Sigma J Eng Nat Sci, Vol. 44, No. 3, pp. 2263−2285, June, 2026

Sigma Journal of Engineering and Natural Sciences
Web page info: https://sigma.yildiz.edu.tr
DOI: 10.14744/sigma.2026.2094

Review Article

Semiconductor thin films: Deposition methods and applications

Mehmet Fatih GÖZÜKIZIL[1,*], Enes NAYMAN[1], Sinan TEMEL[2], Fatma Özge GÖKMEN[3]

[1]*Sogut Vocational School, Bilecik Seyh Edebali University, Bilecik, 11600, Türkiye*
[2]*Department of Physics, Bilecik Seyh Edebali University, Bilecik, 11000, Türkiye*
[3]*Vocational School, Bilecik Seyh Edebali University, Bilecik, 11000, Türkiye*

ARTICLE INFO

Article history
Received: 19 December 2024
Revised: 13 February 2025
Accepted: 27 March 2025

Keywords:
Semiconductors; Sol-Gel; Sputtering; Thin Films; Vapour Deposition

ABSTRACT

Today, semiconductor thin films have a very important place in electronic and optoelectronic device technology. Semiconductor thin films, with their broad range of applications, can achieve high performance by adjusting parameters. This performance is directly related to deposition methods. Deposition methods enable semiconductor thin films to exhibit unique properties, such as enhanced electrical conductivity, improved optical transparency, and tailored surface morphology which are not achievable in bulk materials. For instance, thin films produced by chemical vapor deposition can achieve higher purity and better uniformity compared to their bulk counterparts. New alternative methods for the deposition of semiconductor thin films have emerged with the development of technology. In this study, deposition methods of semiconductor thin films are reviewed under three main headings: vapor, liquid and solid phase deposition. Under each main heading, the most commonly used deposition methods in the literature are described. Application areas of semiconductor thin films in technology are summarized.

Cite this article as: Gözükızıl MF, Nayman E, Temel S, Gökmen FÖ. Semiconductor thin films: Deposition methods and applications. Sigma J Eng Nat Sci 2026;44(3):2263−2285.

INTRODUCTION

The part of the material that comes into contact with the external environment is defined as the surface. They interact with the environment through their surfaces [1]. External appearance and color, mechanical properties (friction, wear, corrosion, etc.), optical properties (light transmission, absorption, reflection, etc.), electrical properties [2] and thermal properties [3] of materials are some of the properties affected by the surface. In general, these properties are determined by the surface behavior of the material. Materials can be used more effectively by making only partial changes on the surface without changing them completely. Preventing corrosion by painting metals and improving the surface of the materials instead of completely renewing it, such as gold-plated products, will provide significant raw material and resource efficiency [4, 5]. In addition, in some cases, the properties expected from the mass of the mate- rials and those expected from the surface may be different or opposite. Sometimes, as an alternative approach for high-cost and rare materials that

***Corresponding author.**
*E-mail address: fatih.gozukizil@bilecik.edu.tr

This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkilic

Published by Yıldız Technical University Press, İstanbul, Turkey

require advanced technologies for their production, thin film coating is applied to their surfaces. This is preferred to improve the properties of the materials or to make it suitable for special requirements. Thin films are basically structures consisting of a substrate and a thin layer formed by coating the substrate with various methods [6, 7]. The size (thickness) of thin films is on the nanometer (nm) – micrometer (μ) level (10 nm – 1 μ) [8]. The thickness of thin films used in applications such as microelectronics (diode, transistor, etc.) [9–15] sensors [16–23]and photovoltaic systems (solar cells, etc.) [24–27] is at the nanometer level. Micrometer-level thin films are generally produced to increase the mechanical properties or surface quality of the material system [28]. Having a small thickness alone is not sufficient to be considered a thin film [29, 30]. For example, a copper film that has been thinned and transformed into a foil by drawing cannot be deemed a thin film. A thin film is produced on a surface using any thin film coating technique until copper reaches the desired thickness, starting from scratch. While foil copper forms from top to bottom in a bulk manner, thin film copper forms from bottom to top in a gradual manner. In this case, the properties of foil copper will differ from those of thin film copper. The ability to deposition on different surfaces under desired conditions with controllable parameters is one of the most significant advantages of thin film production [31]. Thin films exhibit unique properties compared to bulk materials due to their reduced dimensionality and increased surface-to-volume ratio. These films often demonstrate enhanced electrical conductivity, improved optical transparency, and better mechanical flexibility, which are critical for applications in microelectronics, sensors, and photovoltaic systems. For instance, ZnO thin films deposited via sol-gel methods show higher transparency and conductivity compared to bulk ZnO, making them ideal for transparent conductive electrodes in solar cells. Additionally, thin films can be engineered to have tailored bandgaps, which is not easily achievable in bulk materials, enabling their use in optoelectronic devices. Another advantage is that systems made of thin films can be produced from nanometers to micrometers, which means they take up less space, and their deposited surface can be measured and examined [32, 33]. Semiconductors also have a very important place in thin film technology [34]. In order for semiconductors to become conductors and for their electrical properties to change, they must be stimulated at least as much as the band gap value. In addition, conductivity can be increased by interfering with the movement of electrons in the internal structure of the material with the help of external energies such as optical and thermal processes. Semiconductors; It is used as final and auxiliary material in many applications such as electronic circuit elements, various chip productions, detection and warning mechanisms [35–37] of different sensors, optoelectronic products [38, 39] and detectors [40]. In this way, it contributes to technological development. Semiconductor thin film deposition is an important method in the pro- duction of various materials used in applications. With different thin film deposition methods, semiconductor thin films are produced by depositing atoms or molecules of the target coating material in layers on a determined substrate surface. Thin film deposition methods are basically examined under three main headings: vapor, liquid and solid deposition, depending on the phase in which the target coating material is located. These methods have been developed and diversified. Semiconductor thin film deposition methods are shown in Figure 1.

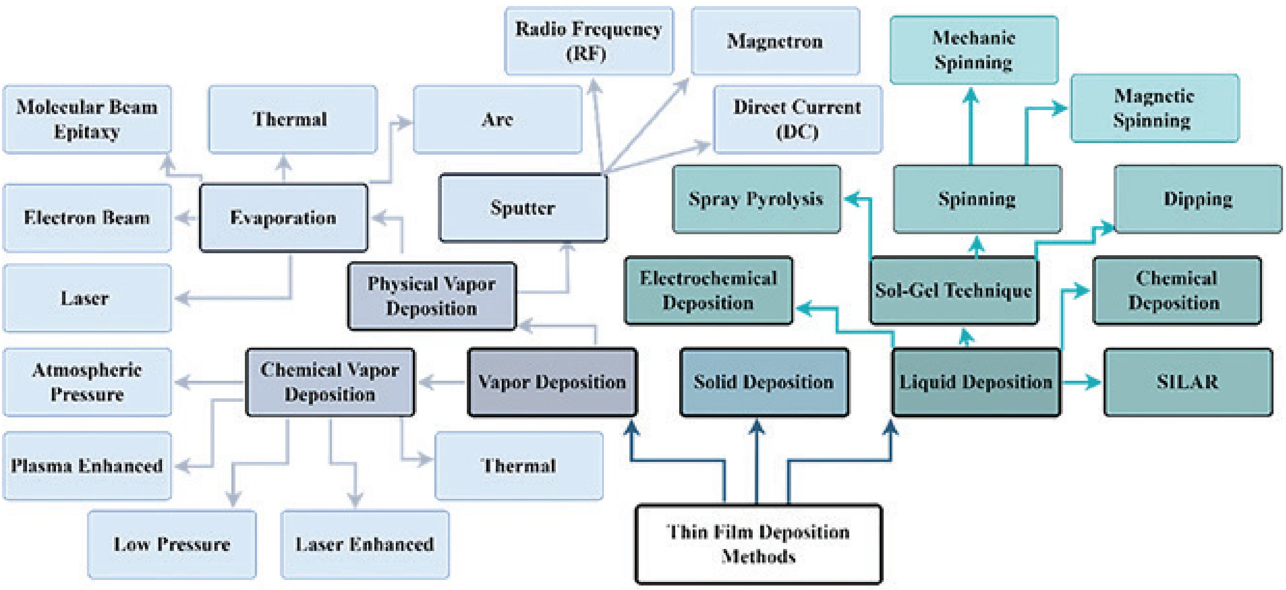

Figure 1. Thin film deposition methods [drawn by author].

The wide range of application areas of semiconductor thin films, the ability to develop new application areas by producing films with different properties and the ability to obtain materials with the desired properties have encouraged researchers to carry out many studies in this field. In Table 1, the numbers of semiconductor thin film articles published in the" Web of Science"," Scopus" and" TR Index" databases in the last 10 years are given separately according to their deposition methods.

Publications in Scopus and Web of Science databases were searched for the title" Thin Film" in the title, abstract and keywords used by the authors and studies conducted in the last 10 years were compiled. It was determined that the keyword thin film was used in 107890 publications in the Scopus database and in 125188 publications in the Web of Science database. It was determined that 4553 different keywords were used in studies on thin films and 152 of these words were repeated in 5 separate publications. Considering this distribution of the keywords used in the publications, the bibliometric network map was created in the VOSviewer program in Figure 2.

Semiconductor thin films are one of the most frequently studied topics in the literature today. When this keyword network map is examined as a summary of the studies carried out in the literature on thin film production methods in the last 10 years; It was observed that physical vapor deposition, chemical vapor deposition, sol gel, SILAR, electrochemical deposition methods and methods developed by these methods were widely used. In addition, it was determined that the structural, optical, electrical properties and surface morphologies of the produced thin films were generally characterized. Studies show that they can be used in many different areas such as composite materials, wearable technologies, biological materials and solar cells. Sönmezoğlu and his colleagues conducted a similar study titled" Thin film production techniques" in 2012 and presented thin film deposition methods under this title [32]. In their study titled" An Overview of Basic Thin Film Production Techniques" in 2023, Karakuş and Koç basically examined thin film production techniques and discussed the advantages and disadvantages of the techniques [41]. Coşğun and colleagues have outlined the chemical vapor deposition method and its variations in their study titled" Chemical Vapor Deposition Methods in Thin Film Production" identifying the advantageous and disadvantageous parameters of these methods [42]. In a study titled "Overview of thin film deposition techniques" in 2019, Abegunde and colleagues conducted a review of the existing literature on different deposition techniques used for surface modification and coating [43]. Within the scope of this study, semiconductor thin film methods were compiled from current sources in the literature under one title.

Table 1. Thin film deposition method studies conducted in the last decade

Deposition method		Web of Science	Scopus	TR Index
Vapor deposition	**Physical vapor deposition**			
	Thermal evaporation	324	2085	66
	Electron beam evaporation	372	1683	59
	Arc evaporation	151	438	11
	Molecular beam epitaxy	202	1431	7
	Laser evaporation	37	95	8
	Sputtering			
	Radio frequency (RF) sputtering	377	649	12
	Magnetron sputtering	306	1916	49
	Direct current (DC) sputtering	358	180	9
	Chemical vapor deposition			
	Atmospheric pressure	148	781	11
	Low pressure	278	226	2
	Plasma enhanced	219	507	15
	Laser enhanced	97	37	3
Liquid deposition	Sol-gel dip coating	1219	848	30
	Spin coating	2055	2481	95
	Spray pyrolysis	3057	3748	60
	Chemical deposition	602	1588	59
	Electrochemical deposition	1481	1907	133
	SILAR	627	310	39

