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Hybrid Perovskite Thin Film

Akin Olaleru, Eric Maluta, Joseph Kirui and Olasoji Adekoya

Abstract

Hybrid perovskite thin film offers diverse advantages like low cost deposition techniques, less material consumption and superior optoelectronic properties. These merits including high voltage and high efficiency performance in a wide range of high light intensity are sufficient to distinguish perovskite thin films/ devices from their contenders as a thin film technology with greater potential for industrial applications. Perovskite thin film technology demonstrates potency in a variety of applications in optoelectronic devices especially photovoltaic applications. The National Renewable Energy Laboratory (NREL) of the USA categorizes a number of thin films technologies including perovskite thin film, as emerging photovoltaics with the bulk of them yet to be commercially applied but are still in the research or developmental stage. In this chapter, various processing methods and material combinations as well as current trends in this technology are subjects of discussion.

Keywords: Perovskite thin film, deposition techniques, low-cost, properties, solar energy

1. Introduction

Thin film is a two dimensional material layer ranging from fractions of a nanometer (single layer) to various micrometers in thickness deposited on a substrate, including plastic, glass or metal, so as to attain properties that cannot be realized at all with the same material in its bulk form. Thin-film is developed by depositing a single or multiple layers of absorbing materials on substrate for photovoltaic and optoelectronic applications. The definite property of a thin film is due to the special approach of creating it, by means of evolutionary addition of atoms or molecules. Thickness is the basic property of thin film and is firmly connected to diverse properties which vary with thickness.

1.1 Different types of thin film devices?

There are various classes of thin film devices which are widely employed in optical devices and semiconductors as well as other applications. Thin film devices are used in the form of optical filters, such as photograph, microscopes. Thin film semiconductor also finds applications in fields of microelectronics, micro-circuitry, solar cells and integrated circuits are possible type of thin film devices. In addition, common thin film devices are mirrors which are made of a thin film of reflective material like aluminum which is attached to the glass substrate. Presently in the market, thin films are being introduced to deliver drug. The film permits the drug to penetrate the bloodstream rapidly in complete contrast swallowed pills or liquid suspensions.

In this chapter, we are going to narrow down to thin film photovoltaics (PVs) major. The reasons for wide usage are not far-fetched; firstly, film thickness differs from a few nanometer (nm) to micrometer (μm) which is much thinner than the traditional crystalline silicon PV cell (c-Si) that utilizes wafers of up to 200 μm thick. Accordingly, thin film cell more flexible and lighter in weight. Secondly, thin film technologies allow drastically reduced quantities of active material in a cell, which makes the thin films much cheaper than their bulk counterparts.

Thin films photovoltaics are called based on their main light absorbing material as shown in **Figure 1**. The commercial thin film photovoltaics are mainly based on the following technologies:

- Cadmium Telluride (CdTe)
- Amorphous Silicon (a-Si)
- Copper Indium Diselenide (CIS)
- Gallium Arsenide (GaAs)

These thin film technologies are employed widely in optoelectronic devices and semiconductors, although there are different applications also. Most of the thin films used are developed out of a variation of different metals and materials, each with its own properties and applications.

Unfortunately, these earlier thin film technologies are still relatively expensive to manufacture. The cost has been a major restriction in the way of expanding the market in addition the high temperature requirements in production and the low absorption rate of photons by these films contribute to their weaknesses.

Light-harvesting layer, referred to as the main premise of any given PV technology, assumes a key function in deciding the most suitable manufacturing technique [1]. For instance, traditional silicon wafer photovoltaic cells demand energy-intensive vacuum processes and hence, normally developed in a batch process. Second generation thin-film solar cells use direct band gap micron-thick absorber (CdTe, CIGS) layer for effective conversion of solar to electric energy.

The employment of thin absorber layer eases the acceptance of high efficiency device fabrication on a variety of substrates. On the other hand, the requirement of high-vacuum and costly precursor materials restricted the commercial feasibility of thin film photovoltaic cells.

