ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue IX, September 2025

Advancements in Precursors, Materials, Deposition Techniques for Thin Film Research in Electronic Devices: A Mini Review

Mahindra S. Bores, Rajendrakumar B. Ahirrao

Uttamrao Patil Arts and Science College, Dahiwel, Tal. -Sakri, Dist.-Dhule, Pin:424302, Maharashtra, India.

DOI: https://doi.org/10.51583/IJLTEMAS.2025.1409000003

Abstract: The rise of two-dimensional (2D) materials such as graphene, transition metal dichalcogenides (TMDs), and hexagonal boron nitride (h-BN) has opened new pathways for flexible and wearable electronic devices. However, large-area, scalable, and defect-free deposition of 2D thin films remains a critical challenge for their practical integration. In this mini-review, we focus on emerging deposition methods for 2D materials in flexible electronics, including chemical vapor deposition (CVD), atomic layer deposition (ALD), molecular beam epitaxy (MBE), solution-based methods, and printing approaches. We provide a comparative assessment of cost, scalability, film quality, and compatibility with flexible substrates, highlighting both the promise and limitations of current approaches. We also discuss controversies, such as trade-offs between scalability and performance, and identify gaps where current deposition strategies fail. Finally, perspectives on future research directions are presented, emphasizing hybrid deposition approaches and environmentally benign processing routes.

Keywords: 2D materials, Flexible electronics, Deposition techniques, Graphene, TMDs, Scalability

I. Introduction:

Thin films, with thicknesses ranging from a few nanometers to several micrometers, can be deposited on various substrates using different techniques. They have attracted considerable attention in electronic devices due to their unique properties and functionalities, which often differ significantly from their bulk counterparts. Thin films are essential for enhancing performance, reducing cost, and enabling miniaturization in transistors, solar cells, sensors, and displays. Their properties depend strongly on composition, structure, and morphology, factors that are largely governed by the choice of precursors, materials, and deposition techniques. Precursors may be inorganic or organic, solid, liquid, or gas; the film-forming materials may be metals, semiconductors, or polymers, either single-phase or composite. Deposition methods, whether physical or chemical, vacuum or atmospheric, batch or continuous, determine the resulting film quality and application potential. Thus, progress in thin film research relies on developing new precursors, materials, and deposition strategies, as well as improving existing ones, to achieve high-quality and functional films for next-generation devices. Within this broad field, flexible and wearable electronics place even more stringent demands: materials must be lightweight, mechanically robust, and maintain excellent electronic performance under bending or stretching. Two-dimensional (2D) materials,such as graphene, transition metal dichalcogenides (TMDs, e.g., MoS_2, WS_2, WSe_2), and hexagonal boron nitride (h-BN) have emerged as strong candidates because of their atomically thin structures, high carrier mobilities, and tunable band gaps [1–2].

The central challenge, however, lies in deposition. Scalable growth of wafer-scale, defect-free 2D thin films on flexible substrates remains difficult. Conventional thin film methods (e.g., sputtering, evaporation) fall short when applied to atomically thin crystals, as they often result in poor crystallinity or substrate incompatibility. To overcome these barriers, emerging deposition techniques including chemical vapor deposition (CVD), atomic layer deposition (ALD), molecular beam epitaxy (MBE), solution-based processes, and printing methods have become the focus of intense research.

This review provides a critical and focused evaluation of these emerging approaches, with emphasis on their performance, scalability, and limitations in flexible electronics. Rather than a broad overview of thin films in general, we specifically highlight how deposition strategies are shaping the future of 2D material integration into flexible and wearable devices.

II. Thin Films and Deposition Methods for 2D Materials

Overview of Thin Films

Thin film deposition refers to the process of applying a very thin layer of material,ranging from a few nanometers to several micrometers,onto a substrate to tailor physical, chemical, or electronic properties. Thin films have been in use for more than 5000 years, dating back to ancient chemical gilding of metals such as gold on jewelry and artifacts [3]. The modern era of thin film deposition began in the 19th century with the advent of vacuum systems and electrical power, enabling techniques such as sputtering and vacuum evaporation.

Since then, numerous techniques have been developed, including physical vapor deposition (PVD), chemical vapor deposition (CVD), atomic layer deposition (ALD), sol–gel processing, spin coating, and spray pyrolysis. Each approach carries unique advantages and limitations depending on cost, scalability, material compatibility, and substrate requirements.

Thin film technology underpins a wide range of applications, including:

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue IX, September 2025

- **Electronics:** transistors, memory devices, sensors, displays.
- **Energy:** photovoltaic cells, thin-film batteries.
- **Optoelectronics:** LEDs, optical filters, precision optics.
- **Biomedical:** implants, biosensors, drug delivery coatings.

The synthesis and deposition process critically determine thin film quality, directly influencing the performance of resulting devices [4].