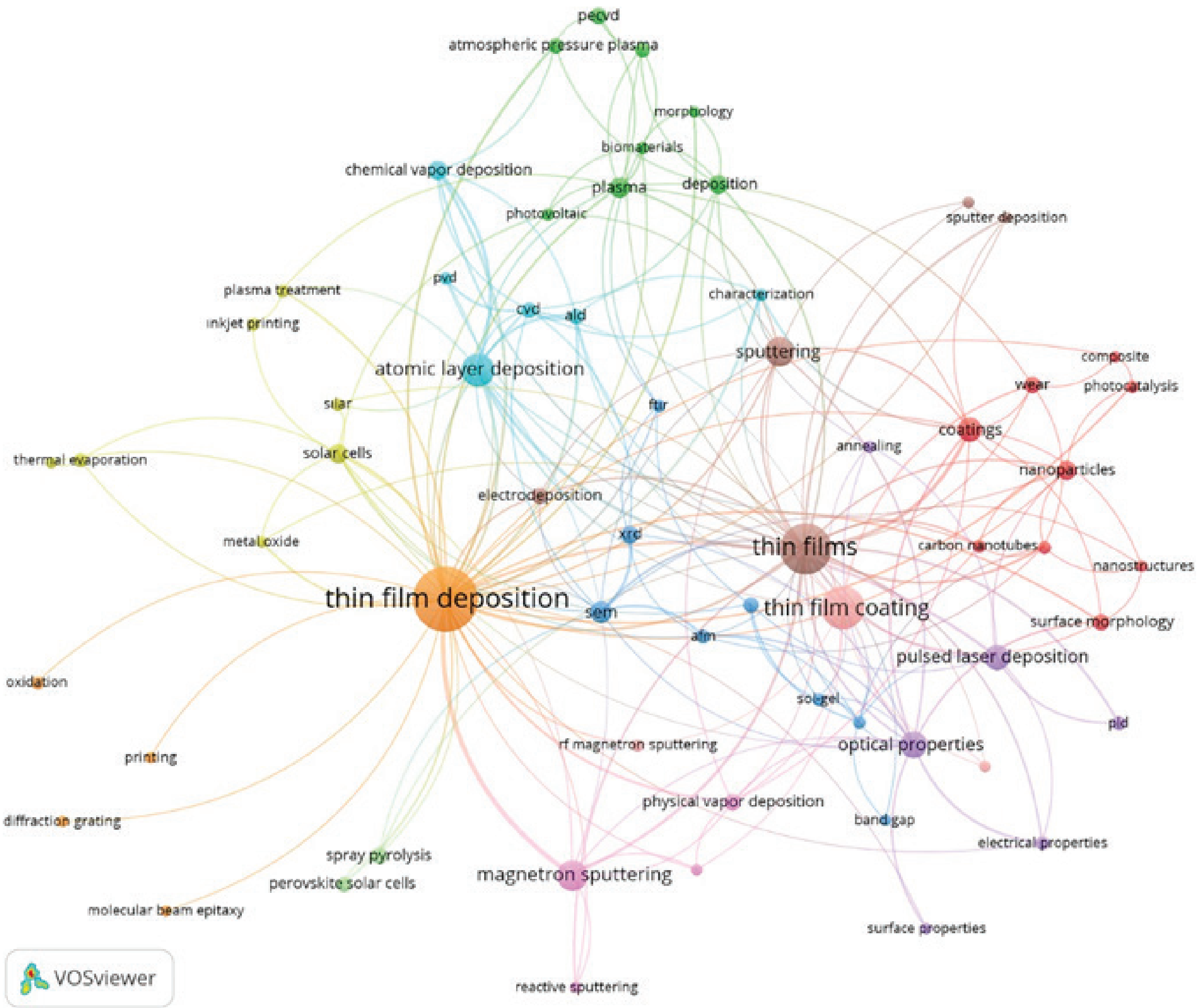

Figure 2. Bibliometric network map by keyword [drawn by author].

Schematic representations of the determined methods were originally designed and explained in 3D. Application areas are summarized.

DEPOSITION METHODS OF SEMICONDUCTOR THIN FILMS

Vapor Deposition

These are methods of obtaining high quality thin films without any limitation in the coating material and substrate material made in the vapor phase. Vapor-phase deposition (e.g., PVD, CVD) offers high-quality, uniform films with excellent adhesion and purity but it is often expensive and requires high vacuum conditions [1]. In general, vapor deposition can be divided into two categories: physical vapor deposition (PVD) and chemical vapor deposition (CVD).

Physical Vapor Deposition

Generally, different metals and alloys are evaporated and transferred from the target source onto a substrate. This method has been developed since the mid-19th century and continues to be applied today [44–46]. The target coating material, which is heated and evaporated, is deposited as a thin layer on the surface of the substrate material. Solid coating material consisting of ionized and reactive gases, ionized by focusing high energy into a plasma, is deposited on the substrate surface in a controlled manner [47, 48]. In other words, the evaporation of atoms separated from the surface of the target material by the bombardment of high-energy gas ions accelerated by a determined system and their deposition on the substrate surface can be defined as physical vapor deposition. The physical vapor deposition method, which has been developed and changed over many years of studies, is divided into two subgroups: evaporation and sputtering [49].

Evaporation

Substances have unique physical properties such as distinctive melting, boiling and evaporation temperatures. In the evaporation method, first the target coating material is evaporated by heating. The target material, which is evaporated, condenses and deposits on the substrate surface. Various heating systems can achieve evaporation of the target material. It is the heating and evaporation of the target material, which is usually placed in a vacuum or inert gas environment, and is transported to the low-temperature substrate surface, forming a film layer.

Thermal Evaporation Method

Thermal evaporation is a method of thin film deposition by evaporating metal mate- rials, usually as target materials, in a high vacuum chamber below 10 mbar [50, 51]. The thermal evaporation method is shown in Figure 3.

In this method, the target material is placed in a crucible made of metal that is resistant to high temperatures. The target material in the crucible is heated and evaporated with the thermal heater. The coating material spread into the evaporating environment accumulates on the surface of the substrate placed in the vacuum chamber. Thus, thin film deposition at the desired thickness can be performed. Semi- conductors can be deposited on different surfaces such as thin films, various metals and conductive bonding coatings by thermal evaporation. Thermal evaporation is simple and cost-effective but limited to low-melting-point materials [52–54].

E-BEAM EVAPORATION METHOD

Among the evaporation methods, electron beam (E-beam) metal deposition is another widely used vacuum method. The obvious difference of this method, which is basically similar to the thermal evaporation method, is the direct heating of the target material. Figure 4 shows the electron beam evaporation method. Here, the tar- get material to be evaporated is placed in a crucible made of metal resistant to high temperatures.

In the accelerator crucible emitted from the filament placed on the platform under the crucible, the accelerated electron beam is directed by the magnetic field created by magnetic cylinders, focuses on the target material and evaporates the material by heating it by bombardment [55]. Effective energy transfer occurs compared to thermal heaters. In addition, since the crucible is not heated directly and can be cooled with water, evaporation of the metal crucible and impurities of the coating are prevented. As the target material is heated directly, it can be utilized as an appropriate method for materials that evaporate at high temperatures [56]. Evaporated material atoms accumulate in layers on the substrate surface. This method is particularly advantageous for refractory metals and ceramics due to its highly localized and precise energy transfer. Moreover, reactive E-beam evaporation where reactive gases such as oxygen or nitro- gen are introduced into the chamber enables the deposition of compound films like oxides and nitrides with controlled stoichiometry. Evaporated material atoms

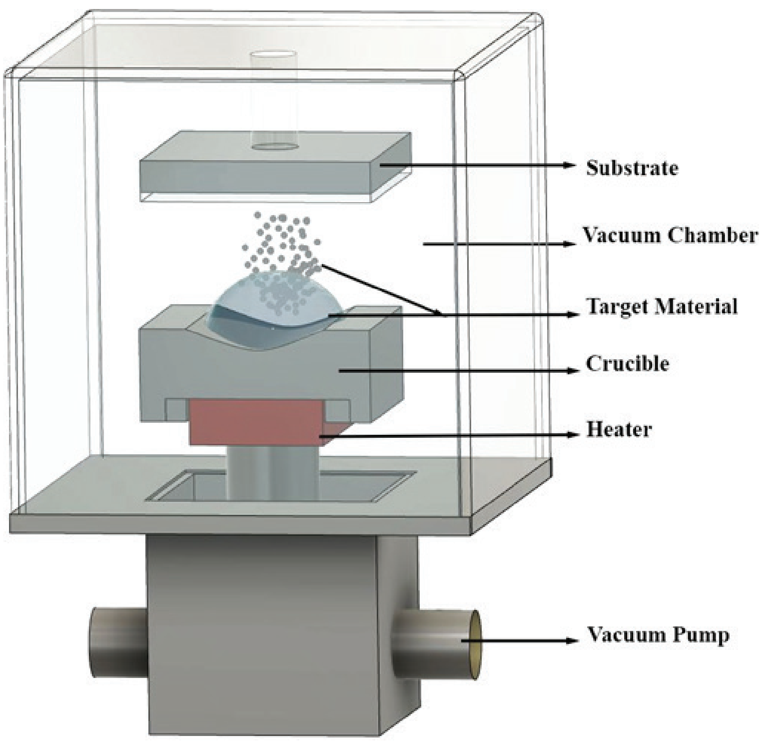

Figure 3. Thermal evaporation method [drawn by author].

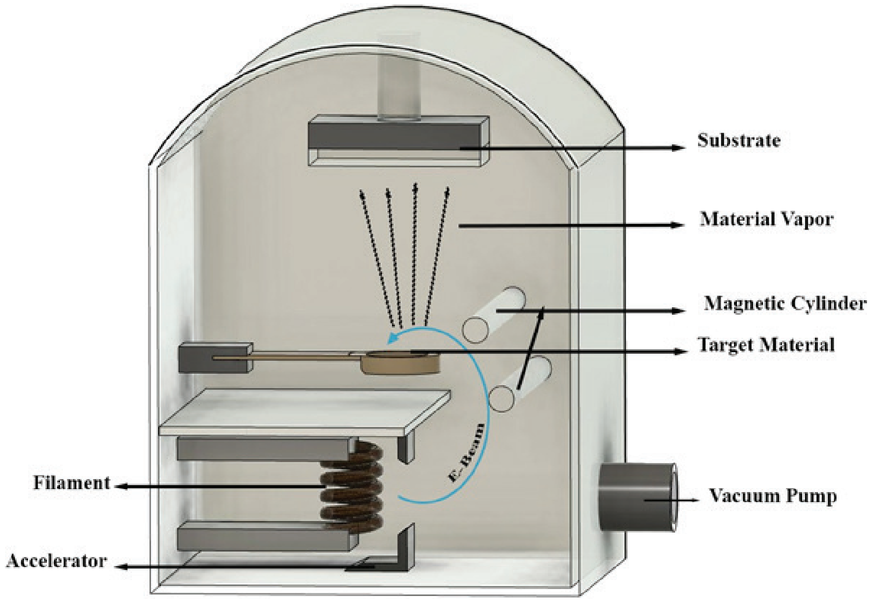

Figure 4. E-beam evaporation method [drawn by author].

accumulate in layers on the substrate surface. However one limitation of E-beam evaporation is its directional deposition characteristic which may result in uneven coverage on substrates with complex geometries. E-beam evaporation allows for higher melting-point materials and better film purity but is more complex and expensive [55].

ARC EVAPORATION METHOD

The target coating material is vaporized and ionized using the arc. This method is divided into cathodic and anodic arc. In an anodic arc, the target material to be vaporized in the vacuum chamber is placed as the anode and an electron gun to bombard electrons is placed as the cathode. Electrons accelerated from the electron gun bombard the anode. With this bombardment, energy is transferred to the material in the anode and the anode material heats up first. As the voltage is regularly increased, the material in the anode continues to heat up, melts and vaporizes. When the voltage applied between the electrodes is increased and maintained, the anode material forms a bright plasma. This plasma spreads towards the walls of the vacuum chamber

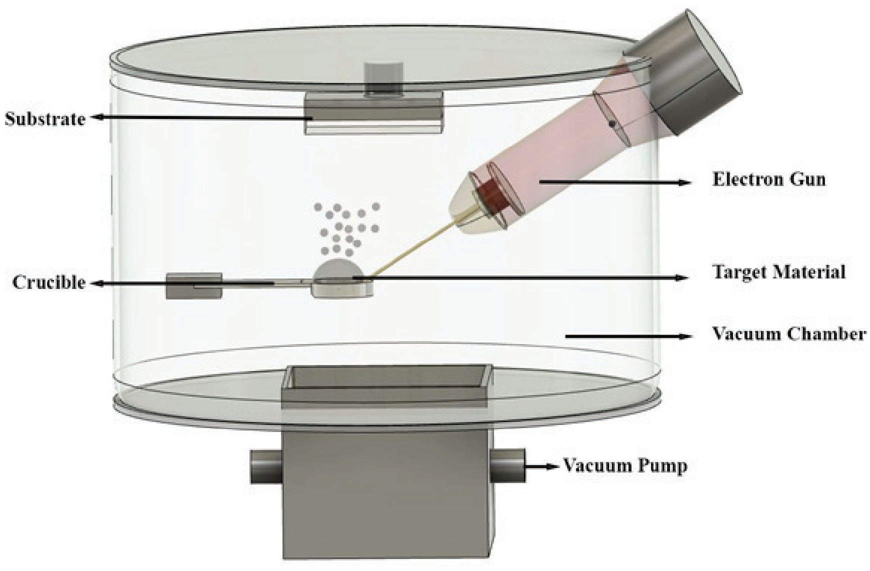

Figure 5. Arc evaporation method.

in which it is located. Therefore, the substrate placed in this chamber is coated with the target material as a thin film. In cathodic arc, the target material to be vaporized is placed in a vacuum chamber as the cathode and the substrate material as the anode. An arc is formed on the cathode with low voltage and high current. The target material, which reaches very high temperatures with the resulting arc, melts and evaporates. Thus, the cathode material is vaporized and coated on the substrate. The energy transfer in arc evaporation is highly efficient due to the direct conversion of electrical energy into thermal energy, leading to high deposition rates and strong film adhesion. Additionally, the highly ionized plasma produced in this method ensures that the deposited films are dense and exhibit minimal contamination. However the formation of microdroplets or macro particles that can affect film smoothness and uniformity is a negative aspect of the study. Recent advancements in filtered arc evaporation have addressed this issue by incorporating magnetic filters to remove macroparticles, thereby improving surface quality [57]. The arc evaporation method is shown in Figure 5.

In the arc evaporation method, it is possible to create a high vacuum or even extremely high vacuum chamber with a vacuum pump. Working in a vacuum chamber improves the quality of the thin film coating by reducting oxidation and impurities that may occur by removing different gases in the medium. A high vacuum, typically below 10–6 mbar, is particularly important for achieving high-purity metal oxides and superconducting films, as it effectively minimizes oxidation and contamination. There is no need for additional heat treatment such as annealing for crystallization in thin films deposited in the arc evaporation method, which can be operated at high temperatures. In other words, better quality metal oxide semiconductor thin films and superconducting films can be deposited and can be used with developing technological applications [58–60]. Arc evaporation is suitable for high-purity films and can operate at high temperatures without additional annealing [58].

