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JOURNAL`S UNIVERSITY OF BABYLON FOR ENGINEERING SCIENCES (JUBES)
مـــجلـة جـــامعة بـــــابـل للعلـــــوم الهندسية
Vol. 33, No.5. \ 2025 ISSN: 2616 - 9916

Nanocoating Techniques of Thin Films: A Comprehensive Review

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Received:	9/9/2025	Accepted:	28/10//2025	Published:	30/10/2025

Abstract

Thin films are crucial nanostructures that form the essential foundation for innovations in electronics, energy, catalysis, and biomedicine. Their fabrication technique directly influences their morphology, crystallinity, and function, determining device performance. This review focuses on thin film deposition and fabrication techniques, providing a comparative overview of the significance of nanomaterials and their associated synthesis procedures, including physical vapor deposition PVD, chemical vapor deposition CVD, solution-based deposition SBD, hydrothermal processing, and green synthesis. The surface properties and efficiencies of materials significantly influence their performance, as supported by comparative tables and schematics. Metallic thin film forming chemicals, such as chalcogenide precursors, are used in cutting edge applications in various fields. Applications in solar energy, catalysis, sensing, biomedicine, optoelectronics, solar cells, selective solar coatings, solid state solar cells, photochemical solar cells, photoconductors, optical imaging, holographic recording, and all optical storage systems are mentioned. These applications can be attained by modifying surfaces with coatings to fabricate thin films. The current challenges, such as environmental concerns, reproducibility, and scalability, are identified, while offering a viewpoint on hybrid approaches and green nanotechnology.

Keywords: Synthesis, Nanocoating, Fabrication, Thin Films, PVD, CVD, SBD, Solar Cells.

1. Introduction

Thin film deposition is a technology that involves applying a super thin, single layer of material. Thin films represent two critical dimensions of nanomaterials of thicknesses from a few nanometers to several micrometers, which are vitally important in photovoltaics, optoelectronics, and protective coatings [1]–[3]. Thin films, generally less than 100 nm thick or only a few atomic layers, are deposited onto a substrate or an existing coating to create nanostructured layers. These films exhibit size-dependent electronic, optical, and catalytic behaviors arising from their high surface-to-volume ratio and pronounced quantum confinement effects [4], [5]. The controlled synthesis of these nanostructures is central to performing targeted functionalities. Thin films excel in providing uniform, stable coatings, enhanced reactivity and tunability. Their comparative study not only clarifies their distinct roles but also illuminates hybrid opportunities for advanced applications [6]. There are several factors contributing to this limitation. First, many deposition methods demand relatively large amounts of precursor materials. Second, the reproducibility of results can often be challenging. Third, most techniques are unsuitable for the small-scale conditions typical of laboratory research. Consequently, the approaches explored are generally more appropriate for fabricating individual, small-area substrates, utilizing methods such as spin coating, doctor blading, and casting, among others [7].

Preparing thin films is currently attractive owing to their relative simplicity, inexpensiveness, and advantages over large area deposition. Since these techniques are performed at low-temperatures, the substrate exhibits antioxidant behavior, helping prevent rust. This technique is compatible with a wide variety of substrates, including semiconductors such as silicon, insulating materials like glass, and various metals. These are sequential procedures that permit crystals to acquire an improved grain structure and optimal orientation. The thin film deposition mechanism is based on constructing a layer or layers on the desired substrate in a thickness range from multiples of angstroms to microns, subjected to the distinct experimental conditions [1], [2], [5]. Film growth on substrates can occur through adsorption of colloidal particles, in which growth proceeds cluster by cluster, or by the condensation of ions directly from the solution phase or complex state in an ion-by-ion process, depending on the deposition environment [6]. The quality and characteristics of thin film deposition or coating are influenced by several factors, including substrate temperature, deposition rate, chamber pressure, and other processing conditions [8]. Significant efforts have been made to reduce the cost of photovoltaic and optoelectronic consumer products, to enhance affordability and marketability. A viable approach to attain this is by using thin films instead of bulk crystals in these devices. Bakly et al. reported that synthesizing new materials to produce highly efficient thin films for such devices remains a major challenge in scientific research today [5], [8]. The controlled synthesis of thin films through deposition processes plays a vital role in various industrial applications.

In general, thin film deposition techniques are categorized into three main classes: physical vapor deposition PVD, chemical vapor deposition CVD, and solution-based deposition SBD. Each technique offers distinctive and competitive advantages concerning film quality, cost, and scalability. The classification of techniques utilizes vacuum evaporation, chemical vapor deposition[1], electrodeposition[9], and solution-based deposition, which includes chemical bath deposition CBD [10]. Solution-based deposition SBD is a low-cost solution-based technique used to prepare thin films. Unlike physical vapor deposition PVD and chemical vapor deposition CVD, solution-based deposition SBD improves crystal orientation and grain structure, albeit at a relatively slow rate. Thin films fabricated via solution-based deposition SBD are being developed for applications in solar energy and photonics, including both photothermal and photovoltaic energy conversion technologies [10].