Evolution Toward Nanomaterials and 2D Systems

By the mid-20th century, vacuum evaporation and sputtering had become standard for semiconductors such as silicon (Si) and germanium (Ge), paving the way for the microelectronics industry. In the late 20th and early 21st centuries, the advent of nanomaterials further transformed thin film research. Materials such as quantum dots, carbon nanotubes (CNTs), and graphene introduced unprecedented electrical, optical, and mechanical properties at the nanoscale.

- **Quantum dots (QDs):** Semiconductor nanocrystals with quantum confinement effects, applied in displays and solar cells [5].
- **Carbon nanotubes (CNTs):** Films of CNTs exhibit exceptional electrical and thermal conductivity, with strong potential in flexible electronics [6].
- **Graphene:** A monolayer of carbon atoms with ultrahigh carrier mobility, extensively investigated for transistors, transparent conductors, and flexible devices [7].

The emergence of two-dimensional (2D) materials such as graphene, transition metal dichalcogenides (TMDs), and hexagonal boron nitride (h-BN) has redefined the scope of thin film deposition. Unlike bulk thin films, these atomically thin crystals require specialized deposition strategies to maintain their unique properties.

Deposition Methods for 2D Materials

Chemical Vapor Deposition (CVD)

CVD is currently the most established method for large-area graphene and TMD growth. Hydrocarbon or chalcogenide precursors decompose at high temperatures on catalytic substrates (Cu, Ni, sapphire).

- **Advantages:** High crystallinity, wafer-scale growth.
- **Limitations:** Requires >700 °C, transfer needed for flexible substrates, grain boundaries form.

Atomic Layer Deposition (ALD)

ALD allows atomic-scale thickness control via self-limiting precursor pulses. Initially optimized for oxides, it has been adapted to ultrathin MoS_2 and WS_2.

- **Advantages:** Excellent uniformity, conformal coating on flexible/3D substrates.
- **Limitations:** Slow growth, limited precursors, films often require annealing.

Molecular Beam Epitaxy (MBE)

MBE uses ultra-high vacuum to grow epitaxial layers with atomic precision [6].

- **Advantages:** High-quality heterostructures, precise control.
- **Limitations:** Extremely costly, low throughput, poor scalability.

Solution-Based Methods

Exfoliation and chemical synthesis allow films to be deposited by spin coating, dip coating, or self-assembly [7].

- **Advantages:** Low cost, room-temperature processing, polymer compatibility.
- **Limitations:** Poor thickness control, nanosheet restacking, reduced mobility.

Printing Techniques

Inkjet, aerosol jet, and screen printing enable direct deposition of 2D nanosheet inks on flexible substrates [8,9].

- **Advantages:** Scalable, mask-free, patternable, room-temperature.
- **Limitations:** Ink formulation challenges, limited resolution, lower film quality than epitaxial methods.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue IX, September 2025

Precursors used for preparation of thin films:

Hybrid organic-inorganic thin films by molecular layer deposition (MLD) for rechargeable batteries. These thin films are synthesized from molecular precursors that contain both organic and inorganic components, such as metal alkoxides, metal carboxylates, and metal amidinates. The precursors are alternately deposited on a substrate by vapor phase or liquid phase methods, forming thin films with tunable composition and structure [8].

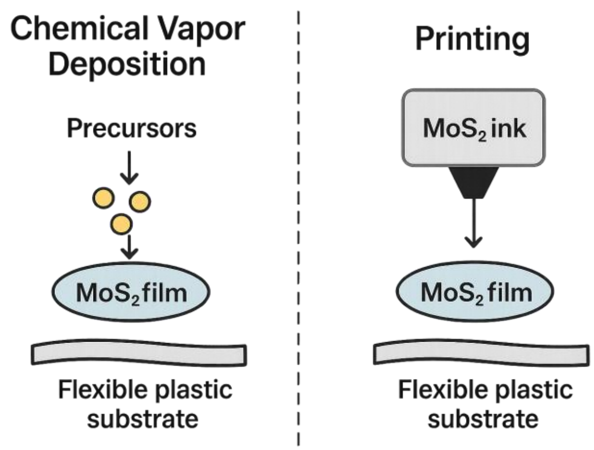

Fig.1.Schematics showing CVD versus printing approaches for MoS_2 films on flexible plastic substrates.

Table.1. comparision of various techniques.