MOLECULAR BEAM EPITAXY METHOD

Molecular beam epitaxy (MBE) is an advanced thin film deposition method where the film thickness is effectively controlled in a high vacuum chamber below 10 mbar. Epitaxy can be defined as the deposition of nano-thick films in a single crystal layer by directing the arrangement of atoms and molecules on a substrate compatible with a thin-layer crystal structure. Each of the target coating materials such as Al [61], In, As, Si, Ga [62] are placed separately in the cylinder part of the effusion cells. The material atoms in the heated and vaporized effusion cells can deposit films of the desired content on the substrate surface. The covers placed in front of the effusion cell cylinders can be closed and opened in milliseconds. The covers of the target effusion cell determined according to the desired content are opened for the set time, focusing on the substrate surface and film deposition begins. The substrates are heated in a low-pressure and high-vacuum working environment, usually at temperatures between 450 °C and 650 °C [63]. In this way, the desired composition can be obtained in the deposited films and the film can be grown epitaxially. In addition,

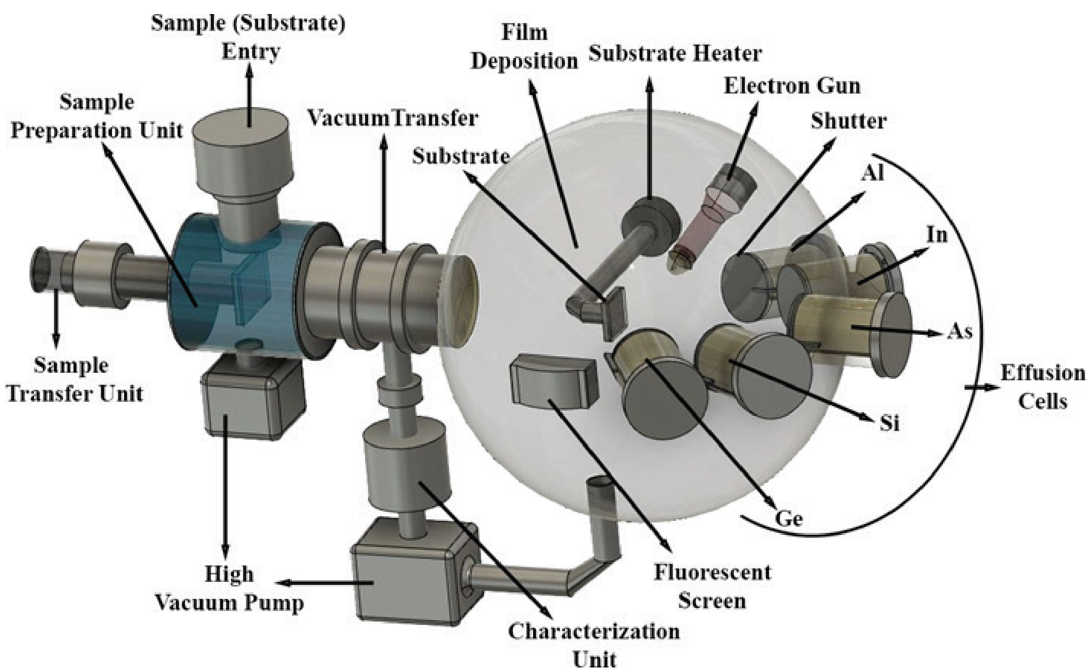

Figure 6. Molecular beam epitaxy method [drawn by author].

the rod on which the substrates are placed is rotated at the desired speed to ensure the homogeneity of the deposited film. Figure 6 shows the molecular beam epitaxy method schematically.

In general, the various advantages of the MBE method over other methods are; These can be listed as being able to deposit sensitive films at the molecular level, obtaining a controlled film [64] during deposition at the desired thickness, and growing the film by doping in different parts of the substrate [65]. Despite these, negative aspects can be listed as providing a vacuum environment, constantly operating the high vacuum pump and system actively for sustainability, high investment and installation costs, and not being suitable for mass production in parallel with the low film deposition speed. MBE offers atomic-level control and high-quality epitaxial growth but is costly and slow, making it less suitable for mass production [64, 65].

LASER EVAPORATION METHOD

In the laser vaporization method, firstly, the laser beams coming from the laser source are focused with a lens. The laser beam is reflected by a mirror in a vacuum onto the target material placed in the crucible. Finally, a thin film is deposited by vaporizing the material and directing it to the substrate surface. The properties of the film are determined by the wavelength of the laser beam produced by the laser source used and the radiation absorption characteristics of the target material to be evaporated. Figure 7 shows the laser evaporation method. Metals that have high melting temperatures and can absorb laser light can be evaporated with this method and used for film deposition.

SPUTTERING

In general, sputtering process can be defined as the disassembly or detachment of atoms from the solid material surface by bombardment of ions. That is, the target material is bombarded with accelerated positively charged ions. Then the atoms are detached from the surface and the atoms scattered on the substrate surface to be coated form a film layer. The sputtering process begins by filling an inert gas between the electrodes. Gas plasma is formed by applying voltage between the electrodes. The positively charged ions in the plasma focus on the cathode, accelerate, collide and break off neutral atoms. The detached neutral atoms are directed to the substrate surface at the anode and deposite. Thus, the thin film is deposited on the substrate surface. Generally, the sputtering method is classified according to the power source used. It can be classified with 3 different power sources: Radio Frequency (RF), Radio Frequency Magnetron and Direct Current (DC) sputtering method.

RF Sputtering Method

Since Radio Frequency (RF) power source is used for the sputtering process, it is called RF Scattering Method. It is the method of film deposition in a low-pressure chamber where high vacuum is provided by a vacuum pump. Thanks to the vacuum, other gases in the atmosphere of the coating chamber are minimized. The electromagnetic waves generated by the RF used as a power source cause the target material atoms on the cathode to ionize with the vibration frequency. The high-energy ionized target material, which is accelerated and scattered is transported to the substrate on the anode and film formation occurs. This technique is particularly advantageous for depositing dielectric films

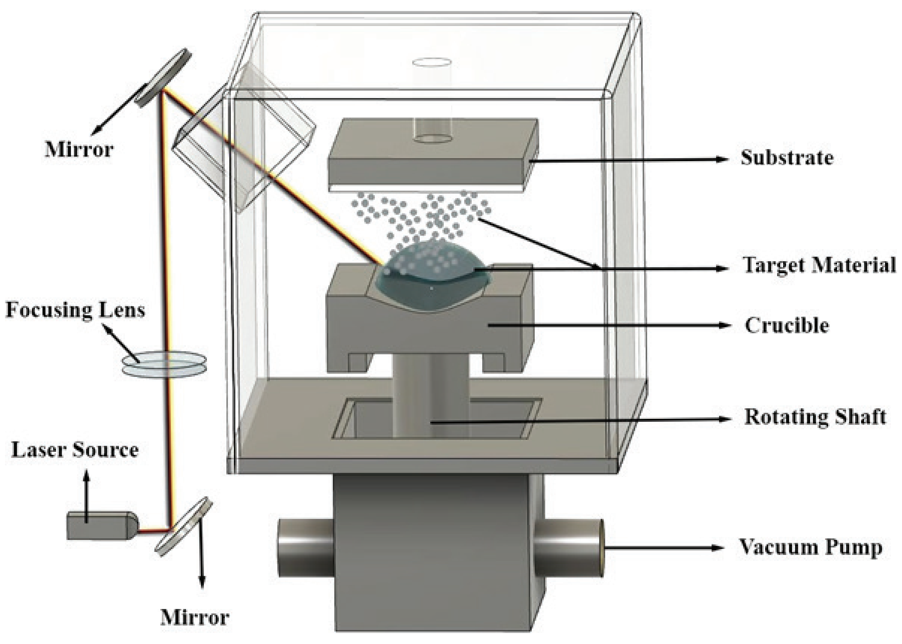

Figure 7. Laser evaporation method [drawn by author].

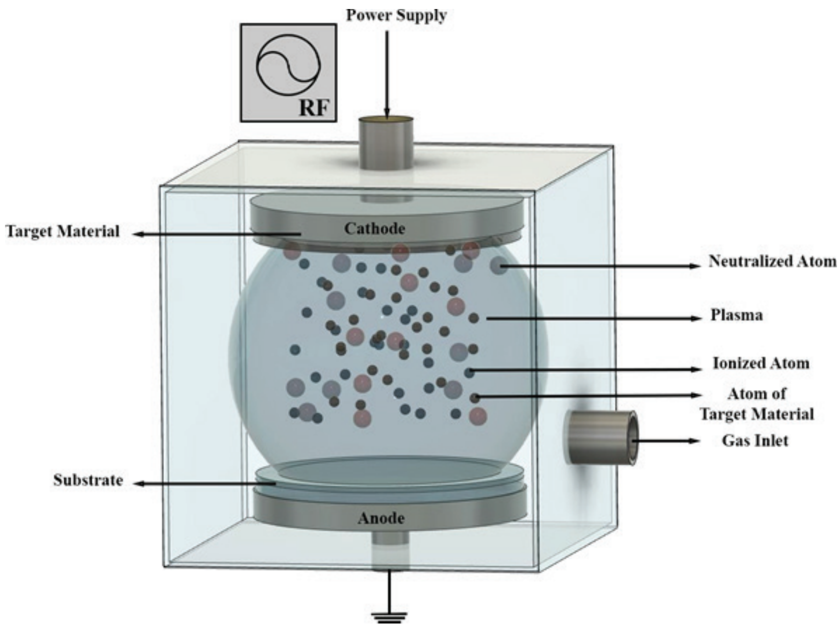

Figure 8. RF sputtering method [drawn by author].

such as SiO2 and Al2O3, as the RF field helps to sustain plasma stability. Different from the DC spraying method, the RF spraying method is suitable for conductive and insulating materials. However, it generally exhibits lower deposition rates and requires impedance matching networks to optimize power transfer, making the process more complex. The RF scattering method is shown in Figure 8.

RF Magnetron Sputtering Method

The difference of the method from RF sputtering is that in addition to radio frequency, a magnetic field is formed with a power supply. The electrons of the target material on the cathode are moved in the direction of the spiral orbit formed by the magnetic field [48]. The lengthening of the paths of electrons entering the spiral orbit and their

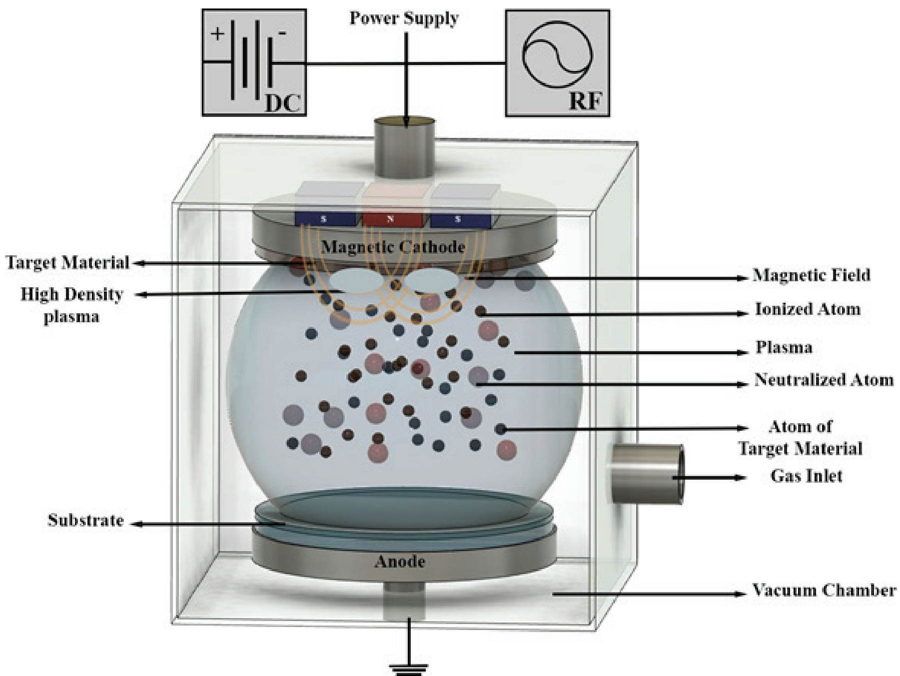

Figure 9. Magnetron sputtering method [drawn by author].

collision with neutral noble gas atoms increase the ion concentration on the target material surface, causing increased sputtering and the formation of high-density plasma. In this way, target material ions deposite more effectively as a film on the substrate surface on the anode. The combination of RF power and a magnetic field confines the plasma near the target surface, significantly enhancing ionization efficiency and increasing the deposition rate. This method is particularly advantageous for the deposition of high-quality films with good homogeneity and adhesion properties. The RF magnetron sputtering method is widely used for complex materials with high entropy alloys and transparent conductive oxides. This technique is also suitable for coating heat-sensitive substrates, as the high plasma density enables film deposition at lower temperatures. The RF magnetron sputtering method is given in Figure 9.

RF and RF magnetron sputtering methods can also be used for thin film coating on metal [66, 67] and insulating substrates [68].