The development of thin-film fabrication methods has progressed over nearly two centuries, beginning with the earliest demonstrations of physical vapor deposition (PVD) in the mid-19th century, when Grove and Faraday first reported the vaporization of metal under low pressure, laying the foundation for modern vacuum deposition techniques [11]. Chemical vapor deposition (CVD) emerged later in the 1950s and 1960s with the advancement of semiconductor manufacturing, particularly following the pioneering work of Derjaguin and colleagues, who established CVD as a major route for the development of silicon semiconductors and high-purity composites [12]. Solution-based deposition (SBD) methods, including sol-gel and spin-coating, developed rapidly during the 1970s and 1980s due to their low cost, tunability, and suitability for anodized thin films and nanostructures [13]. Although hydrothermal processing was first mentioned by Clarence in 1941 for the manufacture of quartz, it evolved into a versatile approach for manufacturing nanomaterials during the 1990s with the advent of high-pressure sterilizers and controlled precursor chemistry [14]. More recently, green manufacturing techniques have gained increasing momentum since the mid-2000s, utilizing plant extracts, microorganisms, and biomolecules as reducing and stabilizing agents to produce environmentally friendly nanocoating with low chemical risks [15]. These developments collectively reflect a continuous evolution from high-energy vacuum-based technologies to more sustainable, tunable, and scalable nanomaterial fabricating methods.

The controlled synthesis of materials into thin films, known as deposition, is essential in many applications [1], [2], [5]. At present, synthesizing new materials for high efficiency thin film solar cells is a major challenge in scientific research. Semiconductors made from elements abundant on Earth could enhance the sustainability of photovoltaic technology. Figure 1 and Table 1 illustrate nanomaterials used as thin films in advanced energy and nanotechnology applications, showing the effect of doping ratio "**x**" on unit cell volume "**a**". Many deposition techniques, including atomic layer epitaxy (atomic layer deposition), rely on precise control of the nucleation process. The process can be described by examining key surface phenomena, including adsorption, desorption, and surface diffusion.

Thin films composed of mixed or doped materials, such as $Cd_{1-x}Zn_xS$, are particularly appealing because their physical and electronic properties fall between those of the parent compounds "CdS and ZnS". This alloyed semiconductor is a valuable transparent metal sulfide for photovoltaic applications, serving effectively as a window layer due to its low ultraviolet absorption and wide band gap, typically exceeding 2.4 eV. Moreover, $Cd_{1-x}Zn_xS$ exhibits good lattice compatibility with CdS/CdTe and CIGS structures, see Figure 1. These films can generate built-in electric fields at heterojunction interfaces, function as buffer layers within solar cells, and provide low resistivity that enhances overall junction performance [5].

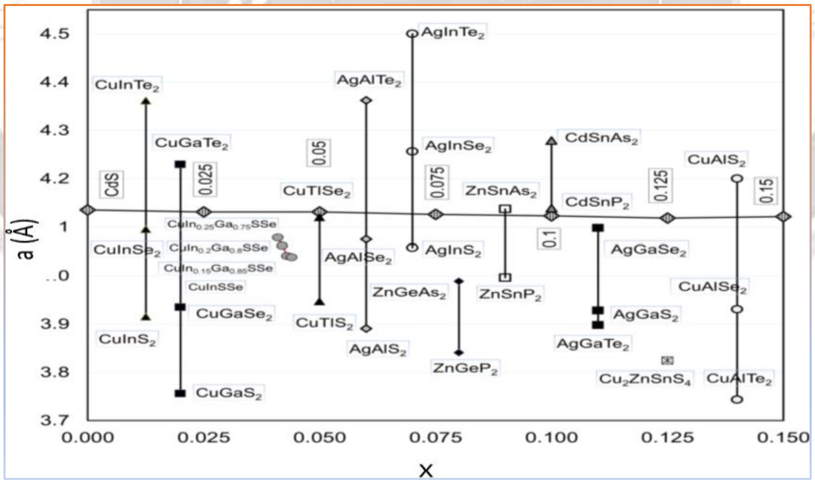

Figure 1. Thin films of different nanomaterials are used in energy applications, reproduced with permission from reference [5].

A variety of materials employed in different nanostructured systems, including photovoltaics, sensors, and diagnostic devices, are presented in Figure 1 and Table 1. Meanwhile, a summary of thin films fabricated by various techniques, along with their applications in the field of nanostructures, is provided in Table 2.

Table 1. Summary of thin films fabricated by different techniques along with their applications.

#	Thin Films	Fabrication Method	Applications	Ref.
1	ZnS/CdS	Spin coating	Solar cells	[8]
2	ZnO/CuO	Spin coating	Solar cells	[16]
3	BaS/Sb_2S_3	Spin coating	Photovoltaics, sensors, & optoelectronics,	[17]
4	IGZO/ZnO/Cu_2O: N	DC magnetron sputtering	Solar cells	[18]
5	TiO_2	Atomic layer deposition	Biomedical	[19]
6	SnO_2-Mn_2O_3	Aerosol assisted chemical vapor deposition (AACVD)	Photovoltaic	[20]
7	CeO_2-TiO_2	Aerosol assisted chemical vapor deposition (AACVD)	Photoelectrochemical	[21]
8	Co-Ti-O	Sol-gel	Photocatalytic activity	[22]
9	Ag-Cu_2O-CuO	RF magnetron sputtering	Photocatalytic & catalytic	[23]
10	$CuCrO_2$	Spin coating	Transistors	[24]
11	CdZnO	Spray pyrolysis	Optoelectronics	[25]
12	CdZnS	Spin coating	Solar cells	[5]
13	NiO-CuO-ZnO	Drop casting	Electrocatalyst	[26]
14	ZnO: F	LPCVD	Photodetectors and solar cells	[27]

The types of thin films used in various applications, especially in solar cell fabrication and photovoltaic applications, are presented in Table 2.

Table 2. Applications of thin films.