Technique	Cost	Scalability	Film Quality	Substrate Compatibility	Key Limitation
CVD	High	Medium	Excellent (crystalline)	Poor (requires transfer)	High T° growth
ALD	Medium	Low	Good (uniform)	Excellent	Limited precursors
MBE	Very High	Very Low	Excellent (epitaxial)	Poor	Expensive, low throughput
Solution -based	Low	High	Moderate	Excellent	Defects, restacking
Printing	Low	High	Low–Moderate	Excellent	Ink optimization

Carbon nanotubes (CNTs) for thin film transistors and circuits. CNTs are synthesized from hydrocarbon precursors, such as methane, ethylene, and acetylene, by various methods, such as chemical vapor deposition (CVD), plasma-enhanced CVD, and arc discharge. The CNTs are then dispersed in solvents and deposited on substrates by spin coating, inkjet printing, or spray coating, forming thin films with high electrical and thermal conductivity [9].Metal oxides for thin film solar cells and sensors. Metal oxides are synthesized from metal salts, metal alkoxides, metal nitrates, or metal acetates, by various methods, such as sol-gel, spray pyrolysis, atomic layer deposition (ALD), or electrochemical deposition. The metal oxide thin films have wide band gaps, high transparency, and good stability, and can be used as electrodes, buffer layers, or active layers in solar cells and sensors. Two-dimensional (2D) materials for thin film devices. 2D materials are synthesized from elemental precursors, such as graphite, sulfur, selenium, or tellurium, by various methods, such as mechanical exfoliation, liquid exfoliation, CVD, or molecular beam epitaxy (MBE). The 2D materials are then transferred to substrates by dry transfer, wet transfer, or stamping, forming thin films with unique physical and chemical properties[10].

Thin film Materials:

Organic Materials:

Organic Semiconductors (OSCs): Organic materials like pentacene and poly(3-hexylthiophene) (P_3HT) are widely used in organic thin-film transistors (OTFTs) [11].

Organic Photovoltaic Materials: Donor-acceptor polymers, such as poly(3-hexylthiophene):[6,6]-phenyl-C61-butyric acid methyl ester (P3HT:PCBM), are popular for organic solar cells [12]

Inorganic Materials:

Metal Oxides: Transparent conducting oxides (TCOs) like indium tin oxide (ITO) are extensively used in optoelectronic devices [13].

Perovskite Materials: Hybrid perovskites, such as methylammonium lead halide (MAPbX3), have gained attention in thin-film solar cells [14].

2D Materials:

Graphene: A single layer of carbon atoms, graphene is employed in transparent conductive films and electronic devices [15].

Transition Metal Dichalcogenides (TMDs): Materials like molybdenum disulfide (MoS2) and tungsten diselenide (WSe2) are used in thin-film transistors [16]

Nanomaterials:

Carbon Nanotubes (CNTs): Single-walled carbon nanotubes are utilized in thin-film transistors and flexible electronics[17].

Quantum Dots: Semiconductor quantum dots are employed in thin films for applications like displays and sensors [18].

Organic-Inorganic Hybrid Materials:

Organic-Inorganic Perovskite: Organic-inorganic hybrid perovskites, such as formamidinium lead iodide (FAPI), are utilized in thin-film solar cells.

Organic-Inorganic Nanocomposites: Hybrid materials combining organic polymers with inorganic nanoparticles for various applications.

Thin film Deposition Techniques:

Deposition is a technique that involves the controlled formation of thin films of materials on a substrate. Deposition can be achieved by various physical or chemical methods, depending on the desired properties and applications of the thin films. Thin films are widely used in electronic devices, such as microelectronics, optoelectronics, solar cells, and sensors, due to their enhanced surface characteristics and reduced dimensions. In this mini review, we will discuss some of the advanced deposition techniques for thin film research and their advantages and challenges.