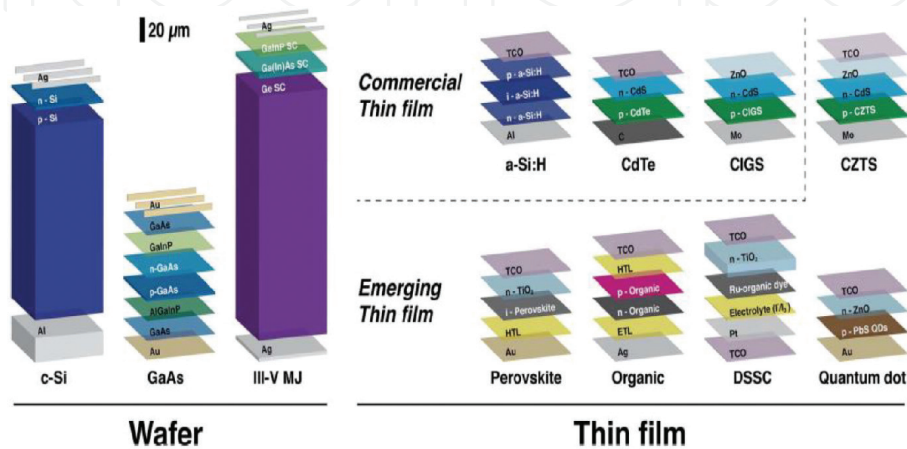


Figure 1. PV device architectures: Wafer-based and thin-film technologies. Main absorber layers are marked by white color [1].

In recent times, the National Renewable Energy Laboratory (NREL) has categorized various thin-film technologies as emerging photovoltaics, although most of these technologies are still in the research and developmental stage, and yet to be industrially used. Many of these technologies use organic materials, like organometallic compounds and inorganic materials. These emerging thin films photovoltaics (technologies) fall under the third and fourth generations, which include:

- Organic solar cell
- A dye-sensitized solar cell (DSSC) or “Grätzel cell”
- Copper zinc tin sulfide solar cell (CZTS)
- Quantum dot solar cell
- Perovskite solar cells (PSCs)

The emerging thin films photovoltaics offered a golden opportunity for low-temperature and non-vacuum processability.

However, some of these technologies have low efficiencies, and moreover the stability of the absorbing materials is inherently too short for industrial applications. A great number of studies are ongoing on these thin film technologies as they have the potential to accomplish the goal of ushering in the much anticipated low-cost and energy-effective photovoltaic cells.

Among these emerging thin films, the perovskite thin film which serve as the focal point of this chapter provided the promising window to replace the dominant silicon photovoltaics in the market and also help mitigate the energy crisis globally. This is possible owing to desirable properties given below.

2. Materials profile for hybrid perovskite

A hybrid perovskite is a semiconductor consisting of organic, inorganic materials/species and halides. These materials are widely used as light-absorbers in perovskite solar cells. The excitement for hybrid perovskite materials has been connected to a large extent to the interesting attributes of the inorganic components, which impart thermal stability and the considerable degree of structural order [2]. In addition, the organic component properties likewise play a part in the great properties of halide perovskite including mechanical adaptability and minimal effort in production [3]. Consequently, the probability of merging the properties of normal inorganic crystals with those of organic solids has motivated recent research into the flexible properties of organic–inorganic hybrid perovskite materials.

This family of hybrid perovskite materials has been extensively employed in optoelectronics. The use of halide perovskites in PV cells has made a major quantum leap in the field of emerging PV technologies in recent years. The power conversion efficiencies (PCEs) of PSCs have demonstrated a notable rise from the pioneering value of 3.8% in 2009 to the latest record of 25.5 and 29.5% for the single junction device and the tandem with silicon (Si) respectively [4]. Besides the sphere of PV, the three-dimensional halide perovskites as well as low-dimensional perovskites have been largely investigated for applications in transistors and light emission.

The properties that render perovskite materials as the preferred choice for PV technology are summarized as follows:

2.1 Charge generation

The superb absorption properties together with low exciton binding energy enables perovskite-based solar cells to absorb light throughout visible wavelengths and beyond. This leads to a high population of charge carriers (both electrons and holes) inside the same absorbing material (ambipolar class material), which has great impact on the transport, recombination, and extraction of charges. This promotes low energy-loss by the charges produced and enhances their accumulation at the electrodes. Hence, this results in high PCEs in perovskite solar cells.