Thin Film	Application	Thin Film	Application	Thin Film	Application	Thin Film	Application
Epi-Si	*Semiconductor material*	a-Si	*Solar cells*	Ge	*Tunnel diodes, solar cells*	SiC	*Protective against oxidation*
BN	*Diffusion source, crucible material*	BP	*Photovoltaics*	AlN	*Dielectric, piezoelectric for acoustic wave beam*	AlP	*Electroluminescent diodes*
AlAs	*Electroluminescent diodes, solar cells*	AlSb	*Solar cells*	GaN	*Electroluminescent diodes*	GaP	*Electroluminescent diodes*
ZnSe	*Photoconductor, laser diodes*	ZnTe	*Electro-optical applications*	CdS	*Photoconductors, laser diodes, solar cells, detectors*	$CdS_{1-x}Se_x$	*Lasers*
$Zn_{1-x}Cd_xS$	*Lasers*	$Cd_{1-x}Hg_xTe$	*Photoconductors, laser, photo diodes*	$Pb_{1-x}Sn_xTe$	*Photoconductors, laser, photo diodes*	$Pb_{1-x}Sn_xSe$	*Lasers*
PbS	*Photoconductors, lasers*	PbTe	*Infrared detectors*	$PbS_{1-x}Se_x$	*Lasers*	PbSe	*Lasers*
PbO	*Photoconductors*	SiO_2; PSG; BSG	*ASG passivation, etching mask, gate dielectric in MOS structure*	Si_3N_4	*Diffusion/oxidation masks, anti-reflection coatings in solar cells*	GaAs	*Semiconductor material*
GaSb	*Laser diodes*	InP	*Gun diodes, laser diodes*	InAs	*Laser diodes, Hall effect diodes*	InSb	*Photo electrodes*
$GaAs_{1-x}P_x$	*High temp. rectifiers, electroluminescent, laser diodes*	$InAs_{1-x}P_x$	*Photo cathodes, electro-optical applications*	$InAs_{1-x}Sb_x$	*Laser diodes*	$GaAs_{1-x}Sb_x$	*Laser diodes, photo cathodes*
$Ga_{1-x}In_xAs$	*Laser diodes, photo cathodes*	$Ga_{1-x}In_xP$	*Luminescent diodes*	$Ga_{1-x}Al_xAs$	*Laser diodes, solar cells*	$In_{1-x}Al_xP$	*Electroluminescent diodes, laser diodes*

These films include a wide range of materials such as metal oxides, chalcogenides, perovskites, and organic semiconductors, each offering unique optical, electrical, and structural properties.

2. Thin Film Fabrication Techniques

Thin films are efficiently fabricated using a variety of techniques, including physical vapor deposition PVD, chemical vapor deposition CVD, and solution-based deposition SBD. The PVD, containing thermal evaporation and sputtering, requires a physical transfer of the material from source to substrate in a vacuum environment, as illustrated in Figure 2. Nevertheless, the CVD depends on the chemical reactions of volatile precursors at high temperature, in most cases ranging between 300–1100 °C. In turn, the CVD involves specific methods that include low-pressure chemical vapor deposition (LPCVD), plasma-enhanced chemical vapor deposition (PECVD), metal-organic chemical vapor deposition (MOCVD), and atomic layer deposition (ALD), each of which offers distinct advantages for thin film growth. Conversely, solution-based deposition SBD is a solution-based chemical method which is different from vapor-based PVD and CVD techniques. These techniques differ in terms of deposition time, film quality, efficiency, cost, and application, with particular emphasis on the surface coating methods employed during the deposition process. A general comparison of PVD, CVD, and SBD methods is provided in Table 2. This field focuses specifically on the growth of thin films with thicknesses less than ten micrometers. Various techniques are used to grow films at the nano and micro scales, particularly in the solar cell industry.

Table 2. Comparison of PVD, CVD, and SBD techniques.

Technique →	Physical Vapor Deposition **PVD**	Chemical Vapor Deposition **CVD**	Solution-Based Deposition **SBD**
Type	Physical	Chemical	Chemical
Phase	Vapor	Vapor	Solution
Temperature	Often high	High (300–1100 °C)	No heat or low (< 100 °C)
Environments	Vacuum/Controlled Atmosphere	Aqueous/Ambient High temp/gas	Aqueous
Reaction Mechanism	Physical deposition of particles	Surface chemical reaction	Chemical deposition of particles

A. Physical Vapor Deposition PVD

In the physical vapor deposition PVD method, there are no chemical reactions that occur during the process. Rather, the source material is vaporized in a vacuum environment and condensed on the substrate [28]. The material transfer is simply physical, with atoms or molecules moving from the source to the substrate in the absence of any chemical transformation. The temperature of the evaporation process is medium to high, depending on the method. These are often done under controlled vacuum or in low-pressure gas. The quality of fabricated film has high control over film thickness and uniformity. Typically, the process is employed for depositing thin films ranging from 10 to 10,000 nm in thickness. PVD enables dense, uniform films, but requires costly vacuum systems and is less suited for large areas. These processes are versatile and can be used for various applications, including multilayer deposition coating, very thick deposits with graded compositions, free standing, and hybrid structure formation. Three fundamental steps of physical vapor deposition follow [29]–[32].

The film fabrication processing by PVD includes several steps, which are initially the generation of vapors phase species, transportation of atoms/molecules from source to substrate, and finally, film growth on the surface [33]. Physical Vapors Deposition PVD consists of various deposition techniques, as classified in Figure 2.