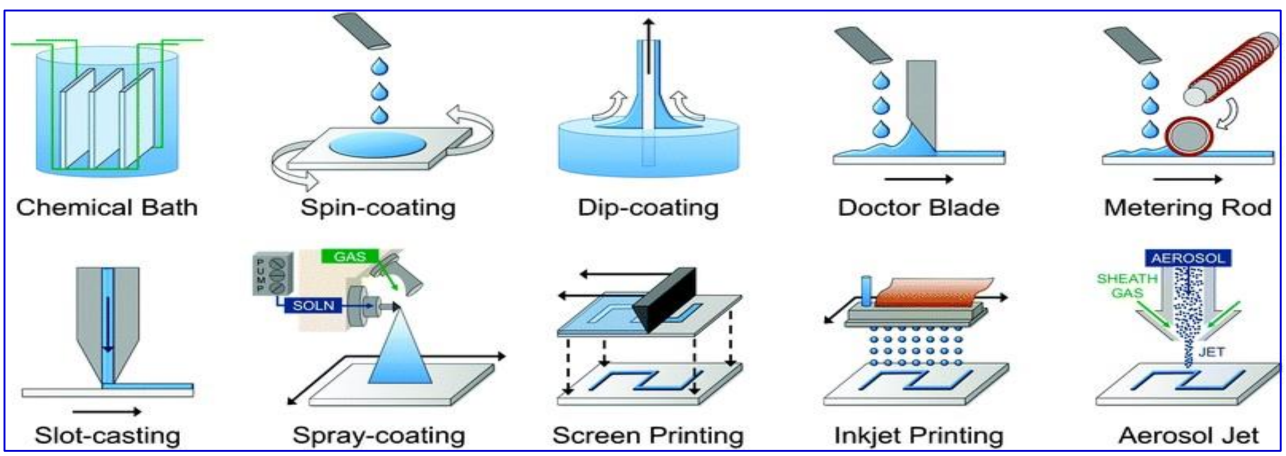

Fig.1. Schematics of thin film deposition methods

Thin films are essential for the fabrication and performance of various electronic devices, such as transistors, solar cells, sensors, and displays. Thin films can be deposited by different techniques, depending on the desired properties, applications, and substrates. In this mini review, we will discuss some of the advanced deposition techniques and their examples with precursors used for thin film research.

1. Chemical Bath Deposition (CBD): One of the advanced deposition techniques is chemical bath deposition (CBD), which involves immersing a substrate in a solution containing metal salts, complexing agents, and pH buffers, and inducing the formation of a thin film by a chemical reaction. CBD is a simple, low-cost, and scalable technique that can produce thin films of various materials, such as oxides, sulfides, and selenides, with controlled composition, morphology, and crystallinity. CBD can also be used to create nanostructured thin films with enhanced optical, electrical, and catalytic properties. Some examples of precursors used for CBD are zinc acetate, thiourea, and ammonia for ZnS thin films [19], copper sulfate, sodium selenosulfate, and sodium hydroxide for Cu_2Se thin films [20], and cadmium chloride, sodium citrate, and sodium hydroxide for CdO thin films [21].

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue IX, September 2025

2. Spin Coating: Another advanced deposition technique is spin coating (SC), which involves dispensing a solution containing a film-forming material onto a rotating substrate and spreading it uniformly by centrifugal force. SC is a widely used technique for depositing thin films of polymers, organic compounds, and sol-gel materials, due to its simplicity, versatility, and high speed. SC can also produce thin films with uniform thickness, smooth surface, and good adhesion. Some examples of precursors used for SC are poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) for conductive polymer thin films [22], polyvinylpyrrolidone (PVP) and silver nitrate for silver nanoparticle thin films [23], and tetraethyl orthosilicate (TEOS) and ethanol for silica thin films .

3. Dip Coating (DC): The dip coating (DC),A third advanced deposition technique is dip coating (DC), which involves dipping a substrate into a solution containing a film-forming material and withdrawing it at a controlled speed. DC is a simple, low-cost, and flexible technique that can produce thin films of various materials, such as ceramics, metals, and polymers, with controlled thickness, porosity, and structure. DC can also be used to create multilayered thin films with different functionalities and properties. Some examples of precursors used for DC are titanium isopropoxide, acetic acid, and ethanol for TiO_2 thin films , polyethylene glycol (PEG) and iron chloride for Fe_2O_3 thin films , and polyvinyl alcohol (PVA) and gold chloride for gold nanoparticle thin films [24-28]

4. Doctor blade (DB): Doctor blade is a technique that involves spreading a solution containing a film-forming material over a substrate using a blade with a fixed gap. DB is a simple, low-cost, and scalable technique that can produce thin films of various materials, such as ceramics, metals, and polymers, with controlled thickness and morphology. DB can also be used to create multilayered thin films with different compositions and structures. Some examples of precursors used for DB are zinc acetate, thiourea, and ammonia for ZnS thin films [29], titanium isopropoxide, acetic acid, and ethanol for TiO_2 thin films [30], and polyvinylpyrrolidone (PVP) and silver nitrate for silver nanoparticle thin films [31-35].

5. Metering rod (MR): Metering rod (MR) is a technique that involves applying a solution containing a film-forming material onto a substrate using a rod with a fixed diameter. MR is a simple, low-cost, and versatile technique that can produce thin films of various materials, such as polymers, organic compounds, and sol-gel materials, with uniform thickness and smooth surface. MR can also be used to create patterned thin films with different shapes and sizes. Some examples of precursors used for MR are poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) for conductive polymer thin films [36], polyvinyl alcohol (PVA) and gold chloride for gold nanoparticle thin films , and tetraethyl orthosilicate (TEOS) and ethanol for silica thin films [37-38].

6. Slot-casting (SC): Slot-casting (SC) is a technique that involves extruding a solution containing a film-forming material through a slot-shaped nozzle onto a substrate. SC is a simple, low-cost, and scalable technique that can produce thin films of various materials, such as ceramics, metals, and polymers, with controlled thickness and width. SC can also be used to create continuous thin films over large areas and curved surfaces. Some examples of precursors used for SC are copper sulfate, sodium selenosulfate, and sodium hydroxide for Cu_2Se thin films , polyethylene glycol (PEG) and iron chloride for Fe_2O_3 thin films , and cadmium chloride, sodium citrate, and sodium hydroxide for CdO thin films [39-40].