DC Sputtering Method

It is the method in which the voltage applied to the electrodes is applied with a direct current DC power source. It can be defined as the sputtering method by applying DC voltage to two plane electrodes where the target material is placed on the cathode surface and the substrate is placed on the anode surface. DC sputtering is considered the most straightforward and cost-effective sputtering method, making it a widely used technique for thin film deposition. It is highly efficient for conductive materials such as metals and alloys, ensuring high deposition rates. However it is not suitable for insulating materials due to charge build up on the target surface. Recent advancements in pulsed DC sputtering have addressed this limitation by periodically reversing the polarity, preventing charge accumulation and enabling the deposition of insulating materials [69]. While metal materials are commonly preferred [70] as target materials, there is no sputtering in insulating materials. The target material ions in the resulting low-density plasma deposited on the substrate surface and form thin film layers. DC sputtering method is shown in Figure 10.

Direct current (DC) magnetron scattering method can also be obtained by adding magnets to the DC scattering method. This method is applied similarly to the DC sputtering method [71]. It can be preferred depending on the thin film structure and properties that are intended to be deposited [72, 73].

Chemical Vapor Deposition

Another of the effectively used vapor deposition methods is this method in which evaporation is done chemically. It is the formation of a solid film on the substrate surface from the reaction of a carrier gas and the heated target material in a closed chamber with adjusted pressure. Figure 11 shows the chemical vapor deposition method. Chemical decomposition energy; It is provided by thermal, optical and electrical methods. The chamber temperature is generally around 850-1100 C [74–76]. The processing time is between 2-4 hours and the coating thickness is around 10 nanometers [77, 78].

Thin film deposition stages in the method; The order follows: mixing of gases sent to the system, contact of the

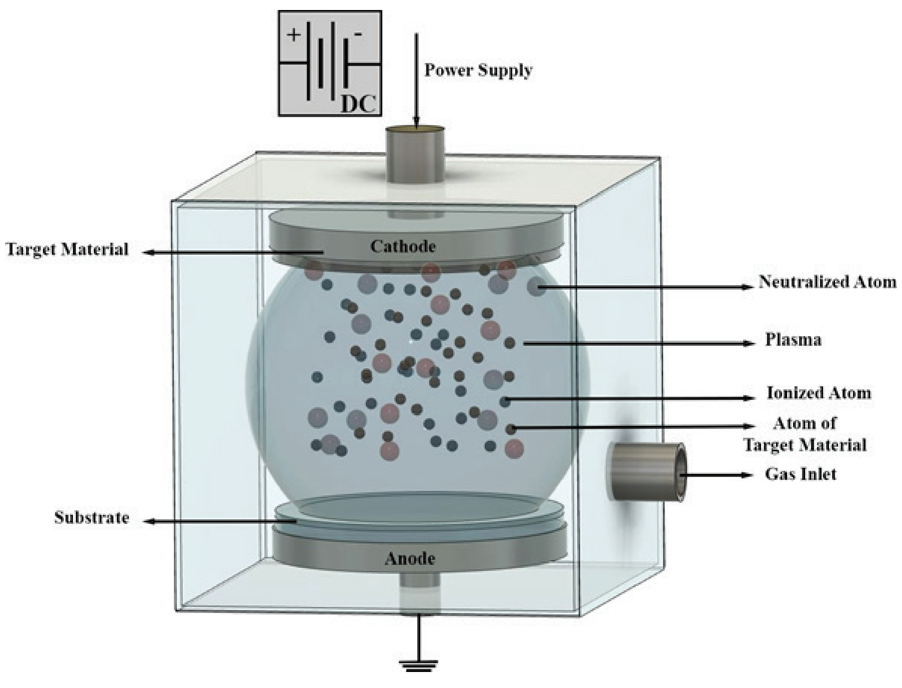

Figure 10. DC sputtering method [drawn by author].

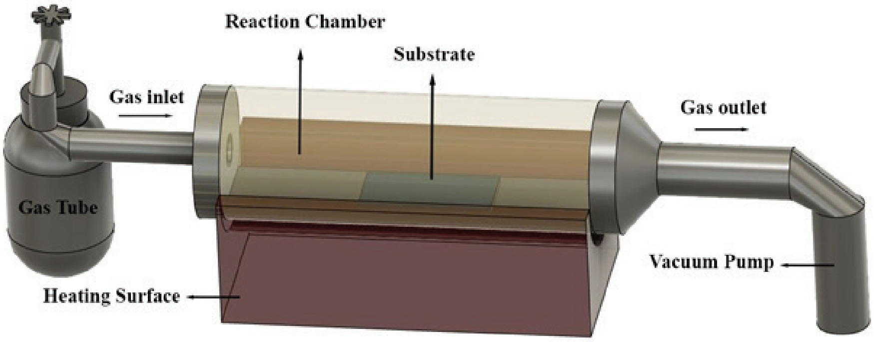

Figure 11. Arc chemical vapor deposition [drawn by author].

gas mixture with the material to be coated at high temperature, chemical reactions occurring on the surface, formation of waste gases, and removal of gases from the system. Thin films are produced with chemical vapor deposition methods applied at atmospheric pressure (APCVD) [79, 80], low pressure (LPMOCVD) [81, 82], plasma assisted (PECVD) [83–85], and laser assisted (LECVD) [86, 87]. The PECVD technique uses plasma to enhance chemical reactions, allowing for the deposition of high-quality films at lower temperatures. PECVD is widely used in the aerospace industry to deposit thermal barrier coatings and wear-resistant layers on turbine blades and other high-temperature components. The ability to deposit films at lower temperatures also makes PECVD suitable for coating temperature-sensitive materials such as polymers and composites. The LACVD method uses laser energy to locally heat the substrate, allowing films to be deposited with precise spatial control. LACVD is particularly useful for producing nanostructured films and patterned coatings required for nanomachines and micro-electromechanical systems (MEMS). Recent studies have demonstrated the use of LACVD to deposit graphene- based films and carbon nanotubes that exhibit exceptional mechanical and electrical properties. Chemical vapor deposition technology is actively used in durable materials [88] used in machine production, various final and auxiliary materials used in the electronics industry [89], high-temperature resistant ceramic coatings [90, 91]. CVD is used successfully not only in obtaining coatings but also in the production of nickel and titanium metal. Moreover, it is widely preferred in optical fibers and telecommunications, nano machines, composites, fibers and powder production, semiconductor technologies (circuit elements) [92, 93], and developing military and aerospace indutries [94, 95]. CVD is particularly advantageous for applications requiring excellent conformal coverage, allowing uniform coatings on complex geometries and high-quality, dense films. Advances in the fields of PECVD and LECVD have expanded the capabilities of these methods, enabling the deposition of high-performance films at lower temperatures [86]. CVD processes require toxic or flammable precursors and are energy-intensive due to the high temperatures involved. PVD methods, particularly sputtering, involve the physical ejection of target atoms in a vacuum environment and their deposition onto a substrate. Whilst sputtering provides precise control over film composition and adhesion, it typically exhibits lower deposition rates and may not offer the same level of conformal coating as CVD [48]. PVD techniques are highly effective for depositing a wide range of materials, including metals, alloys and ceramics. This makes them a preferred option for applications requiring precise composition control and strong film adhesion.

Liquid Deposition

Liquid-phase deposition methods, such as sol-gel and SILAR, offer advantages such as low cost, the ability to easily incorporate various additives, and the capability to create multi-layer structures. These methods are typically carried out at room temperature and do not require complex vacuum systems, making them suitable for a wide range of applications. However, liquid-phase deposition may result in lower film density compared to vapor-phase methods, and post-deposition annealing is often necessary to improve the film's crystallinity and mechanical properties.

Sol Gel Method

Sol gel is the gelation that occurs when solid nano-sized powders dissolved in a liquid grow by bonding to each other, forming continuous three-dimensional network structures. Sol is the structure consisting of a solid phase dispersed in a liquid phase. It can be defined as the absence of precipitation of nanosolid particles dispersed in the liquid. The solid phase in the sol structure can be mixed in different ways and dis- tributed homogeneously. Gel is the solid-like wet structure that can show solid and liquid properties by forming a 3-dimensional network structure of solid particles. In other words, the sol turns into a gel when the nanosolid particles inside come together to form network structures. The viscosity of the sol structure increases and becomes unable to flow at the gelation point. Chemistry of sol gel solution affected by parameters such as pH, solvent, temperature, time, catalyst and mixing [96].

Sol gel method; It is widely used with its advantages such as being able to cover large surfaces sim- ply, not requiring vacuum, performing the deposition process at room temperature and being able to deposit homogeneous multilayer films. It can be used to deposit almost all types of single and multi-component oxide films [97]. In the sol gel method; It is possible to produce thin films with the desired physical properties and thickness by doping with different materials by changing the parameters such as concentration of the prepared solution, coating time, number of layers, annealing temperature and time. Spin coating, dip coating and spray coating are commonly used methods for sol gel thin film deposition [98, 99].

Sol Gel Spin Coating Method

This method; It is done by dropping a drop of the prepared sol gel solution into the center of the substrate rotated at high speeds and rotating it for various periods of time. As the rotation speed increases, the dropped solution disperses on the substrate surface and spreads in the form of a film, and the excess is removed. The spin coating method occurs in five basic stages as shown in Figure 12. These five basic stages are respectively; 1- Dropping the coating sol-gel solution onto the center of the substrate surface, 2- Rotating the substrate at different speeds and times, 3- Evaporation of the solvent, 4- Repeating the process to obtain multilayer thin films, 5- Annealing of the deposited thin film.

In the spin coating method, the spinning process can be carried out in two different ways as mechanical and magnetic [100]. The films to be produced can be varied by changing different parameters such as spin speed, spin time, number of coating layers, volume of dropped solution and annealing temperature [101]. The low cost and rapid production of this method make it widely used. Additionally, spin coating is widely employed in the semiconductor industry for depositing dielectric layers and photoresists but its application is generally limited to flat substrates, making it less suitable for large-area coatings [102].

Sol Gel Dip Coating Method

In this method, the substrate material is dipped in the prepared sol gel solution. After waiting for a certain period of time, it is withdrawn from the solution at a constant rate under atmospheric conditions and controlled temperature. After deposition, annealing is applied at high temperatures to crystallize the thin films. Figure 13 shows the stages of the dip coating method.

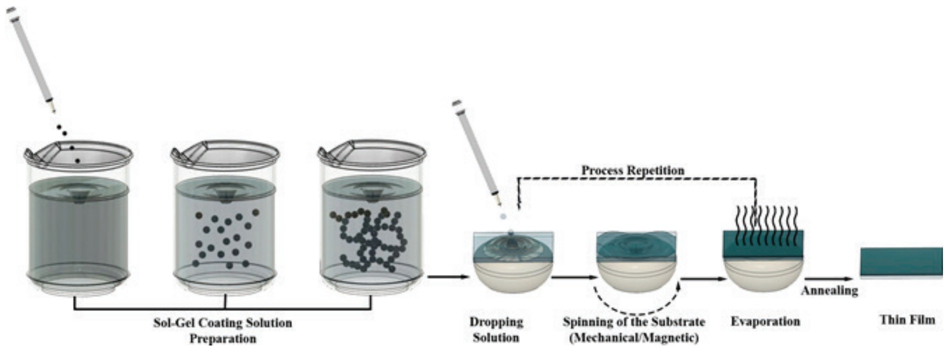

Figure 12. Sol gel spin coating method steps [drawn by author].

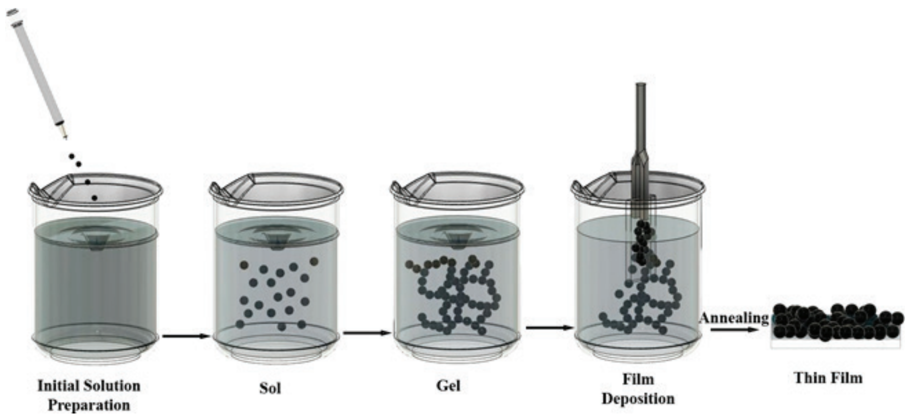

Figure 13. Sol gel dip coating method steps [drawn by author].

The thickness of thin films can be varied depending on the dipping and withdrawal speed of the substrate materials, the surface tension of the sol-gel solution, and the solution's concentration and viscosity [103, 104]. Dip coating is a simple and scalable technique, making it suitable for coating large or irregularly shaped substrates. There are possibilities for changes in film thickness due to fluctuations in withdrawal speed and solution viscosity [105].