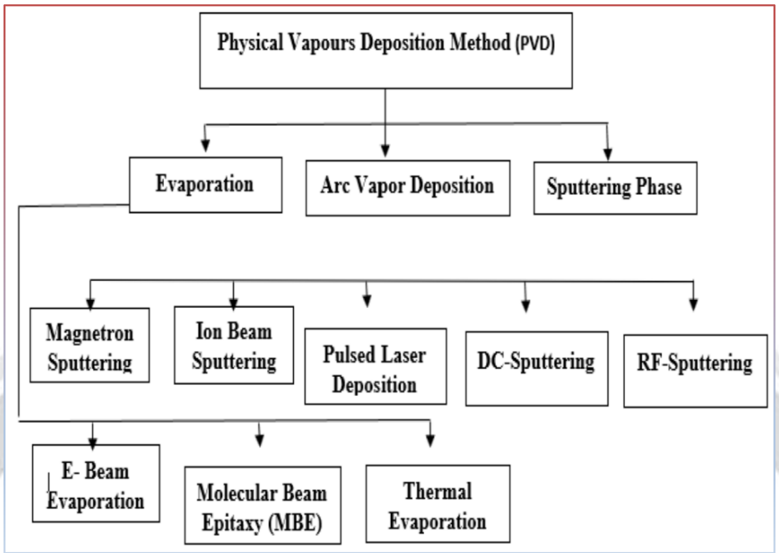

Figure 2. Classification of PVD techniques, reproduced with permission from reference [34].

As shown in Figure 2, the PVD method can be classified into four main techniques as follows:

1) Thermal Evaporation Technique

Thermal evaporation is a physical vapor deposition procedure, in which a solid material, typically in powder or particle form, is heated above its melting/sublimation temperature in a high-vacuum environment with unreactive gases. The source material is placed in a vessel or container and heated over a resistive heating element until vaporization. As a result of the vacuum and the relatively low substrate temperature, the vaporized atoms proceed right at the substrate, typically following a line-of-sight path. Upon reaching the surface, the vapor condenses and solidifies, slowly building a thin, uniform film across successive deposition cycles [35]. In addition to its advantages, the method exhibits several limitations, including poor step coverage, restricted use with high-melting-point materials, potential contamination arising from reactions between the crucible and the source material, and difficulty in maintaining stoichiometric accuracy for multicomponent systems [11]. Control of crystal growth during deposition can be achieved by regulating the substrate temperature, deposition rate, chamber vacuum, and source–substrate distance, while post-deposition annealing is often employed to enhance crystallinity and reduce defect densities [36]. Previous studies have confirmed these effects; for example, thermally evaporated CdS films showed improved crystalline orientation and a slight reduction in optical band gap when higher substrate temperatures were applied, demonstrating the crucial role of adatom mobility in defining the final film structure. Figure 3 illustrates the basic mechanism of the thermal evaporation deposition method.

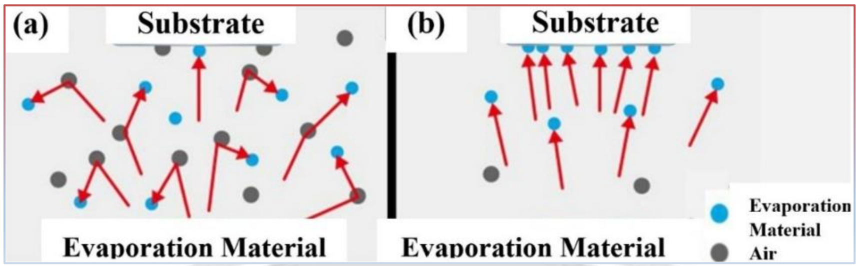

Figure 3. The mechanism of the thermal evaporation technique for thin film preparation in the presence of (a) air and (b) vacuum [37].

As shown in Figure 3, the material in the thermal evaporation technique is intended to be heated until it evaporates. This is followed by deposition as a condensed layer on a cooler substrate in a low-pressure environment under atmosphere (a) or vacuum (b).

2) Sputtering

The sputtering method is a physical vapor deposition, in which the atoms are ejected from a solid target by bombarding it with high-energy ions under an inert atmosphere, usually Ar+ gas. These atoms condense on the substrate to form a film [38]. Figure 4 illustrates the basic mechanism of the vapor deposition using the sputtering method.

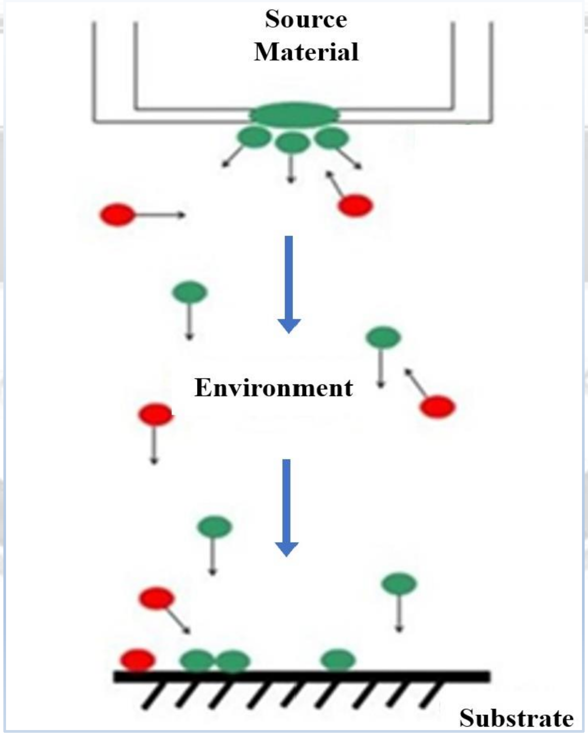

Figure 4. Vapor deposition for thin film preparation by the sputtering method [39].

As illustrated in Figure 4, thin film evolution takes place along a rapid material transfer mechanism, where energetic atoms or molecules are sputtered from the solid target surface. These filtered molecules of a broad distribution of kinetic energies travel through the chamber toward the substrate. Upon arrival, they condense and accumulate, resulting in the growth of dense, uniform thin films that take advantage of the inherent strengths of this deposition method.