7. Spray coating (SP) : Spray coating (SP) is a technique that involves atomizing a solution containing a film-forming material into fine droplets and spraying them onto a substrate. SP is a simple, low-cost, and flexible technique that can produce thin films of various materials, such as oxides, sulfides, and phosphides, with controlled composition, structure, and porosity. SP can also be used to create nanostructured thin films with enhanced optical, electrical, and catalytic properties. Some examples of precursors used for SP are zinc nitrate, ammonium sulfide, and ethanol for ZnS thin films , copper nitrate, thiourea, and ethanol for CuS thin films , and indium nitrate, phosphoric acid, and ethanol for InP thin films[41-43] .

8. Screen printing (SPR): Screen printing (SPR) is a technique that involves transferring a solution containing a film-forming material through a mesh screen onto a substrate using a squeegee. SPR is a simple, low-cost, and versatile technique that can produce thin films of various materials, such as metals, semiconductors, and polymers, with controlled thickness and pattern. SPR can also be used to create multilayered thin films with different functionalities and properties. Some examples of precursors used for SPR are silver paste for silver thin films , titanium dioxide paste for TiO_2 thin films , and poly(3-hexylthiophene) (P3HT) and [6,6]-phenyl-C61-butyric acid methyl ester (PCBM) for organic solar cell thin films [44-45].

9. Inkjet printing (IP) is a technique that involves ejecting a solution containing a film-forming material through a nozzle onto a substrate using a piezoelectric or thermal actuator. IP is a simple, low-cost, and precise technique that can produce thin films of various materials, such as metals, semiconductors, and polymers, with controlled thickness and shape. IP can also be used to create complex thin film structures, such as nanocomposites, heterostructures, and graded films. Some examples of precursors used for IP are silver nitrate and ethylene glycol for silver thin films , lead iodide and dimethylformamide for PbI2 thin films , and poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) and water for conductive polymer thin films [46-47] .

10. Aerosol jet (AJ): Aerosol jet (AJ) is a technique that involves generating a mist of a solution containing a film-forming material and delivering it through a nozzle onto a substrate using a carrier gas. AJ is a simple, low-cost, and flexible technique that can produce thin films of various materials, such as metals, semiconductors, and polymers, with controlled thickness and resolution. AJ can also be used to create thin films on non-planar and irregular substrates and to create three-dimensional thin film structures.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue IX, September 2025

Some examples of precursors used for AJ are silver nitrate and ethylene glycol for silver thin films , zinc acetate and ethanol for ZnO thin films , and poly(3-hexylthiophene) (P3HT) and chlorobenzene for organic thin film transistors [48-49] .

6. Applications of thin films in Electronic Devices:

Thin films are essential for the fabrication and performance of various electronic devices, such as transistors, solar cells, sensors, and displays. Thin films can be deposited by different techniques, depending on the desired properties, applications, and substrates. In this mini review, we will discuss some of the applications of thin films in electronic devices and their advantages and challenges.

One of the applications of thin films is in solar cells, which are devices that convert solar energy into electricity. Thin films can be used to create photovoltaic cells that have high efficiency, low cost, and flexibility. Thin films can also be used to create multijunction solar cells that have higher performance and stability. Some examples of thin film materials used for solar cells are cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and perovskite [50].

Another application of thin films is in optics, which are devices that manipulate light for various purposes. Thin films can be used to create optical coatings that have different functions, such as reflection, transmission, absorption, polarization, and filtering. Thin films can also be used to create light-emitting devices, such as LEDs and OLEDs, that have high brightness, low power consumption, and long lifetime. Some examples of thin film materials used for optics are zinc oxide (ZnO), titanium dioxide (TiO_2), and organic compounds [51].

A third application of thin films is in computers, which are devices that process and store information. Thin films can be used to create microelectronic components, such as transistors, diodes, and capacitors, that have high speed, low noise, and high integration. Thin films can also be used to create memory devices, such as flash memory and resistive memory, that have high density, low voltage, and fast switching. Some examples of thin film materials used for computers are silicon (Si), germanium (Ge), and graphene[52].

Therefore thin films are crucial for the development and innovation of electronic devices, which can be performed by various methods, depending on the desired properties, applications, and substrates. Each application of thin films has its own advantages and challenges, which need to be considered and optimized for the specific device system. The development of new thin film materials and the improvement of existing ones will enable the production of high-quality, functional, and novel electronic devices for various fields.

7. Challenges and Future Directions of Thin films:

(a) Challenges:

Scalability vs. Quality Trade-off: High-quality crystalline films (CVD, MBE) lack scalability. Scalable methods (printing, solution-based) often compromise mobility and uniformity.