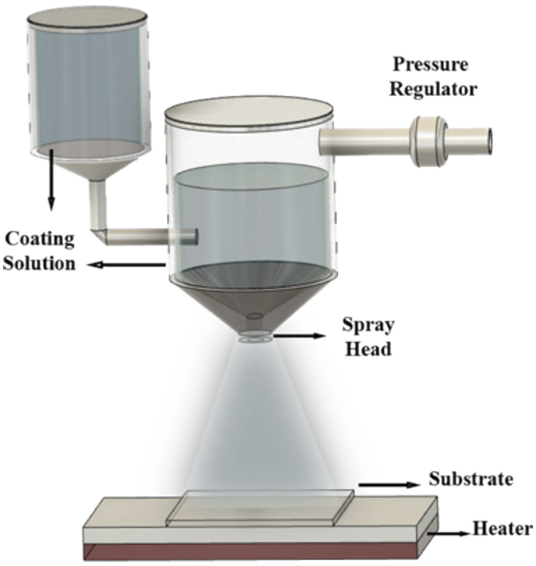

Figure 14. Sol gel spray coating method [drawn by author].

SOL GEL SPRAY COATING METHOD

The sol gel spray method was first introduced for the preparation of transparent conductive oxide films. This method is based on spraying the prepared sol gel solution onto the substrate from a certain distance. Properties of thin films obtained with this method: depends on spray distance, sol gel solution concentration, substrate temperature and solution pH. The sol gel spray coating method is shown in Figure 14. Spray coating is a highly versatile technique that enables film deposition on complex geometries. Nevertheless precise control of spray parameters, such as nozzle distance and solution flow rate, is essential to achieve uniform films [106].

Chemical Bath Deposition Method

This method can be defined as the deposition of thin films on the surfaces of substrates at the desired temperature using baths prepared with specified amounts of chemicals. First of all, the substrate material is dipped in the coating solution in the prepared bath. The pH of the bath solution is very important. The temperature and pH of the coating solution must be kept constant while the film is deposited. Therefore, it is necessary to use a temperature and pH controlled system [107]. Additionally, mixing the coating solution at specified speeds affects thin film formation. In particular, selenite [108, 109], sulphide [110, 111] and oxide thin films are successfully deposited using the chemical bath deposition method [112]. The chemical bath deposition method is shown in Figure 15. It has the features of not needing the use of complex devices and being simple,

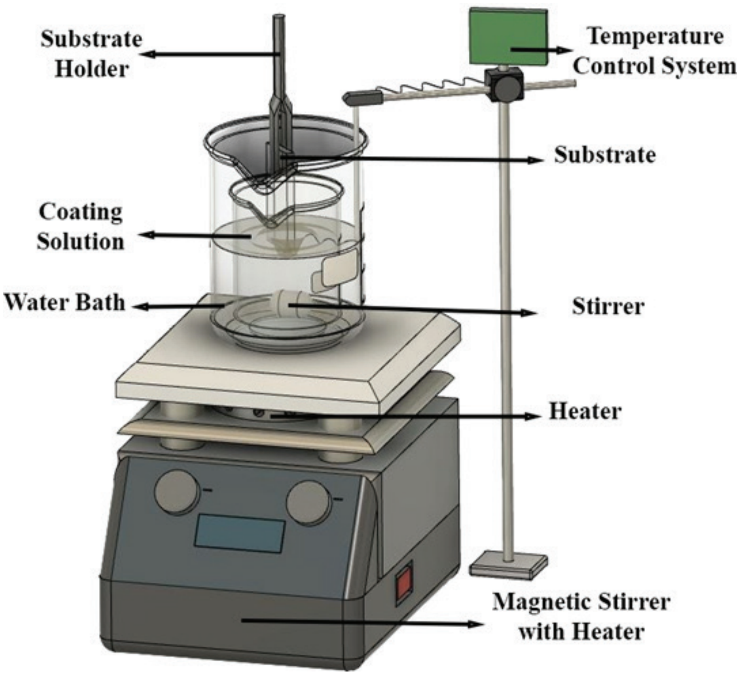

Figure 15. Chemical bath deposition method [drawn by author].

useful and portable. In addition, it has advantages such as no waste material, being repeatable and allowing the coating of substrates of different shapes. With these features, the chemical bath deposition method can be preferred over other methods. Studies, especially in recent years, aim to improve parameters such as pH, temperature, and precursor concentration to increase film quality and reproducibility. This method is particularly effective for depositing metal chalcogenides and oxides, making it highly suitable for photovoltaic and sensor applications [113–115].

Electrochemical Deposition Method

It is a method of depositing a thin film on a solid substrate with the help of reactions taking place in a prepared solution. It has a cheap and easy-to-prepare mechanism. This mechanism is formed by dipping the counter electrode, reference electrode and working electrode connected to the power source into the electrolyte solution. On the basis of electrochemical deposition, it is the process of depositing metal ions from an electrolytic solution by reducing them on the cathode. Recent advancements in pulsed electrochemical deposition have enhanced film quality by enabling better control over nucleation and growth processes. This technique is particularly beneficial for producing nanostructured films with high surface area, making it ideal for applications in electrochemical sensors and energy storage devices [116, 117]. Figure 16 shows the electrochemical storage method.

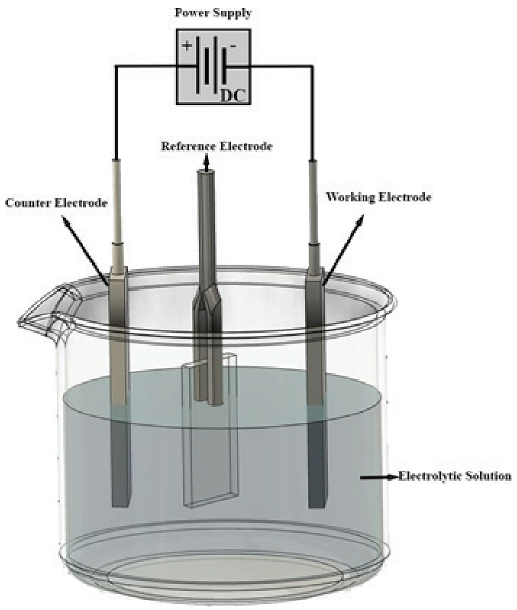

Figure 16. Electrochemical deposition method [drawn by author].

SILAR Method

The SILAR method stands for successive ionic layer adsorption and reaction. Following the adsorption and reaction processes of the ions in the prepared solution, rinsing is carried out by immersion in deionized water in order to prevent homogeneous precipitation that may occur in the solution. It is also defined as the process of depositing another substance on top of a substance deposited on the surfaces of substrate materials. Thin film deposition is carried out by consecutively dipping the substrate material into more than one prepared solution. Figure 17 shows the SILAR method.

The SILAR method is a cost-effective, simple and safe thin film deposition method that can be applied at low temperatures [118, 119]. In this method, doping can be carried out by adding organic or inorganic substances to the cationic and anionic solution. As another advantage, triple, quadruple or more compounds can be easily obtained. One of the most important advantages is that there is no choice of substrate mate- rial and the substrate size can be changed. Thin film growth can be produced by the SILAR method at room temperature. This method allows for precise control over film composition and stoichiometry, making it particularly useful for depositing ternary and quaternary compounds, such as Cu2ZnSnS4 (CZTS) for solar cell applications. Furthermore its scalability and

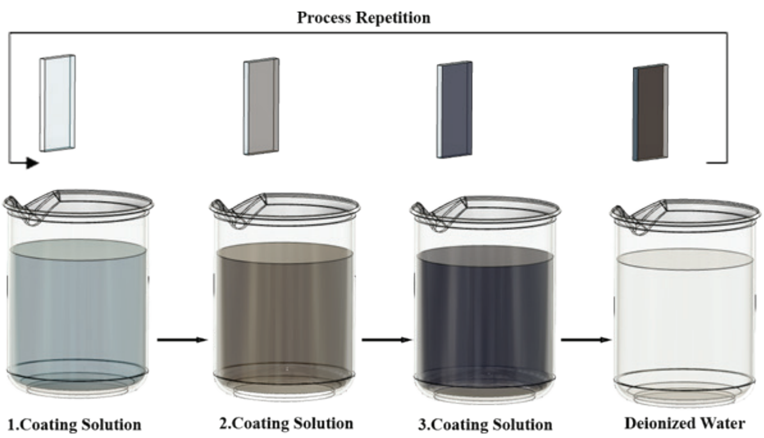

Figure 17. SILAR method [drawn by author].

ability to deposit a wide range of materials, including metal oxides, sulfides, and selenides, enhance its potential for industrial applications [120, 121].

Solid Deposition

Solid deposition is a technique for forming thin films or coatings without transitioning through a liquid or vapor phase. It involves the direct transfer of a solid precursor onto a substrate using mechanical, thermal or chemical processes. This method provides advantages such as uniform film formation, minimal waste production, and compatibility with temper. Solid-phase deposition (e.g., mechanical abrasion) is less common but useful for producing nanocrystalline materials, though it lacks the precision of vapor and liquid methods. Solid deposition, which is basically divided into two different methods: devitrification and mechanical abrasion, is less preferred than liquid and vapor deposition methods. Mechanical etching is defined as obtaining nanocrystalline materials as a result of the abrasion of coarse-grained structures on material surfaces. Powders of homogeneous (usually stoichiometric) composition, such as pure metals, inter-metallic or prelubricated powders are ground in a high-energy ball mill. Micro- and nano-structured materials can be produced by recombining the broken, high-energy particles in the ground material. By adjusting the grain sizes depending on the etching time and amount, extremely fine structures can be obtained. High purity, intermetallic and immiscible alloys in micro and nano dimensions can be obtained [122]. Devitrification is the obtaining of micro- and nano-structured coatings by con- trolled crystallization of amorphous materials within a certain temperature and time. In general, it can be defined as a method of rapid solidification. The crystal phase first nucleates on the free surface and amorphous crystalline structures form. Then, the amorphous phase obtained by rapid solidification crystallizes by lowering the temperature. Surface roughness causes the nucleation phase to be prolonged. When the nucleation rate increases, the film growth rate decreases. Films with different grain sizes can be produced by controlling crystallization parameters. Changes such as improving the magnetic properties of material surfaces and increasing the pores can be made with this method [123–125].

Application Areas of Semiconductor Thin Films in Technology

Thanks to their different electrical conductivity, ferromagnetic, ferroelectric and super- conductivity properties, thin films; It is widely used in solar cell structures, various parts of batteries, detectors, cosmetics industry, paint improvements [126], dye removal [127], pharmaceutical industry, plastic injection industry, optoelectronic devices [128], sensor applications [129–131] and semiconductor industry. Ge and Si elemental semi- conductors used in semiconductor device technology are inadequate in applications requiring performance due to their low mobility and low conductivity. Another reason for this is that it has an indirect band structure. Semiconductor materials with direct band structure are needed for optoelectronic applications. Group II-VI and group III-V compounds, which have a direct band structure, are very suitable semiconductors for optoelectronic applications. Group II-VI compounds are binary compounds formed between one of the group II elements of the periodic table, Zn, Hg, and Cd and one of the group VI elements O, S, Te, and Se. These compounds have a band gap ranging from 1.7 to 4 eV. Compounds II-VI, which have a wide band gap energy are used in optoelectronic applications in the short wavelength region of light. Group III-V compounds are binary compounds formed between group III elements and group V elements of the periodic table. The operating range of group III-V compounds is limited to wavelengths of 500 nm and above in optoelectronic applications. For this reason, II-VI group compounds are generally used in the production of semiconductor devices with wavelengths below 500 nm and operating in the blue and UV regions [132]. In technological studies, other uses of semiconductor thin films are metal oxides. Semiconductor metal oxide thin films attract a lot of attention in the production of electronic and optoelectronic devices, thanks to their properties such as the ability to form homo and hetero structures, their wide band gaps and their ability to be deposited on hard and flexible surfaces [133–135]. These materials, which have been preferred for many years as reflective or anti-reflective surface coatings thanks to their high refractive index are used with or without additives to increase the efficiency of solar cells as transparent conductive contacts. The fact that it can be used actively in the development and dissemination of energy-saving lighting applications attracts the attention of researchers and is the subject of many studies. In addition, semiconductor metal oxide thin films are ideal candidates for producing ultraviolet photodetectors, as they have a band gap higher than 3 eV. Furthermore, specific Group II-VI compounds such as ZnS, CdSe, and ZnO are widely utilized in UV photodetectors and blue-region optoelectronic devices due to their high electron mobility and direct bandgap, which enable high sensitivity and fast response times. Similarly, Group III-V compounds like GaAs, InP, and GaN are essential for high-efficiency solar cells, LEDs, and laser diodes. Their capability to function under high temperatures and electric fields also makes them ideal for power electronics and high-frequency applications [136, 137]. A number of new trends and alternative techniques have emerged in the field of thin-film semiconductor deposition. Vapour deposition is an effective method for coating nanostructured materials. This technique is carried out by allowing a molten material to penetrate a porous substrate. It is based on the principle of solidification to form a thin film. Molten infiltration enables the production of coatings on complex structures by operating at high temperatures [138]. The reactive molten infiltration technique, meanwhile, is widely used in the production of composite materials. In this method, the molten metal reacts with a porous substrate to form a thin film layer. It plays a significant role in the production of high-performance composite materials [139]. The Atomic Layer Deposition (ALD) method offers high homogeneity and quality in nanoscale coatings. It enables the precise deposition of thin film layers at the atomic level. ALD-based infiltration is widely used in applications such as energy storage, catalysts and sensors [140]. These new techniques hold significant potential in the field of semiconductor thin film deposition. These techniques are expected to be widely adopted in future applications. Depending on future research directions, it is of great importance to decide which thin-film coating methods will be used. The selection of the optimal coating method for semiconductor thin films depends largely on the type of substrate material, film properties, and available resources. Thanks to Chemical Vapour Deposition (CVD) and Physical Vapour Deposition (PVD) methods, it is possible to create high-purity, homogeneous and dense films. CVD is used to produce high-quality films with a high degree of coating compatibility. As a result, it is widely used in the semiconductor industry. PVD, performed using a sputtering method, is employed to apply microelectronic and wear-resistant coatings. It is the preferred choice for applications requiring precise control over film composition and strong adhesion, and enables the production of films with controllable electrical and optical properties. They can be used in high-performance applications such as transistors, diodes and sensors. On the other hand, liquid deposition methods such as sol-gel, SILAR and electrochemical deposition are cost-effective and easy to apply; consequently, they are effectively used for coating large surface areas and in applications where high-vacuum conditions are not feasible. For example, sol-gel methods are widely used for the production of transparent conductive oxides (TCOs) in solar cells and optoelectronic devices due to their ability to deposit homogeneous multilayer films at room temperature. Spray pyrolysis and electrochemical deposition methods, on the other hand, are widely used in industrial applications such as solar cells and flexible electronics. These methods are favoured because they can be easily applied to flexible substrates and carried out at low temperatures. They are suitable for use in wearable technologies and high-volume production. Solid-state deposition methods, such as mechanical abrasion and devitrification, are less common compared to other methods. These methods are useful for producing nanocrystalline materials and coatings with specific mechanical properties, but they lack the precision and homogeneity seen in vapour and liquid-phase methods. They are used primarily in specific applications where mechanical properties are of primary importance, and for this reason, their use is limited. As vacuum systems and vapour deposition methods requiring high energy inputs are costly, liquid deposition methods are generally preferred. Spray pyrolysis and electrochemical deposition methods can be readily applied to industrial production. Methods such as Molecular Beam Epitaxy (MBE) and laser evaporation are suitable for research and small-scale production due to their high costs and low deposition rates. Sol-gel and electrochemical deposition methods are more environmentally friendly compared to CVD and PVD methods, which involve toxic precursors and high energy consumption. Using CVD and PVD methods, the thickness and composition of thin films can be precisely controlled, allowing for the production of high-quality, flawless films. Consequently, these methods are used in high-performance microelectronics. Sol-gel and spray pyrolysis methods are preferred for large-area coatings in solar cells. They are widely used due to their suitability for industrial production and cost advantages. For wear-resistant coatings, spray methods and PVD methods are preferred due to their high adhesion and mechanical properties. In flexible electronics, liquid coating methods such as spin coating and dip coating are used due to their compatibility with flexible substrates and their ability to be processed at low temperatures. The selection of the best thin-film coating method depends on careful evaluation of application requirements, desired film properties, and economic constraints. While vapor deposition methods offer film quality and precision, liquid deposition methods provide a cost-effective and scalable alternative for many applications.