3) Pulsed Laser Deposition PLD

In the pulsed laser deposition (PLD) technique, both the target and the substrate are situated inside a vacuum chamber to clear interference from the surrounding atmosphere. A focused pulsed laser beam is placed into the chamber via a specially designed window or aperture, ensuring accurate interaction with the target material [40].

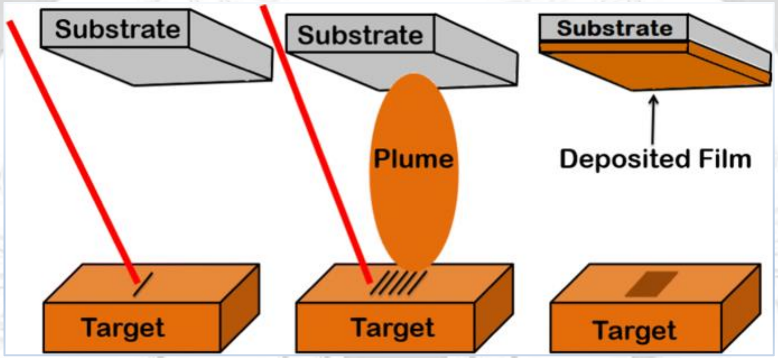

Figure 5. Pulsed laser deposition technique, reproduced with permission from reference [41].

In this method, intense laser pulses are focused onto a target material, generating a plasma plume that transfers and deposits onto the substrate surface. The fundamental working principle of pulsed laser deposition PLD is depicted in Figure 5. PLD is widely employed in the fabrication of microelectronic devices, hybrid materials, superconducting films, optical coatings, and various thin film systems. Unlike many other deposition techniques, PLD offers the distinct advantage that its energy source, the laser, is located outside the vacuum chamber, while still enabling the ablation of nearly all condensed materials [42].

4) Electron Beam Evaporation

The electron beam evaporation method is a physical vapor deposition PVD technique that enables rapid film growth at somewhat low substrate temperatures. It accomplishes deposition rates that range approximately between 0.1–100 m/min. The process occurs under high vacuum conditions, typically around 10–5 torr. An electron beam produced by passing a 5–10 kV current through a heated tungsten filament is directed toward the target material, causing it to evaporate. This method is widely applied in the fabrication of fuel cells, solar absorber layers, biomedical coatings, thermal barriers, wear-resistant, hard coatings, and thin film photovoltaic devices [43]–[45]. Figure 6 illustrates the basic mechanism of thin film deposition using the electron beam evaporation technique. Despite its advantages, this method exhibits some drawbacks, including the potential for substrate damage from high-energy electron bombardment, its limited suitability for materials with low thermal conductivity, and the possibility of non-uniform heating, which can affect the evaporation rate and film quality [46]. Crystal growth during electron beam evaporation can be modified by controlling the substrate temperature, deposition rate, vacuum level, and beam power, while post-deposition annealing is often used to improve grain structure and reduce internal stresses [47]. Previous studies have demonstrated these effects; for example, evaporated TiO2 thin films exhibited improved crystallinity and enhanced optical transmittance when deposited at elevated substrate temperatures, highlighting the crucial role of recycled atomic motion and controlled energy input in determining film structure and properties

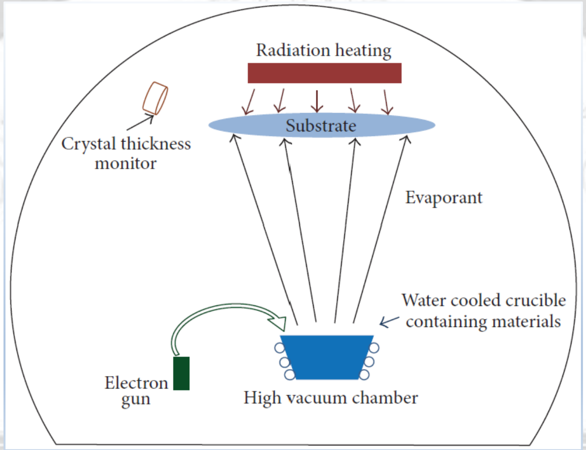

Figure 6. Thin film deposition by the electron beam technique [48].

As shown in Figure 6, a focused electron beam (electron gun) heats the source material, essentially placed in water-cooled crucible, causing it to vaporize and deposit on the substrate.

5) High-Power Impulse Magnetron Sputtering (HiPIMS).

High-power pulsed magnetic spraying (HiPIMS) is an advanced physical vapor deposition (PVD) technique that uses short, high-energy voltage pulses to generate a highly ionized metallic plasma, resulting in dense, smooth, and highly adhesive thin films. The high ionization rate enables better control over the microstructure compared to conventional DC sputtering, resulting in compact, column-free coatings. Studies show that HiPIMS films typically exhibit surface roughness values below 2 nm (RMS), depending on the pulse energy and substrate bias conditions [49]. Atomic force microscope (AFM) images typically show fine-grained, uniform surfaces with significantly fewer nodal defects compared to conventional sputtering. These properties make HiPIMS an ideal choice for applications requiring high-performance barrier layers, rigid coatings, and optical films.

B. Chemical vapor Deposition CVD

CVD is a technology that depends on chemical reactions of volatile precursors at high temperatures, 300–1100 °C. The technology consists of low-pressure chemical vapor deposition LPCVD, plasma enhanced chemical vapor deposition PECVD, metal-organic chemical vapor deposition MOCVD, and atomic layer deposition ALD. It is a self-limiting process that permits material thickness control down to sub-nanometers. CVD is scalable and it permits the production of materials from semiconductors to carbon nanostructures, even if it often involves hazardous precursors. One of these techniques, LPCVD, offers uniform film thickness and excellent step coverage, making it suitable for large area coatings.