Substrate Limitations: Flexible substrates (PET, PEN, PI) degrade under high CVD temperatures, requiring low-temperature alternatives.

Transfer vs. Direct Growth: Graphene transfer from metals introduces cracks/contamination. Direct growth on polymers remains challenging.

Environmental Concerns: Solvent-intensive exfoliation and toxic precursors (e.g., $MoCl_5$) hinder sustainability.

Stability and Reliability: Thin films degrade under temperature, humidity, pressure, and stress. Protective coatings and encapsulation are needed.

Scalability and Reproducibility: Complex techniques (CVD, PLD, printing) require precise control. Maintaining uniformity on large-area/flexible substrates is difficult.

Integration and Compatibility: Thin films must integrate with metals, semiconductors, polymers, ceramics, and diverse substrates (Si, glass, plastics).

(b) Opportunities

1. **Hybrid Methods:** Combining CVD with printing (e.g., electrodes on CVD-grown films) may balance scalability and performance.
2. **Low-Temperature Growth:** Plasma-assisted and laser-assisted CVD show promise for direct polymer growth.
3. **Green Processing:** Development of water-based inks and benign precursors will enable sustainable scaling.
4. **New Materials and Structures:** Exploring nanocrystals, nanowires, nanotubes, graphene, and composites for high conductivity, mobility, sensitivity, and flexibility.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue IX, September 2025

5. **New Techniques and Processes:** Advancing fabrication methods (physical/chemical, vacuum/atmospheric, batch/continuous) to achieve high performance, low cost, and eco-friendly production.
6. **Device Integration:** Beyond transistors: applications in photodetectors, sensors, photovoltaics, optoelectronics, thermoelectrics, and neuromorphic devices.

However, despite the advances in thin film research and fabrication, there are still many challenges and limitations that need to be overcome and addressed. Some of the major challenges are:

Stability and reliability: Thin films are often subjected to various environmental and operational conditions, such as temperature, humidity, pressure, radiation, and mechanical stress, which can affect their properties and performance over time. Therefore, it is important to improve the stability and reliability of thin films by optimizing their composition, structure, morphology, and interface, as well as developing effective protective coatings and encapsulation methods [53].

Scalability and reproducibility: Thin films are often fabricated by complex and sophisticated techniques, such as chemical vapor deposition, pulsed laser deposition, and inkjet printing, which require precise control of the deposition parameters, such as temperature, pressure, flow rate, and voltage. Therefore, it is challenging to scale up and reproduce the thin film fabrication process with high quality and uniformity, especially for large-area and flexible substrates [54].

Integration and compatibility: Thin films are often integrated with other materials and devices to form complex and multifunctional systems, such as heterojunctions, multilayers, and nanocomposites. Therefore, it is crucial to ensure the integration and compatibility of thin films with different materials and devices, such as metals, semiconductors, polymers, and ceramics, as well as with different substrates, such as silicon, glass, and plastic [55].

On the other hand, there are also many opportunities and prospects for the future development and innovation of thin films in electronic devices. Some of the promising directions are:

New materials and structures: Thin films can be made of various materials and structures, such as metals, semiconductors, polymers, and composites, as well as nanocrystals, nanowires, nanotubes, and graphene, which can exhibit novel and enhanced properties and functionalities, such as high conductivity, high mobility, high sensitivity, and high flexibility. Therefore, it is important to explore new materials and structures for thin films, as well as to understand and manipulate their properties and interactions at the nanoscale[56] .

New techniques and processes: Thin films can be fabricated by various techniques and processes, such as physical or chemical, vacuum or atmospheric, and batch or continuous, which can offer different advantages and disadvantages, such as high speed, low cost, high quality, and low temperature. Therefore, it is important to develop new techniques and processes for thin film fabrication, as well as to improve and optimize the existing ones, to achieve high-performance, low-cost, and eco-friendly thin films[57].

New applications and devices: Thin films can be applied to various fields and devices, such as optoelectronics, photonics, photovoltaics, thermoelectrics, sensing, and neuromorphics, which can offer different benefits and challenges, such as high efficiency, low power consumption, high integration, and high complexity. Therefore, it is important to explore new applications and devices for thin films, as well as to design and engineer the thin film systems to meet the specific requirements and demands of the end-users [58] .

Therefore thin films are crucial for the development and innovation of electronic devices, which can be performed by various methods, depending on the desired properties, applications, and substrates. Each challenge and opportunity of thin films has its own significance and potential, which need to be considered and exploited for the specific thin film system. The development of new thin film materials, techniques, and applications will enable the production of high-quality, functional, and novel electronic devices for various fields[59-61].