2.2 Charge transport

Unlike other PV technologies, PSCs convey both electrons and holes for extraction effectively due to its ambipolar transport properties. The superior charge-transport properties of the material with long charge carrier diffusion lengths of more than 5 μm , and corresponding lifetime of $\sim 1 \mu\text{s}$ [5, 6] in single-crystal and poly-crystalline thin films determine the exceptional PCEs of these cells. The diffusion lengths of PSCs are greater than those of most organic solar cells prepared using solution-process technique. The diffusion lengths for both electrons and holes appear to be symmetrical in perovskite solar cells, which is essential for thin-film PV for the effective extraction of both types of carriers.

2.3 Charge recombination/energy utilization

Perovskite materials can effectively separate and transport electrons and holes as a result of quick exciton dissociation, long charge diffusion lengths and probably self-doping at the interface. Research have shown that the unusual properties of perovskites, like quick exciton dissociation and appreciable diffusion lengths, plus shallow trap states due to the presence of impurities, greatly minimize the loss of charge carrier within the perovskite bulk. The energy utilization in PSCs is very high and nearly comparable to that observed in other foremost monolithic crystalline technologies like c-Si-based solar cells.

2.4 Versatile solution processing

Perovskite materials can dissolve in organic polar solvents, thereby enabling excellent-quality thin films to be layered on any surface through simple solutions (spin-coating, spray coating, inkjet printing, slot-die coating, and blade coating). These deposition methods can be easily incorporated into the roll-to-roll fabrication of flexible PSCs.

Consequently, it is vital to attain excellent control through the reaction between the inorganic and organic components, which leads to formation of perovskites with useful properties and device performance. Several process parameters such as deposition techniques, stoichiometry, thermal treatment, solvent engineering and additives which were incorporated into the process to enhance the perovskite thin film qualities will be discussed in the next section.

3. Pathway to perovskite thin film formation

The preparation of the perovskite layer before deposition on a substrate is fundamental for achieving high-efficiency devices. Thin film quality indicators, including crystallinity, grain size, presence of impurity phases, and defects, can

influence the optoelectronic properties immensely. Furthermore, all the needed properties (like simple preparation, absorbance through the entire visible range) PV material are deemed to be affected by the quality of the film. The following parameters influence the quality of the perovskite film:

- Precursor stoichiometry
- Solvent engineering
- Annealing process
- Deposition method

Usually, careful control of these parameters during preparation of perovskite material is required to manufacture high-efficiency PSCs. The charge separation efficiency, recombination dynamics, and long diffusion length of the charge carriers are expected to be influenced by crystallization behavior and morphological evolution of the perovskite film for example, the large grain size can promote better charge transport.

3.1 Precursor stoichiometry

During the last decade, notable development has advanced the field of perovskite PV cells to the vanguard of thin film PV technologies. The stoichiometry of the perovskite material is of great significance as it predetermines the optoelectronic properties of the absorber and thus the device performance.

The stoichiometry of the precursor solution, specially the ratio of the organic and inorganic constituents, highly influences the resulting thin film quality in term of film conformity and carrier behavior. Moreover, precursor solution stoichiometry can effect profound changes in the properties of the perovskite layer along with the performance and stability of perovskite PV devices.

The initial nominal stoichiometry and non-stoichiometry of methylammonium iodide ($\text{CH}_3\text{NH}_3\text{I}$, MAI) and lead halides can be carefully regulated in both solution and vacuum evaporation techniques. The molar ratios of 1:1 and 1:3 have been the most commonly used for perovskite precursors. But other molar ratios which are non-stoichiometric are reported in [7, 8].

Generally, a solution of PbI_2 and MAI with a stoichiometry of 1:1 is employed as the precursor to form a pure perovskite phase. For the mixture of PbCl_2 and MAI solution, a non-stoichiometric mole ratio of 1: 3 is used for the formation of MAPbI_3 .

Any deviation from stoichiometric ratio (PbCl_2 : MAI) can lead to either excessive MAI or unreacted PbCl_2 to remain inside the film, which can be expected to decompose their resulting optoelectronic performance. For example, the MAI and PbI_2 (1: 1 mole ratio) and the mixture of PbCl_2 and MAI solution, a non-stoichiometric mole ratio of 5: 3 is demonstrated to be optimum for the formation of perovskite precursor [8]. It should be noted that the mixed halide shows enhanced film properties, for instance. More compact and improved grain size, in comparison with the pure iodide MAPbI_3 perovskite.