PECVD operates on the substrate at low temperatures by plasma activation, allowing deposition onto heat sensitive materials such as polymers or glass. MOCVD is commonly used in the fabrication of semiconductors such as GaAs and GaN, which are vital materials in LEDs and high frequency electronic devices.

Atomic layer deposition ALD offers accurate composition at the atomic-level, which is particularly valuable for nanostructured and conformal coatings in advanced microelectronics and photovoltaics. ALD is a vapor-phase technique that relies on self-limiting, sequential surface reactions, enabling precise control of layer thickness at the atomic level and achieving exceptional film conformability, even on high-aspect-ratio or porous substrates. This technique produces ultrathin films with precise stoichiometry and unparalleled smoothness, often achieving surface roughness below 1 nm “root mean square (RMS) roughness” due to its layer-by-layer growth mechanism [50]. Atomic force microscopy (AFM) studies frequently reveal near-flat surfaces with uniform atomic terraces and extremely low boundary grain density. ALD has become essential in the fabrication of semiconductor devices, gate insulators, diffusion barriers, and emerging energy materials, where defect-free ultrathin coatings are critical.

Despite its versatility, chemical vapor deposition (CVD) also exhibits several drawbacks, including high processing temperatures, the need for complex gas-processing systems, the potential for contamination from secondary feedstock byproducts, and the difficulty of maintaining uniform consistency across large substrates [51]. Crystal growth in CVD can be regulated by adjusting the feedstock flow rate, chamber pressure, substrate temperature, and gas-phase reaction kinetics, while post-deposition annealing is often used to enhance grain size, reduce defects, and improve film consistency [50]. Previous studies have demonstrated these effects; for example, studies on GaN films grown using MOCVD reported improved crystal quality, reduced dislocation density, and increased light emission when higher substrate temperatures and optimized feedstock ratios were used, highlighting the crucial influence of controlled reaction conditions on the final film properties. Overall, the versatility and ease of control of chemical vapor deposition techniques make them indispensable for the fabrication of modern thin films in energy, optoelectronics, and nanotechnology applications [11], [52], [53].

C. Solution-Based Deposition SBD

Solution-based deposition (SBD) methods operate at low temperatures and offer broad substrate compatibility, making them attractive for flexible and large area device fabrication [13]. Such techniques include spin coating for organic films, perovskites, and polymer-based solar cells; dip coating for sol–gel and protective oxide layers; spray coating for large-area photovoltaics and transparent conductive films; chemical bath deposition CBD for chalcogenide semiconductors like CdS, CdSe, and PbS; and successive ionic layer adsorption and reaction SILAR for controlled layer-by-layer growth of semiconductor films [13], [54], [55]. Other related SBD techniques include inkjet printing, which enables patterned thin film deposition with minimal material waste, doctor blade coating, widely used for perovskite as well as dye sensitized solar cell fabrication, and plasma electrolytic oxidation (PEO) is used to create thick, ceramic-like oxide layers on certain metals such as Ti, Mg, and Al.

These techniques are economical, scalable, and suitable for both rigid and flexible substrates, enabling the economical production of thin films without the need for high vacuum systems. Achieving high film homogeneity, high adhesion strength, and high reproducibility often requires optimizing parameters such as solution concentration, viscosity, deposition rate, and annealing temperature. In particular, controlling solvent evaporation dynamics and precursor chemistry is critical to preventing defects such as pinholes or roughness. Despite these challenges, solution-based methods continue to play a key role in next-generation photovoltaic devices, transparent electrodes, and sensing technologies due to their simplicity, environmental friendliness, and manufacturing compatibility [35], [56].

1) Spin Coating Method

In this process, a measured amount of solution is spread onto the substrate and then spun at a speed, typically between 500 and 8,000 rpm, to spread the liquid. This technique is used to deposit thin, uniform films from liquid precursors onto a flat substrate using centrifugal force. The solid film formation is achieved via solvent evaporation during spinning results. The final thickness is influenced by the spinning speed, solution viscosity, concentration, and solvent properties. Spin coating has been effectively employed to fabricate a variety of thin films, such as cadmium zinc sulfide ($Cd_{1-x}Zn_xS$) layers [5], bis(O-alkylxanthato) derived CdS and ZnS films [8], and functional electronic thin films for optoelectronic applications [17]. This technique provides excellent thickness uniformity, surface smoothness, and reproducibility, making it ideal for research scale deposition. Post-deposition thermal treatment is often applied to improve crystallinity, adhesion, and electronic properties. Despite its advantages, spin coating is less suitable for large-area fabrication due to material wastage. Figure 7 illustrates the basic mechanism of the spin coating deposition technique.

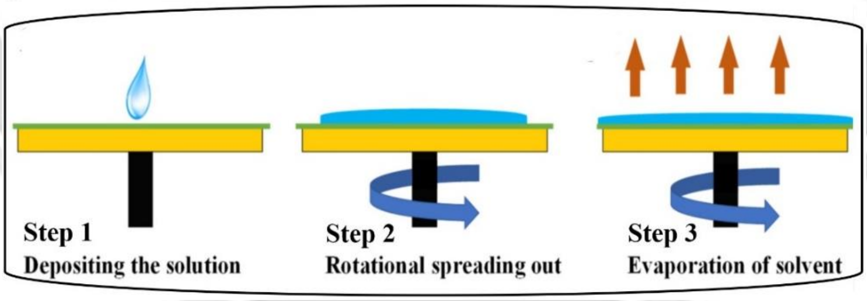

Figure 7. Steps of spin coating of a thin film on a substrate, reproduced with permission from reference [57].