CONCLUSION

In this study, deposition methods of semiconductor thin films are reviewed in detail. Deposition methods are basically divided into three as vapor phase, liquid phase and solid phase deposition. Among these, vapor phase and liquid phase deposition methods are the most studied methods in the literature. Vapor phase deposition is examined under two main headings: evaporation and sputtering. Evaporation is divided into physical vapor deposition (PVD) and chemical vapor deposition (CVD). There are three types of sputtering: RF sputtering, RF magnetron sputtering and DC sputtering. It is possible to produce homogeneous and high-quality thin films of low thickness with vapor phase deposition methods. Vapor phase deposition techniques are best suited for thin films used in electronics and optoelectronic device manufacturing and industrial applications such as solar cells and sensors. These techniques involve high technology and are very costly. Liquid phase deposition basically includes sol gel, chemical bath deposition, electrochemical deposition and SILAR methods. These methods have a wide range of uses thanks to their advantages such as easy coating of substrates of all shapes, low installation and operating costs, no need for vacuum, deposition at room temperature and homogeneous deposition of multilayer thin films. Liquid phase deposition techniques which are often preferred in R&D studies carried out in laboratories where the fundamentals of thin film production techniques are investigated. They are the most suitable for laboratories, especially considering their simplicity of installation and ease of operation. For these reasons, among the thin film deposition methods, the most commonly used methods in the literature are liquid phase deposition methods. The numbers of studies conducted are given in a table according to the methods. Solid phase deposition is of two types: mechanical etching and devitrification. Compared to vapor phase and liquid phase deposition methods, it is a much less preferred method in the literature for thin film deposition. Solid phase deposition techniques are not generally preferred in industry and R&D studies. When we look at the number of thin film studies deposited with all these methods, it can be seen how important thin film technology is and how up-to-date it remains. It has been observed that there are fewer comprehensive studies in the literature on the long-term stability and environmental impact of thin film deposition methods, especially for emerging technologies such as nanomachines and flexible electronics. In addition, it is anticipated that more research is needed on the integration of different deposition techniques to improve film properties for specific applications. In addition, the development of hybrid deposition techniques that combine the advantages of vapor and liquid phase methods and the application of environmentally friendly precursors and methods in thin film deposition processes are proposed as suggestions within the scope of this study. Future research in this direction may contribute to the creation of more sustainable and efficient thin film production processes.

ACKNOWLEDGEMENTS

This work was supported by Bilecik Seyh Edebali University, Project Number 2021-02. BŞEÜ.17-01. The authors would like to thank for this support.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

REFERENCES

[1] Abegunde OO, Akinlabi ET, Oladijo OP, Akinlabi S, Ude AU. Overview of thin film deposition techniques. AIMS Mater Sci 2019;6:174–199. [CrossRef]

[2] Liu K, Ouyang B, Guo X, Guo Y, Liu Y. Advances in flexible organic field-effect transistors and their applications for flexible electronics. NPJ Flex Electron 2022;6:1. [CrossRef]

[3] Chen H, Xu Q, Wang J, Li P, Yuan J, Lyu B, et al. Effect of surface quality on hydrogen/helium irradiation behavior in tungsten. Nucl Eng Technol 2022;54:1947–1953. [CrossRef]

[4] Elaryian HM, Bedair MA, Bedair AH, Aboushahba RM, Fouda AEAS. Synthesis, characterization of novel coumarin dyes as corrosion inhibitors for mild steel in acidic environment: Experimental, theoretical, and biological studies. J Mol Liq 2022;346:118310. [CrossRef]

[5] Hosseingholilou S, Dorranian D. Electrophoretic deposited gold nanoparticle thin film on silver substrate. IET Optoelectron 2023;17:51–60. [CrossRef]

[6] Boulmelh S, Sekhane D, Kaghouche B, Saci L. Physical, electrical and dielectric properties of pure ZnO thin films deposited by SP method: Effect of substrate temperature. In: 2022 2nd International Conference on Advanced Electrical Engineering (ICAEE). 2022. p. 1–6. [CrossRef]

[7] Amananti W, Ardiyanto R, Sutanto H, Nurhasanah I, Tivani I. Analysis of the optical properties of ZnO thin films deposited on a glass substrate by the sol-gel method. J Nat Sci Math Res 2022;8:52–58. [CrossRef]

[8] Stoian M, Maurer T, Lamri S, Fechete I. Techniques of preparation of thin films: Catalytic combustion. Catalysts 2021;11:1530. [CrossRef]

[9] Liang Z, Zhou S, Cai W, Fu X, Ning H, Chen J, et al. Zirconium-aluminum-oxide dielectric layer with high dielectric and relatively low leakage prepared by spin-coating and the application in thin-film transistor. Coatings 2020;10:282. [CrossRef]

[10] Lee H, Lee S, Kim Y, Siddik AB, Billah MM, Lee J, et al. Improvement of stability and performance of amorphous indium gallium zinc oxide thin film transistor by zinc-tin-oxide spray coating. IEEE Electron Device Lett 2020;41:1520–1523. [CrossRef]

[11] Zhuang X, Han S, Huai B, Shi W, Junsheng Y. Sub-ppm and high response organic thin-film transistor NO2 sensor based on nanofibrillar structured TIPS-pentacene. Sens Actuators B Chem 2019;279:238–244. [CrossRef]

[12] Lin FJ, Chen HH, Tao YT. Molecularly aligned hexa-peri-hexabenzocoronene films by brush-coating and their application in thin-film transistors. ACS Appl Mater Interfaces 2019;11:10801–10809. [CrossRef]
[13] Chen D, Xu Y, An Z, Li Z, Zhang C. Thin-film transistors based on wide bandgap Ga2O3 films grown by aqueous-solution spin-coating method. Micro Nano Lett 2019;14:1052–1055. [CrossRef]
[14] Kwon EH, Jang YJ, Kim GW, Kim M, Park YD. Highly crystalline and uniform conjugated polymer thin films by a water-based biphasic dip-coating technique minimizing the use of halogenated solvents for transistor applications. RSC Adv 2019;9:6356–6362. [CrossRef]
[15] Wang R, Kwon HJ, Tang X, Ye H, Park CE, Kim J, et al. Slot-die coating of sol–gel-based organic–inorganic nanohybrid dielectric layers for flexible and large-area organic thin film transistors. Appl Surf Sci 2020;529:147198. [CrossRef]
[16] Amir H, Ponpandian N, Viswanathan C. An electrochemical dopamine sensor based on RF magnetron sputtered TiO2/SS thin film electrode. Mater Lett 2021;300:130175. [CrossRef]
[17] Sertel BC, Sonmez NA, Kaya MD, Ozcelik S. Development of MgO: TiO2 thin films for gas sensor applications. Ceram Int 2019;45:2917–2921. [CrossRef]
[18] Al-Hazeem NZ, Ahmed NM, Matjafri M, Bououdina M. Hydrogen gas sensor based on nanofibers TiO2-PVP thin film at room temperature prepared by electrospinning. Microsyst Technol 2021;27:293–299. [CrossRef]
[19] Sankarasubramanian K, Babu KJ, Soundarrajan P, Logu T, Gnanakumar G, Ramamurthi K, et al. A new catalyst Ti-doped CdO thin film for non-enzymatic hydrogen peroxide sensor application. Sens Actuators B Chem 2019;285:164–172. [CrossRef]
[20] Rajput JK, Pathak TK, Purohit L. Impact of sputtering power on properties of CdO: ZnO thin films synthesized by composite method for oxygen gas sensing application. J Electron Mater 2019;48:6640–6646. [CrossRef]
[21] Nakate UT, Patil P, Ghule B, Nakate YT, Ekar S, Ambare RC, et al. Room temperature LPG sensing properties using spray pyrolysis deposited nano-crystalline CdO thin films. Surf Interfaces 2019;17:100339. [CrossRef]
[22] Kaur M, Shaheera M, Pathak A, Gadkari S, Debnath A. Highly sensitive NO2 sensor based on ZnO nanostructured thin film prepared by SILAR technique. Sens Actuators B Chem 2021;335:129678. [CrossRef]
[23] Tharsika T, Thanihaichelvan M, Haseeb A, Akbar SA. Highly sensitive and selective ethanol sensor based on ZnO nanorod on SnO2 thin film fabricated by spray pyrolysis. Front Mater 2019;6:122. [CrossRef]
[24] Elsheikh AH, Sharshir SW, Ali MKA, Shaibo J, Edreis EM, Abdel-Hamid T, et al. Thin film technology for solar steam generation: A new dawn. Sol Energy 2019;177:561–575. [CrossRef]
[25] Duan Z, Liang X, Feng Y, Ma H, Liang B, Wang Y, et al. Sb2Se3 thin-film solar cells exceeding 10% power conversion efficiency enabled by injection vapor deposition technology. Adv Mater 2022;34:2202969. [CrossRef]
[26] Sinha T, Verma L, Khare A. Variations in photovoltaic parameters of CdTe/CdS thin film solar cells by changing the substrate for the deposition of CdS window layer. Appl Phys A Mater Sci Process 2020;126:867. [CrossRef]
[27] Rahman KS, Harif MN, Rosly HN, Kamaruzzaman MIB, Akhtaruzzaman M, Alghoul M, et al. Influence of deposition time in CdTe thin film properties grown by close-spaced sublimation (CSS) for photovoltaic application. Results Phys 2019;14:102371. [CrossRef]
[28] Abchi A, Belkhir N, Rubio Alonso J. Effect of storage and surface roughness on the SiO2 thin films adhesion behavior. J Adhes Sci Technol 2022;36:168–194. [CrossRef]
[29] Kim H, Horwitz J, Kushto G, Pique A, Kafafi Z, Gilmore C, et al. Effect of film thickness on the properties of indium tin oxide thin films. J Appl Phys 2000;88:6021–6025. [CrossRef]
[30] Alaboodi AS, Hussain Z. Finite element modeling of nano-indentation technique to characterize thin film coatings. J King Saud Univ Eng Sci 2019;31:61–69. [CrossRef]
[31] Karuppaiah M, Sakthivel P, Asaithambi S, Balaji V, Vijayaprasath G, Yuvakkumar R, et al. In-situ deposition of amorphous tungsten (VI) oxide thin-film for solid-state symmetric supercapacitor. Ceram Int 2022;48:2510–2521. [CrossRef]
[32] Sönmezoğlu S, Koç M, Akın S. İnce film üretim teknikleri. Erciyes Univ Fen Bilimleri Enstitusu Derg 2012;28:389–404.
[33] Zhang S, Galuska LA, Gu X. Water-assisted mechanical testing of polymeric thin-films. J Polym Sci 2022;60:1108–1129. [CrossRef]
[34] Lokhande C, Pawar S. Electrodeposition of thin film semiconductors. Phys Status Solidi A 1989;111:17–40. [CrossRef]
[35] Yang Y, Maeng B, Jung DG, Lee J, Kim Y, Kwon J, et al. Annealing effects on SnO2 thin film for H2 gas sensing. Nanomaterials 2022;12:3227. [CrossRef]
[36] Liu J, Lv J, Xiong H, Wang Y, Jin G, Zhai Z, et al. Size effect and comprehensive mathematical model for gas-sensing mechanism of SnO2 thin film gas sensors. J Alloys Compd 2022;898:162875. [CrossRef]
[37] Moumen A, Kumarage GC, Comini E. P-type metal oxide semiconductor thin films: Synthesis and chemical sensor applications. Sensors 2022;22:1359. [CrossRef]