3.2 Solvent engineering

The selection of the precursor solvent plays a key role in any solution method and controls the quality of hybrid perovskite films. In one-step deposition technique, a blend of two separate precursors (for instance methylammonium iodide and lead halides) is employed. Due to the distinctive nature of organic and

inorganic precursors, the fundamental specification is that the solvent must be polar so as to dissolve the precursors, while the physical properties, such as boiling point and vapor pressure, must be determined with respect to the preferred crystallization mechanism, that is, rapid or slow. Currently, γ -butyrolactone (GBL), dimethyl sulfoxide (DMSO), N-Methyl-2-pyrrolidone (NMP), and dimethylformamide (DMF) are the usual solvents in the precursor solution, and their mixture is a possibility to enhance the crystallization [9, 10]. It should be noted that addition of DMSO to the DMF solution aided in monitoring the perovskite crystallization, resulting in improved PV performance.

3.3 Anti-solvent treatment

In addition to the significance of the perovskite precursor–solvent interaction so as to decipher the nature of an intermediate phase in the solvent engineering technique, the application of an anti-solvent likewise plays an important role in the surface morphology and crystalline properties of the perovskite films. The nature of an antisolvent is non-polar solvent (that is, a solvent in which the perovskite is not soluble). Consequently, the inclusion of the anti-solvent onto the precursor deposited on a substrate can generate fast supersaturation and precipitation of the perovskite precursor film by eliminating solvents from the precursor solution, hence, facilitating uniform grain growth with high nucleation density.

Olaleru et al. recorded that dropping ethyl acetate on a perovskite precursor film during the spinning process caused a homogenous perovskite film with good reproducibility [11]. Cohen et al. investigated the relationship between anti-solvent (toluene) treatment and electronic properties of the perovskite films together with surface morphology [9]. The most common antisolvents include toluene, chlorobenzene, and diethyl ether. Other antisolvents investigated including toluene, chlorobenzene, methanol, ethyl acetate and ethanol were found to induce fast crystallization and result in enhanced film quality [9]. Furthermore, the application of a more eco- friendly anti-solvent replacement to toxic chlorobenzene and toluene is greatly needed to minimize health risks.

3.4 Additives

The introduction of little amounts of chemical additives in perovskite precursor solutions have been recorded to offer advantages with regard to crystallinity, film uniformity and the resulting device performance. Additives constitute one more parameter affecting the perovskite morphology. There are different additives reported in the literature for various perovskites. Additive engineering can also enhance the quality of perovskite by modifying the film formation kinetics from a diverse perspective, including morphology modification, defect reduction, and enhancement of cation diffusion into PbI_2 layer [9].

It has been largely documented that the application of additives to the perovskite precursor solution could be a beneficial and logical technique to obtain large size grains in perovskite crystal, defect suppression, and improved stability and ultimately enhanced PCE of PSC devices. A wide spectrum of chemical additive has been recorded depending on the perovskite mixture and the additives manufacturing technique.

3.5 Annealing temperature

The formation of perovskite structure requires sufficient heat treatment whose purpose is twofold; removal of excess solvent remaining on the film and speeding

up crystallization of perovskite structure. Annealing process is one of the major parameters controlling the perovskite formation and morphology. The perovskite annealing is performed at various temperatures; the maximum thermal annealing for $\text{CH}_3\text{NH}_3\text{PbI}_3$ perovskite should not be more than 110°C .

From our work [8, 11], the annealing temperature had strong impact on the formation of perovskite. The under- and over-annealing were both detrimental to cell performance. Under-annealing could cause incomplete conversion to the perovskite and leave residual solvent and ions in the layer, while over-annealing decomposed the perovskite layer into PbI_2 by evaporating MAI from the layer. Therefore, it was necessary to keep annealing temperature below 110°C to avoid PbI_2 formation and annealing time should be kept below 30 min.

A polar solvent including γ -butyrolactone (GBL), dimethyl sulfoxide (DMSO), dimethylformamide (DMF) and N, N-dimethylacetamide (DMA) in perovskite ink deposited on a substrate was removed by annealing temperature on a hot plate or drying in air after the spinning procedure, resulting in supersaturation in the film for nucleation and crystal growth of the perovskites. This technique provides an easy strategy to evaporate solvent for perovskite deposition.