2) Dip Coating

The dip coating technique is simple and is usually utilized for coating substrates with thin films. The process requires dipping a substrate into a solution or suspension containing the desired material and withdrawing samples at a controlled speed, allowing the formation of a uniform layer on the surface. The thickness of the produced film is determined by factors such as viscosity, surface tension, “capillary forces”, and gravitational effects. Additionally, the fluid dynamics of the liquid bath and the surrounding gas atmosphere significantly affect both the film thickness and uniformity. The use of volatile solvents and rapid, well-controlled drying typically leads to the formation of thicker coatings. Figure 8 illustrates the basic mechanism of the dip coating deposition method.

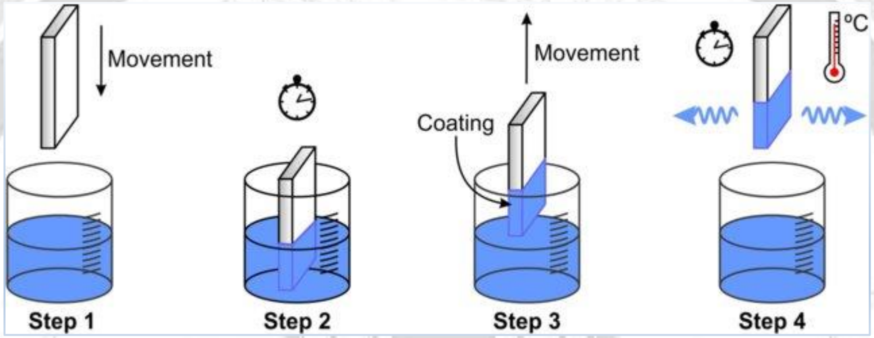

Figure 8. A step-by-step process of thin film formation using the dip coating method, reproduced with permission from reference [58].

Dip coating results in a uniform thin film of liquid deposition upon the substrate, suitable for small slabs and cylinders. Dip coating is commonly used in various industries, including electronics, optics, coatings and nanotechnology [59].

3) Spray coating

This technique is used to deposit thin films of materials onto substrates by spraying a liquid precursor or dispersion onto the substrate surface. This method is often used in a variety of applications, including coatings, optics, electronics, and biomedical. The spray coating goes through a series of distinct stages, beginning with the atomization of the liquid precursor material into fine droplets. The droplets evaporate, impact the substrate surface, spread out, dry, and solidify. The process ultimately leads to the formation of adherent layers, ensuring proper bonding between the deposited solar cell materials and the underlying substrate [60]. In contrast, the spray coating process involves several sequential steps: the atomization of a precursor solution into fine droplets, partial evaporation of these droplets during flight, their impact upon the substrate surface, followed by dynamic spreading, wetting, and coalescence. These stages collectively lead to uniform film formation and subsequent drying to produce a continuous coating layer [61]. Figure 9 illustrates the basic mechanism of the spray coating method.

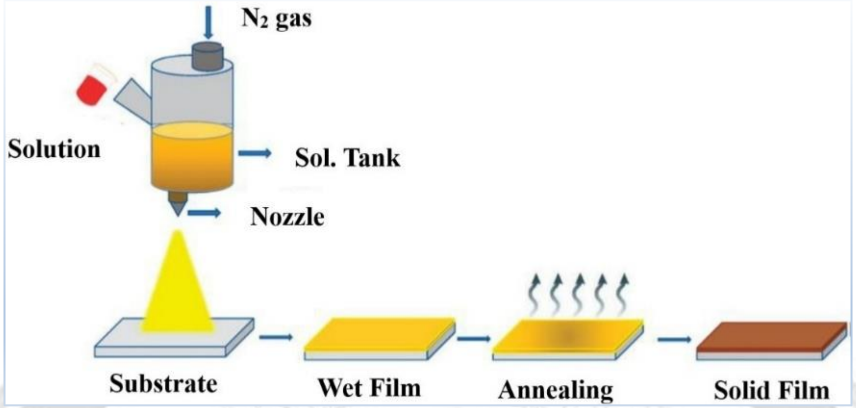

Figure 9. Schematic diagram of the spray coating method, reproduced with permission from reference [62].

4) SILAR Method

The SILAR method, (Successive Ionic Layer Adsorption and Reaction) is classified as a chemical deposition technique, solution-based chemical. Figure 10 illustrates the basic mechanism of the SILAR method. The method is a thin-film deposition technique used to grow thin films with controlled thickness and composition, particularly for semiconductor materials and solar cell applications. SILAR is based on the sequential adsorption of precursor ions or molecules onto a substrate surface, followed by a chemical reaction to form a thin film layer [63].

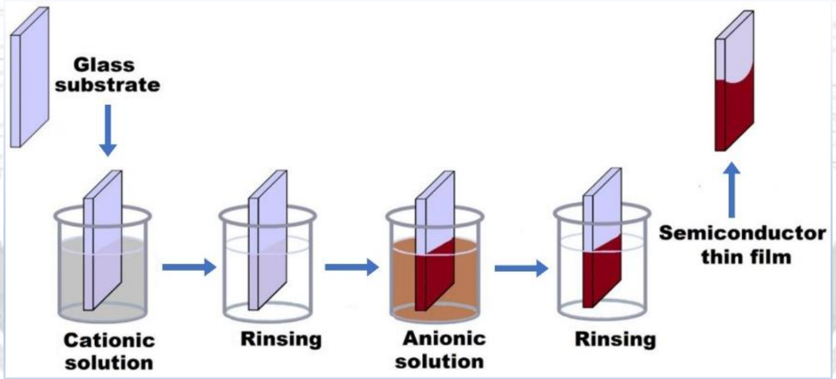

Figure 10. SILAR method for the preparation of thin films [63].