Conclusion

Deposition remains the central challenge in realizing the promise of 2D materials in flexible electronics. While CVD and MBE offer unmatched film quality, solution-based and printing techniques provide scalability. Bridging this gap through hybrid and low-temperature methods is the most promising pathway toward industrially viable, high-performance flexible devices.

References:

1. Chopra, K. L., & Rai, G. (2000). Thin Film Phenomena. Academic Press.
2. Greene, J. E. (2017). Thin Film Solar Cells: Research on Development of n-i-p-type Heterojunction and Back Contact Structures. Journal of Applied Physics, 122(24), 241101.
3. J. E. Greenea, D. B. Willett, Tage Erlander; Review Article: Tracing the recorded history of thin-film sputter deposition: From the 1800s to 2017; J. Vac. Sci. Technol. A 35, 05C204 (2017),https://doi.org/10.1116/1.4998940.
4. A Brief History of Thin Film Deposition Techniques,The Scientific World (2022);A Brief History of Thin Film Deposition Techniques (scientificworldinfo.com)
5. J. Nozik, M. C. Beard, J. M. Luther, M. Law, R. J. Ellingson, Nano Letters, 2010).

6. M. S. Arnold, A. A. Green, J. F. Hulvat, S. I. Stupp, M. C. Hersam, Nature Nanotechnology, 2006.
7. K. S. Novoselov et al., Science, 2004.
8. Handbook on Synthesis Strategies for Advanced Materials, Edited byA. K. Tyagi,
9. Raghumani S. Ningthoujam (2021),Volume-I: Techniques and Fundamentals.
10. He et al., Sci. Adv. 9, eadg8180 (2023) 9 June 2023.
11. Gontrani, L.; Tagliatesta, P.; Donia, D.T.; Bauer, E.M.; Bonomo, M.; Carbone, M. Recent Advances in the Synthesis of Inorganic Materials Using Environmentally Friendly Media. Molecules 2022, 27, 2045. https://doi.org/10.3390/molecules27072045.
12. D. M. de Leeuw, M. M. J. Simenon, A. R. Brown, R. E. F. Einerhand, Synth. Met., 1997..
13. Y. Liang et al., J. Am. Chem. Soc., 2009.
14. M. Singh, K. H. Kim, J. H. Kim, D. H. Yoon, J. Y. Lee, Thin Solid Films, 2014.
15. H. S. Kim et al., Science, 2012.
16. K. S. Novoselov et al., Science, 2004.
17. Splendiani et al., Nano Lett., 2010.
18. P. Avouris, Acc. Chem. Res., 2002.
19. J. Nozik, M. C. Beard, J. M. Luther, M. Law, R. J. Ellingson, Nano Lett., 2010.
20. Ichou, H., Arrousse, N., Berdimurodov, E. et al. Exploring the Advancements in Physical Vapor Deposition Coating: A Review. J Bio Tribo Corros 10, 3 (2024). https://doi.org/10.1007/s40735-023-00806-0.
21. Oke, J.A., Jen, TC. Atomic layer deposition thin film techniques and its bibliometric perspective. Int J Adv Manuf Technol 126, 4811–4825 (2023). https://doi.org/10.1007/s00170-023-11478-y.
22. Jilani, A., Abdel-wahab, M. S., & Hammad, A. H. (2017). Advance Deposition Techniques for Thin Film and Coating. InTech. doi: 10.5772/65702.
23. A comprehensive Guide to Deposition Technique in semiconductor fabrication; From Atoms to Circuits: Understand Deposition Techniques in Semiconductor Fabrication Process (blackridgeresearch.com)
24. George W. Scherer, "Sol-Gel Science: The Physics and Chemistry of Sol-Gel Processing," Academic Press, 1990.
25. Juan C. Insaurralde, "Dip-Coating Technique: Theory, Applications, and Optimization," Materials, 2019, 12, 2409.
26. Juan C. Insaurralde, "Dip-Coating Technique as a Tool for the Deposition of Thin Films," Infrared Spectroscopy - Principles, Advances, and Applications, 2012.
27. C. M. S. Torres, et al., "Improvement of Gas Sensing Properties of TiO2 Thin Films by Dip-Coating," Sensors and Actuators B: Chemical, 2006, 114(2), 677-685.
28. S. Kaciulis, et al., "Effect of the Dip-Coating Speed on the Structural, Morphological, Optical, and Gas Sensing Properties of ZnO Thin Films," Materials Science in Semiconductor Processing, 2018, 78, 52-62.
29. G. R. Patzke, "Hydrothermal Synthesis of Nanomaterials," Inorganic Syntheses, 2013, 35-43.
30. S. H. Lee, et al., "Effect of titanium isopropoxide concentration on electrospinning of titania nanofibers and their photocatalytic properties," Journal of Colloid and Interface Science, 2010, 348(2), 546-551.
31. J. H. Jang, et al., "Flexible Transparent Conductive Films with High Performance and Reliability Using Multilayered Silver Nanowire Electrodes," Advanced Functional Materials, 2014, 24(40), 6281-6290.
32. H. J. Yun, et al., "The investigation of microstructure and optical property of TiO_2 thin films synthesized by doctor blade method," Journal of Alloys and Compounds, 2009, 469(1-2), 23-28.
33. Patil, G.C. (2023). Doctor Blade: A Promising Technique for Thin Film Coating. In: Sankapal, B.R., Ennaoui, A., Gupta, R.B., Lokhande, C.D. (eds) Simple Chemical Methods for Thin Film Deposition. Springer, Singapore. https://doi.org/10.1007/978-981-99-0961-2_12.
34. Butt, M.A. Thin-Film Coating Methods: A Successful Marriage of High-Quality and Cost-Effectiveness—A Brief Exploration. Coatings 2022, 12, 1115. https://doi.org/10.3390/coatings12081115.
35. Nurul Huda Kamarulzaman et al 2020 J. Phys.: Conf. Ser. 1535 012025.
36. D. B. Kelland, "Processing of Thermoplastic Materials," Elsevier, 2013.
37. H. R. Hamilton, "Rod Coating," Encyclopedia of Polymer Science and Technology, John Wiley & Sons, 2002.
38. Sharma, S. Chockalingam, "Handbook of Thin Film Technology," McGraw-Hill, 2020.
39. J. H. Lee, C. Park, "Slot-Die Coating Technology: Critical Elements and Recent Advances," Macromolecular Materials and Engineering, 2019.
40. J. S. Lee, "Slot-Die Coating," Handbook of Deposition Technologies for Films and Coatings, 2010.
41. J. M. Lee, C. S. Ha, "Spray Coating," Handbook of Deposition Technologies for Films and Coatings, 2010.
42. R. Boccaccini, M. J. M. Macossay, "Electrophoretic Deposition of Nanomaterials," Springer, 2012.
43. G. P. Franchini, "Spray Coating Processes," in Handbook of Smart Coatings for Materials Protection, 2014.
44. M. Chawla, "Handbook of Industrial and Systems Engineering," CRC Press, 2021.
45. G. B. Street, R. S. Popovic, "Screen-Printing Technology," Journal of the Society for Information Display, 1977.
46. M. A. Hopper, P. E. Norris, "Inkjet Printing," Encyclopedia of Microfluidics and Nanofluidics, Springer, 2008.
47. S. Magdassi, "The Chemistry of Inkjet Inks," World Scientific, 2010.
48. M. Chiang, "Aerosol Jet Printing for 3D Electronics," in 3D Printing and Additive Manufacturing Technologies, 2020.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue IX, September 2025