4. Scalable fabrication of perovskite thin film

From a technological viewpoint various optoelectronic devices depend on the integration of active thin films in appliances such as solar cells, light-emitting devices, and transistors. Until now, vapor and solution deposition have been the two common routes/methods for effectively preparing hybrid perovskite thin films. One of the merits of hybrid perovskite over in-organic semiconductors is the feasibility of obtaining high quality semiconducting films by simple solution or sublimation processes.

The fabrication of a smooth and pinhole-free large-area perovskite thin film is essential in the quest to attain PSCs' commercial application. The main challenge relies on how to prepare top quality large-area perovskite thin films with a facile scalable deposition method.

Up till now, the understanding of crystal growth processes and precursor solution has resulted in notable development laid down on various scalable deposition methods. This section outlined the striking progress in the preparation of large-area perovskite thin films and PSCs with scalable deposition techniques.

The best route for the deposition of perovskite thin film in the laboratory is spin coating with the aid of antisolvent and additive engineering; but, this technique throws away perovskite solution and is very susceptible to numerous technical requirements, which stifles its selection for the fabrication of large scale perovskite films.

Until the present, the recorded techniques for the fabrication of large-area perovskite thin films (1cm^2) could be mostly divided into the following classes: spin coating, casting, blade coating, spray coating and slot-die coating technologies [12]. Although spin coating has intrinsic weakness for large-area film preparation, it is further mentioned in comparison to other methods [12, 13], which reflect the deficiency in preparing large-area perovskite thin film.

4.1 Spin coating

Spin coating is an easy and common technique widely employed for perovskite thin film deposition in the laboratory. Normally, a little quantity of precursor solution is dropped on the center of the substrate. Then, the substrate is spin at a

high speed so as to spread the coating material by centrifugal force. The precursor solvent is normally volatile and concurrently evaporates during high-speed spinning. Consequently, the dried film with certain thickness is obtained.

Usually, there are two common methods for spin coating deposition of perovskite films. These are; one-step or two-step processing techniques as demonstrated in **Figure 2**. Perovskite thin film can be prepared either by spin-coating a mixed powders of MAX (X: I, Br, Cl) and PbX_2 (X: I, Br, Cl) solution (one-step coating) or by spin-coating PbX_2 accompanied by deposition of MAX (two-step coating).

Majority of current study on perovskite solar cells center on their fabrication using spin coating, which is already proven to attain better thin films with pinhole-free uniformity and carefully controlled crystal growth. Nevertheless, the spin coating is applicable to the manufacturing of non-scalable solution-processed PSCs [12]. It is difficult to expand the technique to enable fabrication of thin film for application in larger area devices. This practical bottleneck situation has strongly prompted scientists and manufacturers to consider new scalable techniques for the manufacturing of large-area perovskite thin films.

4.2 Vapor deposition method

The vapor-deposition techniques as displayed in **Figure 3** are usually performed under high-vacuum conditions. PbX_2 and MAX are deposited concurrently or alternately on the precoated substrate by thermal evaporation from dual sources of PbX_2 and MAX. Perovskite material is made at an adequate temperature and then crystallized into a perovskite film.

The perovskite film obtained from this strategy shows complete coverage, smooth grain structure with grain sizes up to micrometers and complete precursor transformation [14]. Indeed, it has been reported that vapor-deposited perovskite films were highly uniform with crystalline platelets at the nanometer scale [15]. This thermal evaporation method requires a high vacuum, which constraints cost efficiency and large scale production.

4.3 Casting

Casting requires easy transfer of perovskite ink to a target substrate accompanied by a brief heating procedure to evaporate solvent. Film thickness is regulated/influenced by the solid content in the solution and viscosity. The surface tension

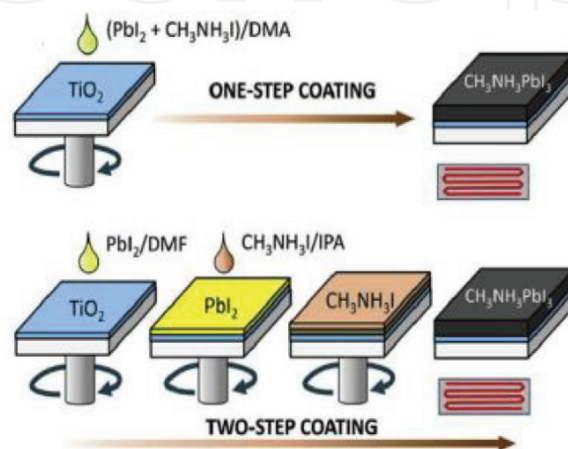


Figure 2.
Spin coating process of perovskite thin film [12].