In SILAR, a substrate is alternately dipped into aqueous solutions containing cationic and anionic precursors. Chemical reactions occur at the substrate surface during each dipping cycle, forming a thin-film layer by layer. These reactions are typically low-temperature, solution-based chemical processes, not involving vapor or physical bombardment.

5) Plasma Electrolytic Oxidation (PEO).

Plasma electrolytic oxidation (PEO), also known as microarc oxidation, is an electrochemical technique used to create thick, ceramic-like oxide layers on valve metals such as Ti, Mg, and Al. This process relies on dielectric breakdown processes that induce micro-discharges, resulting in hard, corrosion-resistant surfaces with heterogeneous microstructures. Due to their plasma-sparking nature, PEO coatings typically exhibit medium to high surface roughness (50–500 nm RMS) and feature crater-like morphologies and porous networks, as demonstrated by AFM and SEM analyses [64]. These properties can be controlled by the electrolyte composition, current density, and pulse waveform to enhance functional features such as corrosion resistance, photocatalytic activity, and biocompatibility.

Previous studies have shown that obtaining highly homogeneous nanocoatings depends strongly on both the deposition mechanism and the energy delivered to the growing film. Physical vapor deposition techniques, particularly magnetron sputtering, consistently produce uniform, dense coatings with controlled grain size due to their line-of-sight, high-energy deposition environment [11]. Chemical vapor deposition methods, including ALD and LPCVD, provide exceptional conformality and thickness precision on complex geometries, making them preferred for ultrathin functional layers in microelectronics [50]. Solution-based deposition routes such as sol–gel and spin coating enable low-cost fabrication but often require post-annealing to reduce porosity and improve uniformity [13]. Hydrothermal processing offers good crystallinity at low temperatures, though uniformity depends strongly on precursor concentration and autoclave conditions [14]. Green-synthesis approaches using plant extracts or bio-templates have shown promise for environmentally friendly nanocoating production, but their reproducibility and large-area homogeneity remain under investigation [15], [65].

Conclusion

The techniques of nanostructured film coating can be classified based on the fabrication method. Thin film technology includes various methods and applications of deposition, growth, and nucleation. The techniques, including PVD, CVD, and SBD via the chemical bath deposition (CBD), have their advantages and limitations emphasized. Thin films represent complementary nanostructures whose fabrication techniques are defined by their performance. Provide stability and uniformity, while delivering tunability and high surface reactivity. Hybrid strategies that combine both paradigms of size with performance and cost with mass production are likely to dominate future technologies in energy, catalysis, sensing, and biomedicine. Achieving environmentally sustainable, cost-effective, and reproducible synthesis will remain the key challenge for industrial adoption.

Conflict of interest

The authors declare no conflict of interest.

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JOURNAL`S UNIVERSITY OF BABYLON FOR
ENGINEERING SCIENCES (JUBES)
مـــجلـة جـــامعة بــــابـل للعلـــــوم الهندسية

Vol. 33, No.5. \ 2025

ISSN: 2616 - 9916

تقنيات الطلاء النانوي للأغشية الرقيقة: مراجعة شاملة

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الخلاصة

الأغشية الرقيقة عبارة هياكل نانوية بالغة الأهمية لانها تشكل الأساس الجوهري للابتكارات في مجال الإلكترونيات والطاقة والحفز الكيميائي والطب الحيوي. تؤثر تقنية تصنيع الاغشية النانوية بشكل مباشر على شكلها وبلورتها ووظيفتها، مما يحدد أداء الجهاز. تركز هذه الدراسة (المراجعة) على تقنيات ترسيب وتصنيع الأغشية الرقيقة، مقدمة نظرة عامة مقارنة على أهمية المواد النانوية وإجراءات تصنيعها المرتبطة بها. تشمل هذه التقنيات الترسيب الفيزيائي للبخار (PVD) ، والترسيب الكيميائي للبخار (CVD) ، والترسيب القائم على المحاليل (SBD) .، تؤثر خصائص سطح المادة وكفاءتها بشكل كبير على أدائها، كما هو مبين في الجداول والمخططات المقارنة. تستخدم المواد الكيميائية المعدنية المشكّلة للأغشية الرقيقة، مثل سلائف الكالكوجينيد، في تطبيقات متطورة في مجالات مختلفة. تناقش هذه المقالة تطبيقات في الطاقة الشمسية، والتحفيز، والاستشعار، والطب الحيوي، والإلكترونيات البصرية، والخلايا الشمسية، والطلاءات الشمسية الانتقائية، والخلايا الشمسية ذات الحالة الصلبة، والخلايا الشمسية الكيميائية الضوئية، والموصلات الضوئية، والتصوير الضوئي، والتسجيل الهولوغرافي، وجميع أنظمة التخزين الضوئي. يمكن تحقيق هذه التطبيقات عن طريق تعديل الأسطح بالطلاءات لتصنيع أغشية رقيقة. تصنف هذه المقالة التحديات الحالية، مثل المخاوف البيئية، وقابلية التكرار، وقابلية التوسع، مع تقديم وجهة نظر حول الأساليب الهجينة وتكنولوجيا النانو الخضراء.

الكلمات الدالة: التخليق، الطلاء النانوي، التصنيع، الأغشية الرقيقة، الترسيب الفيزيائي للبخار (PVD)، الترسيب الكيميائي للبخار (CVD)، الترسيب الكيميائي للمحاليل (SBD)، الخلايا الشمسية.