49. P. Malshe et al., "Aerosol Jet Printed 3D Electronics," in 3D Printing and Additive Manufacturing Technologies, 2020.
A. I. Bouwstra, "Jet Printing for Printed Electronics," in Printing Technology for Electronic Devices, 2019.
50. Electricalvoice;(2022),Semiconductor Thin Films and Their Applications in Electronics Engineering;Semiconductor Thin Films and Their Applications in Electronics Engineering | Electricalvoice.
51. Kwan, H.-J. Applications of Thin Films in Microelectronics. Electronics 2022, 11, 931. https://doi.org/10.3390/electronics11060931
52. Matt Clancy,Thin Film Applications in Various Fields (2022),Thin Film Applications in Various Fields | Korvus Technology.
53. J. E. Greenea, D. B. Willett, Tage Erlander; Review Article: Tracing the recorded history of thin-film sputter deposition: From the 1800s to 2017; J. Vac. Sci. Technol. A 35, 05C204 (2017),https://doi.org/10.1116/1.4998940.
54. A Brief History of Thin Film Deposition Techniques,The Scientific World (2022);A Brief History of Thin Film Deposition Techniques (scientificworldinfo.com)
55. J. Nozik, M. C. Beard, J. M. Luther, M. Law, R. J. Ellingson, Nano Letters, 2010).
56. M. S. Arnold, A. A. Green, J. F. Hulvat, S. I. Stupp, M. C. Hersam, Nature Nanotechnology, 2006.
57. K. S. Novoselov et al., Science, 2004.
58. Handbook on Synthesis Strategies for Advanced Materials, Edited byA. K. Tyagi,Raghumani S. Ningthoujam (2021),Volume-I: Techniques and Fundamentals.
59. He et al., Sci. Adv. 9, eadg8180 (2023) 9 June 2023.
60. Gontrani, L.; Tagliatesta, P.; Donia, D.T.; Bauer, E.M.; Bonomo, M.; Carbone, M. Recent Advances in the Synthesis of Inorganic Materials Using Environmentally Friendly Media. Molecules 2022, 27, 2045. https://doi.org/10.3390/molecules27072045.