[38] Sanchela AV, Wei M, Cho HJ, Ohta H. Optoelectronic properties of transparent oxide semiconductor ASnO3 (A=Ba, Sr, and Ca) epitaxial films and thin film transistors. J Vac Sci Technol A 2022;40:010801. [CrossRef]
[39] Nguyen NN, Lee H, Lee HC, Cho K. van der Waals epitaxy of organic semiconductor thin films on atomically thin graphene templates for optoelectronic applications. Acc Chem Res 2022;55:673–684. [CrossRef]
[40] Kim J, Jeong S, Sarawut S, Kim H, Son SU, Lee S, et al. An immunosensor based on a high performance dual-gate oxide semiconductor thin-film transistor for rapid detection of SARS-CoV-2. Lab Chip 2022;22:899–907. [CrossRef]
[41] Karakuş E, Koç MM. Temel ince film üretim tekniklerine bir bakış. Kırklareli Univ Muh Fen Bil Derg 2023;9:213–236. [CrossRef]
[42] Coşğun A, Taşçıoğlu A, Yılmaz G. İnce film üretiminde kimyasal buhar biriktirme yöntemi ve çeşitleri. Mehmet Akif Ersoy Univ Fen Bilimleri Enstitusu Derg 2021;12:351–363. [CrossRef]
[43] Abegunde OO, Akinlabi ET, Oladijo OP, Akinlabi S, Ude AU. Overview of thin film deposition techniques. AIMS Mater Sci 2019;6:174–199. [CrossRef]
[44] Gupta G, Tyagi R, Rajput S, Saxena P, Vashisth A, Mehndiratta S. PVD based thin film deposition methods and characterization/property of different compositional coatings: A critical analysis. Mater Today Proc 2021;38:259–264. [CrossRef]
[45] Qadir M, Li Y, Wen C. Ion-substituted calcium phosphate coatings by physical vapor deposition magnetron sputtering for biomedical applications: A review. Acta Biomater 2019;89:14–32. [CrossRef]
[46] Murphy M. Vacuum coating (physical vapor deposition). Met Finish 1997;95:32. [CrossRef]
[47] Abegunde OO, Akinlabi ET, Oladijo OP, Akinlabi S, Ude AU. Overview of thin film deposition techniques. AIMS Mater Sci 2019;6:174–199. [CrossRef]
[48] Deng Y, Chen W, Li B, Wang C, Kuang T, Li Y. Physical vapor deposition technology for coated cutting tools: A review. Ceram Int 2020;46:18373–18390. [CrossRef]
[49] Baptista A, Silva F, Porteiro J, Míguez J, Pinto G, Fernandes L. On the physical vapour deposition (PVD): Evolution of magnetron sputtering processes for industrial applications. Procedia Manuf 2018;17:746–757. [CrossRef]
[50] Javaid K, Ashfaq M, Saleem M, Amin N, Ali A, Mahmood K, et al. Structural and thermoelectric properties of nanostructured p-SnO thin films grown by e-beam evaporation method. Int J Hydrogen Energy 2022;47:15547–15555. [CrossRef]
[51] Zhao LA, Zhang Y, Sun K, Song L, Xu H, Guo X, et al. Crown-ether modified thermally evaporated perovskite light-emitting devices with increased operational stability. J Lumin 2022;252:119317. [CrossRef]
[52] Kaewsuwan D, Wongpinij T, Euaruksakul C, Chanlek N, Triamnak N, Lertvanithphol T, et al. Photoluminescence of tin dioxide (SnO2) nanostructure grown on Si (001) by thermal evaporation technique. Radiat Phys Chem 2023;206:110805. [CrossRef]
[53] Patel NF, Bhakhar SA, Jagani HS, Solanki GK, Pataniya PM. Synthesis, characterization and optoelectronic application of Bi2Se3 thin film prepared by thermal evaporation technique. Opt Mater 2023;136:113403. [CrossRef]
[54] Bae SR, Heo DY, Kim SY. Recent progress of perovskite devices fabricated using thermal evaporation method: Perspective and outlook. Mater Today Adv 2022;14:100232. [CrossRef]
[55] Zheng J, Ye L, He M, He D, Huang Y, Yu J, et al. Electrical and optical properties of amorphous silicon carbide thin films prepared by e-beam evaporation at room temperature. J Non Cryst Solids 2022;576:121233. [CrossRef]
[56] Zainal N, Samsudin MEA, Taib MIM, Ahmad MA, Shuhaimi A. Influence of post-ammonia annealing temperature on e-beam evaporation deposited GaN layer on patterned sapphire substrate. Superlattices Microstruct 2020;148:106722. [CrossRef]
[57] Schalk N, Tkadletz M, Mitterer C. Hard coatings for cutting applications: Physical vs. chemical vapor deposition and future challenges for the coatings community. Surf Coat Technol 2022;429:127949. [CrossRef]
[58] Li Z, Huang J, Zhang Z, Zhao F, Wu Y. Preparation of high purity nano-silicon powders by direct current arc plasma evaporation method. Mater Sci Eng B 2018;229:6–12. [CrossRef]
[59] Liu ZR, Zhang J, Sun X, Du JW, Wang SQ, Chen L. Microstructure, mechanical properties, and oxidation behavior of arc-evaporated Cr–Al–O–N coatings with various Cr/Al ratios. Ceram Int 2023;49:16412–16421. [CrossRef]
[60] Geng D, Xu YX, Peng B, Li H, Wang Q, Kim KH. Comparative study on mechanical and tribological properties of Cr–Al–N and Cr–Al–O coatings deposited by cathodic arc evaporation. Tribol Int 2023;177:107989. [CrossRef]
[61] Joshi N, Debnath AK, Aswal DK, Muthe KP, Kumar MS, Gupta SK, et al. Morphology and resistivity of Al thin films grown on Si (111) by molecular beam epitaxy. Vacuum 2005;79:178–185. [CrossRef]
[62] Avdienko PS, Sedova IV, Galimov AI, Rakhlin MV, Kirilenko DA, Sorokin SV. Molecular beam epitaxy and polarized excitonic emission of layered GaTe/GaAs thin films. J Cryst Growth 2022;592:126716. [CrossRef]
[63] Klochkov AN, Vinichenko AN, Samolyga AA, Ryndya SM, Poliakov MV, Kargin NI, et al. Growth by molecular beam epitaxy and characterization of n-InAs films on sapphire substrates. Appl Surf Sci 2023;619:156722. [CrossRef]

[64] Tsuboi K, Su N, Kobayashi S, Sugimoto K, Kobayashi M. Molecular beam epitaxy of stoichiometric tin–telluride thin films. J Cryst Growth 2022;597:126805. [CrossRef]

[65] Qian K, An Y, Cai H, Yang K, Qian J, Ding H, et al. The transition of growth behaviors of moderate Sn fraction Ge1-xSnx (8%<x<15%) epilayers with low temperature molecular beam epitaxy. J Cryst Growth 2023;601:126954. [CrossRef]

[66] Zeng X, Pelenovich V, Neena D, Xu C, Zhang X, Pogrebnjak A, et al. Thermal stability of high entropy graded solar selective absorbers deposited by non-equilibrium RF magnetron sputtering. J Alloys Compd 2023;944:169248. [CrossRef]

[67] Suárez S, Pacha J, Fernández S, Gómez-Mancebo MB, Sánchez FJ, Martínez C, et al. Parameters to be considered for the development of highly photoactive TiO2 layers on aluminium substrates by RF magnetron sputtering for treating polluted air. Catal Today 2023;413:113970. [CrossRef]

[68] Pandey A, Tyagi S, Singh BP, Kumar L. Surface morphological and optical evolution of RF sputtered AZO films for optoelectronic devices. Physica B Condens Matter 2022;647:414393. [CrossRef]

[69] Soetedjo H, Siswanto B, Aziz I, Sudjatmoko. Deposition of Cu-doped PbS thin films with low resistivity using DC sputtering. Results Phys 2018;8:903–907. [CrossRef]

[70] Najm N, Ataiwi AH, Anaee RA. Effect of indium coating on corrosion behavior of AZ31 Mg alloy by DC sputtering. Mater Today Proc 2022;62:4551–4555. [CrossRef]

[71] Sanjana T, Sunil MA, Shaik H, Kumar KN. Studies on DC sputtered cuprous oxide thin films for solar cell absorber layers. Mater Chem Phys 2022;281:125922. [CrossRef]

[72] Shumilin AI, Fomin AA. Tantalum-containing coatings with superhard inclusions produced by DC-magnetron sputtering. Int J Refract Met Hard Mater 2023;112:106133. [CrossRef]

[73] Jangid MK, Sharma SS, Ray J, Yadav DK, Lal C. Structural, optical and electrical characterizations of Mg/Ti/Ni multilayer thin films deposited by DC magnetron sputtering for hydrogen storage. Int J Hydrogen Energy 2023;48:37921–37929. [CrossRef]

[74] Katamune Y, Izumi A, Ichikawa K, Koizumi S. Heavy phosphorus doping of diamond by hot-filament chemical vapor deposition. Diam Relat Mater 2023;135:109789. [CrossRef]

[75] Ghanghass A, Sameera I, Bhatia R. Multilayer growth of tungsten disulphide using thermal chemical vapour deposition. Mater Today Proc 2023;74:197–201. [CrossRef]

[76] Gao X, Xiao R, Zhang Y, Chen Z, Kang H, Wang S, et al. Etching effect of hydrogen and oxygen on the chemical vapor deposition graphene on Cu. Thin Solid Films 2022;758:139436. [CrossRef]

[77] Feng ZC, Lin HH, Xin B, Tsai SJ, Saravade V, Yiin J, et al. Structural characteristics of 3C–SiC thin films grown on Si-face and C-face 4H–SiC substrates by high temperature chemical vapor deposition. Vacuum 2023;207:111643. [CrossRef]

[78] Shen Q, Song Q, Xiao C, Fu Q, Li W, Zhang S, et al. Ultrahigh thermal conductive graphite film via the in-situ construction of aligned nanographene skeleton using chemical vapor deposition. J Mater Sci Technol 2023;148:1–9. [CrossRef]

[79] Kuruganti VV, Wurmbrand D, Buck T, Seren S, Zeman M, Isabella O, et al. Industrially viable diffused IBC solar cells using APCVD dopant glass layers. Sol Energy Mater Sol Cells 2023;251:112111. [CrossRef]

[80] Deelen J, Illiberi A, Kniknie B, Steijvers H, Lankhorst A, Simons P. APCVD of ZnO:Al, insight and control by modeling. Surf Coat Technol 2013;230:239–244. [CrossRef]

[81] Chen MC, Cheng YC, Huang CY, Wang HC, Lin KI, Yang ZP. The action of silicon doping in the first two to five barriers of eight periods In0.2Ga0.8N/GaN multiple quantum wells of blue LEDs. J Lumin 2016;177:59–64. [CrossRef]

[82] Jung SC, Bang HJ, Lee H, Kim H, Ha HH, Yu YH, et al. Degradation behaviors of naproxen by a hybrid TiO2 photocatalyst system with process components. Sci Total Environ 2020;708:135216. [CrossRef]

[83] Abd Hair AH, Salleh KM, Purhanudin N, Khairunnisa-Atiqah MK, Mazlan NSN, Awang R, et al. The influence of PECVD-nitrogen plasma treatment on the surface modification of woven cotton gauze wound dressing. Mater Today Proc 2023;75:51–57. [CrossRef]

[84] Pham DP, Kim H, Choi J, Oh D, Chung YB, Jeon WS, et al. In-situ PECVD-based stoichiometric SiO2 layer for semiconductor devices. Opt Mater 2023;137:113536. [CrossRef]

[85] Hang L, Liu W, Zhang X, Zhou S, Xu J, Li C. Design and preparation of high-transmittance broadband antireflection coatings with tailored refractive indices deposited by PECVD. Vacuum 2023;208:111714. [CrossRef]

[86] An K, Lee HN, Cho KH, Han YJ, Kang KT. Two-step fabrication of thin film encapsulation using laser assisted chemical vapor deposition and laser assisted plasma enhanced chemical vapor deposition for long-lifetime organic light emitting diodes. Org Electron 2021;91:106078. [CrossRef]

