.
14. Selvakumar, N. and Barshilia, H.C., 2012. Review of physical vapor deposited (PVD) spectrally selective coatings for mid-and high-temperature solar thermal applications. *Solar energy materials and solar cells*, *98*, pp.1-23.
15. Carlsson, J.O. and Martin, P.M., 2010. Chemical vapor deposition. In *Handbook of Deposition Technologies for films and coatings* (pp. 314-363). William Andrew Publishing.
16. Sherman, A., 1987. Chemical vapor deposition for microelectronics: principles, technology, and applications.
17. Sahu, N., Parija, B. and Panigrahi, S., 2009. Fundamental understanding and modeling of spin coating process: A review. *Indian Journal of Physics*, *83*(4), pp.493-502.
18. Tyona, M.D., 2013. A comprehensive study of spin coating as a thin film deposition technique and spin coating equipment. *Advances in materials Research*, *2*(4), p.181.
19. Ezekoye, B.A., Offor, P.O., Ezekoye, V.A. and Ezema, F.I., 2013. Chemical bath deposition technique of thin films: a review. *International Journal of Scientific Research*, *2*(8), pp.452-456.
20. Hodes, G., 2007. Semiconductor and ceramic nanoparticle films deposited by chemical bath deposition. *Physical Chemistry Chemical Physics*, *9*(18), pp.2181-2196.
21. Nair, P.K., Nair, M.T.S., Garcıa, V.M., Arenas,´.O., Pena, Y., Castillo, A., Ayala, I.T., Gomezdaza, O., Sanchez, A., Campos, J.J.S.E.M. and Hu, H., 1998. Semiconductor thin films by chemical bath deposition for solar energy related applications. *Solar Energy Materials and solar cells*, *52*(3-4), pp.313-344.
22. Leskelä, M. and Ritala, M., 2003. Atomic layer deposition chemistry: recent developments and future challenges. *Angewandte Chemie International Edition*, *42*(45), pp.5548-5554.
23. Oviroh, P.O., Akbarzadeh, R., Pan, D., Coetzee, R.A.M. and Jen, T.C., 2019. New development of atomic layer deposition: processes, methods and applications. *Science and technology of advanced materials*, *20*(1), pp.465-496.
24. Leskelä, M. and Ritala, M., 2002. Atomic layer deposition (ALD): from precursors to thin film structures. *Thin solid films*, *409*(1), pp.138-146.
25. Lokhande, C.D. and Pawar, S.H., 1989. Electrodeposition of thin film semiconductors. *Physica Status Solidi A*, *111*(1), pp.17-40.
26. Saloniemi, H., Kanniainen, T., Ritala, M. and Leskelä, M., 1998. Electrodeposition of PbTe thin films. *Thin Solid Films*, *326*(1-2), pp.78-82.
27. Karuppuchamy, S., Nonomura, K., Yoshida, T., Sugiura, T. and Minoura, H., 2002. Cathodic electrodeposition of oxide semiconductor thin films and their application to dye-sensitized solar cells. *Solid State Ionics*, *151*(1-4), pp.19-27.
28. Nur, U.S., Ying, K.K. and Khuan, N.I., Electrodeposition: Principles, Applications and Methods.
29. Cho, A.Y., 1979. Recent developments in molecular beam epitaxy (MBE). *Journal of Vacuum Science and Technology*, *16*(2), pp.275-284.
30. Ginley, T.P., Wang, Y. and Law, S., 2016. Topological insulator film growth by molecular beam epitaxy: A review. *Crystals*, *6*(11), p.154.
31. Wang, X. and Yoshikawa, A., 2004. Molecular beam epitaxy growth of GaN, AlN and InN. *Progress in crystal growth and characterization of materials*, *48*, pp.42-103.
32. Nunn, W., Truttmann, T.K. and Jalan, B., 2021. A review of molecular-beam epitaxy of wide bandgap complex oxide semiconductors. *Journal of materials research*, pp.1-19.
33. Perednis, D. and Gauckler, L.J., 2005. Thin film deposition using spray pyrolysis. *Journal of electroceramics*, *14*, pp.103-111.
34. Jung, D.S., Park, S.B. and Kang, Y.C., 2010. Design of particles by spray pyrolysis and recent progress in its application. *Korean Journal of Chemical Engineering*, *27*, pp.1621-1645.
35. Falcony, C., Aguilar-Frutis, M.A. and García-Hipólito, M., 2018. Spray pyrolysis technique; high-K dielectric films and luminescent materials: a review. *Micromachines*, *9*(8), p.414.
36. Ukoba, K.O., Eloka-Eboka, A.C. and Inambao, F.L., 2018. Review of nanostructured NiO thin film deposition using the spray pyrolysis technique. *Renewable and Sustainable Energy Reviews*, *82*, pp.2900-2915.

37. Tomar, M.S. and Garcia, F.J., 1981. Spray pyrolysis in solar cells and gas sensors. *Progress in Crystal Growth and Characterization*, *4*(3), pp.221-248.
38. Stoian, M., Maurer, T., Lamri, S. and Fechete, I., 2021. Techniques of Preparation of Thin Films: Catalytic Combustion. *Catalysts*, *11*(12), p.1530.
39. Siciliano, P., 2000. Preparation, characterisation and applications of thin films for gas sensors prepared by cheap chemical method. *Sensors and Actuators B: Chemical*, *70*(1-3), pp.153-164.
40. Ferlauto, A.S., Ferreira, G.M., Pearce, J.M., Wronski, C.R., Collins, R.W., Deng, X. and Ganguly, G., 2002. Analytical model for the optical functions of amorphous semiconductors from the near-infrared to ultraviolet: Applications in thin film photovoltaics. *Journal of Applied Physics*, *92*(5), pp.2424-2436.