[87] Sharma B, Sharma A. Enhanced surface dynamics and magnetic switching of α-Fe2O3 films prepared by laser assisted chemical vapor deposition. Appl Surf Sci 2021;567:150724. [CrossRef]

[88] Singh S, Verma P, Gautam RK, Tyagi R. Effect of counterface materials on friction and wear of graphene-coated steel under dry sliding contact. Mater Today Proc 2021;47:6660–6663. [CrossRef]

[89] Ding J, Chen S, Han N, Shi Y, Hu P, Li H, et al. Aerosol assisted chemical vapour deposition of nanostructured ZnO thin films for NO2 and ethanol monitoring. Ceram Int 2020;46:15152–15158. [CrossRef]
[90] Simon A, Richter H, Reif B, Schuelein M, Sanwald D, Schwieger W. Evaluation of a method for micro-defect sealing in ZSM-5 zeolite membranes by chemical vapor deposition of carbon. Sep Purif Technol 2019;219:180–185. [CrossRef]
[91] Pakula D, Staszuk M, Dziekońska M, Koźmín P, Čermák A. Structure and properties of coating obtained by chemical vapour deposition with the laser microstructuring. Vacuum 2018;153:184–190. [CrossRef]
[92] Ehsan MA, Khan A, Zafar MN, Akber UA, Hakeem AS, Nazar MF. Aerosol-assisted chemical vapor deposition of nickel sulfide nanowires for electrochemical water oxidation. Int J Hydrogen Energy 2022;47:42001–42012. [CrossRef]
[93] Hou J, Fu J, Ali R, Liu Y, Jian X. Constructing carbon-decorated CFx nanocapsule by atomic layer deposition and catalytic chemical vapor deposition for high-capacity lithium primary battery. Appl Surf Sci 2022;596:153570. [CrossRef]
[94] Fu J, Sun Y, Ji Y, Zhang J. Fabrication of robust ceramic based superhydrophobic coating on aluminum substrate via plasma electrolytic oxidation and chemical vapor deposition methods. J Mater Process Technol 2022;306:117641. [CrossRef]
[95] Akyol F, Demir I. Close oxygen coupled low-pressure chemical vapor deposition growth of high quality β-Ga2O3 on sapphire. Mater Sci Semicond Process 2022;146:106645. [CrossRef]
[96] Gozukizil MF. pH effect on structural, morphological and optical properties of ZnO thin films produced by chemical bath deposition method. Eur Chem Bull 2020;9:335–338. [CrossRef]
[97] Uhlmann DR, Suratwala T, Davidson K, Boulton JM, Teowee G. Sol-gel derived coatings on glass. J Non Cryst Solids 1997;218:113–122. [CrossRef]
[98] Balzarotti R, Cristiani C, Francis LF. Combined dip-coating/spin-coating depositions on ceramic honeycomb monoliths for structured catalysts preparation. Catal Today 2019;334:90–95. [CrossRef]
[99] Benrezgua E, Deghfel B, Zoukel A, Basirun W, Amari R, Boukhari A, et al. Synthesis and properties of copper doped zinc oxide thin films by sol-gel, spin coating and dipping: A characterization review. J Mol Struct 2022;1267:133639. [CrossRef]
[100] Gozukizil MF, Temel S, Ozbay N. Production and characterization of Al-doped ZnO thin films with sol-gel magnetic spin coating technique. Sakarya Univ J Sci 2020;24:172–177. [CrossRef]
[101] Gozukizil MF, Temel S, Ozbay N. Some physical properties of CZO thin films produced by a novel magnetic spin coating technique. Sigma J Eng Nat Sci 2021;38:955–960. [CrossRef]
[102] Dahnoun M, Attaf A, Saidi H, Yahia A, Khelifi C. Structural, optical and electrical properties of zinc oxide thin films deposited by sol-gel spin coating technique. Optik 2017;134:53–59. [CrossRef]
[103] Ozturk O, Asikuzun E, Hacioglu ZB, Safran S. Characteristics of ZnO:Er nano thin films produced different thickness using different solvent by sol-gel method. Politeknik Derg 2022;25:37–45. [CrossRef]
[104] Fernández-Hernán JP, López AJ, Torres B, Rams J. Influence of roughness and grinding direction on the thickness and adhesion of sol-gel coatings deposited by dip-coating on AZ31 magnesium substrates: A Landau-Levich equation revision. Surf Coat Technol 2021;408:126798. [CrossRef]
[105] Beyribey B, Bayne J, Persky J. The effect of dip-coating parameters on the thickness and uniformity of BCZYZ electrolyte layer on porous NiO-BCZYZ tubular supports. Ceram Int 2022;48:6046–6051. [CrossRef]
[106] Jacobs M, Vos YD, Middelkoop V. Thickness controlled SiO2/TiO2 sol-gel coating by spraying. Open Ceram 2021;6:100121. [CrossRef]
[107] Murthy MN, Sreelatha CJ, Ravinder G, Anusha S. The effect of solution pH on the structural, surface morphological, and optical characteristics of ZnO thin films synthesized by the chemical bath deposition technique. Mater Today Proc 2022;54:602–607. [CrossRef]
[108] Hussain RA, Hussain I. Copper selenide thin films from growth to applications. Solid State Sci 2020;100:106101. [CrossRef]
[109] Babu P, Reddy KTR, Miles RW. Precursor concentration effect on the properties of ZnIn2Se4 layers grown by chemical bath deposition. Energy Procedia 2011;10:177–181. [CrossRef]
[110] Liu Y, McDowell LL, Su L, Luo Y, Qiu J, Shi Z. Morphological and microstructural evolution of high-quality PbSe epitaxial film on Si substrate by chemical bath deposition. Mater Sci Semicond Process 2022;150:106963. [CrossRef]
[111] Abdulwahab AM, AL-Adhreai AA, Ahmed AAA. Influence of Ni-Co dual doping on structural and optical properties of CdSe thin films prepared by chemical bath deposition method. Optik 2021;236:166659. [CrossRef]
[112] Terasako T, Hamamoto K, Yagi M, Furubayashi Y, Yamamoto T. Structural and photoluminescence properties of zinc oxide nanorods grown on various transparent conducting oxide seed layers by chemical bath deposition. Thin Solid Films 2021;732:138803. [CrossRef]
[113] Temel S, Gokmen F, Yaman E. An energy efficient way to produce zinc-based semiconductor thin films via chemical bath deposition technique. J Sustain Dev Energy Water Environ Syst 2019;7:253–260. [CrossRef]

[114] Sanaullah I, Khan HN, Sajjad A, Khan S, Sabri AN, Naseem S, et al. Improved osteointegration response using high strength perovskite BaTiO3 coatings prepared by chemical bath deposition. J Mech Behav Biomed Mater 2023;138:105635. [CrossRef]
[115] Radaf IME, AlKhalifah MS, El-Bana MS. Highlights on the structural, optical, and optoelectrical properties of novel InSbO3 thin films synthesized by chemical bath deposition. J Non Cryst Solids 2022;588:121612. [CrossRef]
[116] Chu T, Cheng M, Hou S, Yang Y. Modified graphite paper treated by anionic intercalation for manganese removal via electrochemical deposition in water treatment. J Ind Eng Chem 2023;120:504–513. [CrossRef]
[117] Gorejová R, Oriňaková R, Králová ZO, Sopčák T, Šišoláková I, Schnitzer M, et al. Electrochemical deposition of a hydroxyapatite layer onto the surface of porous additively manufactured Ti6Al4V scaffolds. Surf Coat Technol 2023;455:129207. [CrossRef]
[118] Thirumoorthi M, Dhavud SS, Ganesh V, Al Abdulaal TH, Yahia IS, Deivatamil D. High responsivity n-ZnO/p-CuO heterojunction thin film synthesised by low-cost SILAR method for photodiode applications. Opt Mater 2022;128:112410. [CrossRef]
[119] Bagwade PP, Malavekar DB, Magdum VV, Khot SD, Nikam RP, Patil DJ, et al. Nanocrystalline cobalt tungstate thin films prepared by SILAR method for electrocatalytic oxygen evolution reaction. Int J Hydrogen Energy 2023;48:8465–8477. [CrossRef]
[120] Soo JY, Ameruddin AS, Ahmad MK. Co-sensitising cadmium selenide and cadmium telluride quantum dots on titanium dioxide nanorods via the SILAR method. Chem Phys Lett 2022;809:140170. [CrossRef]
[121] Gulduren ME, Taser A, Guney H. Mn-doping-induced tunable bandgap and luminescence properties of SnO2 nanoparticles grown by SILAR method. Opt Mater 2021;121:111606. [CrossRef]
[122] Suryanarayana C. Mechanical alloying of nanocrystalline materials and nanocomposites. Madridge J Nanotechnol Nanosci 2019;4:127–134. [CrossRef]
[123] Bhattacharya D, Tiwari N, Krishna PSR, Bhattacharyya D. Evolution of local atomic structure accompanying devitrification of amorphous Ni-Zr alloy thin films. Thin Solid Films 2022;762:139544. [CrossRef]
[124] Donaldson OK, Hattar K, Trelewicz JR. Metastable tantalum oxide formation during the devitrification of amorphous tantalum thin films. J Am Ceram Soc 2016;99:3775–3783. [CrossRef]
[125] Antonowicz J, Zalden P, Sokolowski-Tinten K, Georgarakis K, Minikayev R, Pietnoczka A, et al. Devitrification of thin film Cu–Zr metallic glass via ultrashort pulsed laser annealing. J Alloys Compd 2021;887:161437. [CrossRef]
[126] Prasad AK, Park JY, Jung HY, Kang JW, Kang SH, Ahn KS. Electrochemical deposition of Ni-WO3 thin-film composites for electrochromic energy storage applications: Novel approach toward quantum-dot-sensitized solar cell-assisted Ni-WO3 electrochromic device. J Ind Eng Chem 2023;117:500–509. [CrossRef]
[127] Kütük N, Boran F, Gürer SC. Mor lahana özütü kullanarak grafen oksitin indirgenmesi ve oksidasyon ile fotokatalitik aktivitesinin incelenmesi. Gazi Univ Muh Mim Fak Derg 2023;38:1331–1344. [CrossRef]
[128] Demirbilek N, Kaya M, Yakuphanoğlu F. Saf ZnO ve katkılı ZnO: Al: Mn x (x=1%, 2%, 3%, 5% at.) yarı iletken ince filmlerin yapısal ve optiksel özellikleri ile üretilen diyotların elektriksel özelliklerinin araştırılması. Gazi Univ Muh Mim Fak Derg 2023;38:1545–1556. [CrossRef]
[129] Er İK. Düşük hidrojen gaz konsantrasyonunda tungsten katkılı ZnO ince filmlerin gaz sensörü uygulamaları. Politeknik Derg 2021;24:1055–1062. [CrossRef]
[130] Han J, Li D, Zhao C, Wang X, Li J, Wu X. Highly sensitive impact sensor based on PVDF-TrFE/nano-ZnO composite thin film. Sensors 2019;19:830. [CrossRef]
[131] Nagmani, Pravarthana D, Tyagi A, Jagadale TC, Prellier W, Aswal DK. Highly sensitive and selective H2S gas sensor based on TiO2 thin films. Appl Surf Sci 2021;549:149281. [CrossRef]
[132] Temel S. Deposition and characterization of (MgO)x(ZnO)1−x thin films [dissertation]. Eskisehir: Eskisehir Osmangazi University; 2015.
[133] Zheng ZH, Shi XL, Ao DW, Liu WD, Li M, Kou LZ, et al. Harvesting waste heat with flexible Bi2Te3 thermoelectric thin film. Nat Sustain 2023;6:180–191. [CrossRef]
[134] Ma F, Ao D, Liu X, Liu WD. Ti-doping inducing high-performance flexible p-type Bi0.5Sb1.5Te3-based thin film. Ceram Int 2023;49:18584–18591. [CrossRef]
[135] Ramarajan R, Joseph DP, Thangaraju K, Kovendhan M. Role of defects on the transparent conducting properties of binary metal oxide thin film electrodes. In: Metal oxide defects. Elsevier; 2023. p. 387–420. [CrossRef]
[136] Yang SC, Lin TY, Ochoa M, Lai H, Kothandaraman R, Fu F, et al. Efficiency boost of bifacial Cu(In,Ga)Se2 thin-film solar cells for flexible and tandem applications with silver-assisted low-temperature process. Nat Energy 2022;8:40–51. [CrossRef]
[137] Kaur D, Debata S, Singh DP, Kumar M. Strain effects on the optoelectronic performance of ultra-wide band gap polycrystalline β-Ga2O3 thin film grown on differently-oriented silicon substrates for solar blind photodetector. Appl Surf Sci 2023;616:156446. [CrossRef]

[138] de Jongh PE, Eggenhuisen TM. Melt infiltration: An emerging technique for the preparation of novel functional nanostructured materials. Adv Mater 2013;25:6672–6690. [CrossRef]

[139] Shahzad S, Iqbal K, Uddin Z. Theoretical study of reactive melt infiltration to fabricate Co-Si/C composites. Chin Phys B 2021;30:116102. [CrossRef]

[140] Subramanian A, Tiwale N, Nam CY. Review of recent advances in applications of vapor-phase material infiltration based on atomic layer deposition. JOM 2019;71:185–196. [CrossRef]