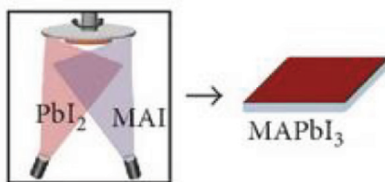


Figure 3.
 Vapor deposition of perovskite layers.

between the perovskite ink and substrate together with perovskite precursor viscosity and annealing temperature will greatly influence the quality and uniformity of the film. The notable benefit of this method is that there is no need for specific equipment during the process. In this procedure, it is feasible to fabricate large-scale perovskite thin film, however, the inadequate monitoring of film thickness together with the imprecise perovskite ink employment are apparent weaknesses of this technique.

Currently, there is scant literature on fabrication of large-scale perovskite thin film with the casting technique [12]. The schematic illustration of this technique is demonstrated in **Figure 4**.

4.4 Blade coating

Blade coating is a highly established, scalable and extensively employed method preferred in fabrication of perovskite thin film for PSCs. It is a promising deposition technique due to little material waste, facile operation, and compatibility with roll-to-roll fabrication [16]. Blade coating was initially employed for manufacturing of dye-sensitized solar cells [16]. But recently, it has been applied to the deposition of large-area perovskite films after skillfully amended [12].

During the blade coating process, a sharp blade is positioned in an appropriate place over the target substrate with the precursor solution in front of the blade as displayed in **Figure 5**. The blade can be moved with linear speed within the substrate to obtain a wet perovskite film. Generally, the thickness of wet layer should be approximately half the distance between the substrate and the blade. The thickness and the quality of the blade coated film is usually ascertained by different physical factors such as surface energy of the substrate, surface tension and solution viscosity [16].

It has been reported that the blade coating generates a uniform wet film from the precursor solution through one-step deposition [18]. Deng et al. made large-area (1 inch²) perovskite film with the doctor blading procedure and it was discovered that the carrier diffusion length of perovskite film obtained was longer than that of the films prepared by spin coating [19].

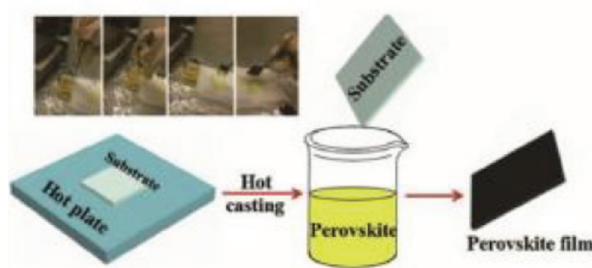


Figure 4.
 Pictorial representation of hot casting and the inset is hot casting procedure [12].

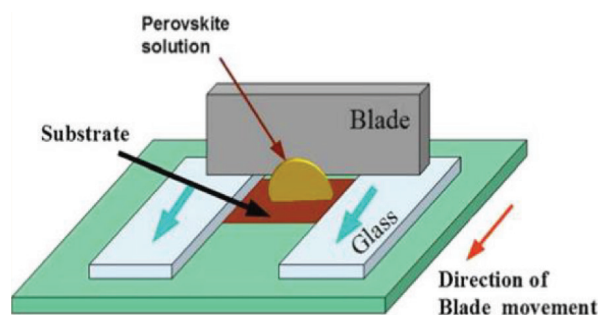


Figure 5.
Schematic of the blade coating technique [17].

4.5 Slot-die coating

Slot-die coating is another widely employed scalable technique for the fabrication of large-area perovskite thin film. It is probably the best fit technology for fabrication of perovskite thin film in manufacturing. Furthermore, the procedure is quite easy and relevant to a wide range of inks with various viscosities.

In this procedure, the precursor is usually applied from the coating head in the direction of substrate as shown in **Figure 6**. The perovskite film could be obtained, after drying and annealing. Quick and precise coating applied to the slot die is beneficial for the preparation of large-scale with high performance [16].

This method is far more expensive for laboratory uses in comparison with the blade coating. For this reason, the slot-die technique is not used often in research labs and the slot-die coated devices have much lower PCE than blade coated PSCs. Outstanding performance has been recorded so far on slot-die-coated PSCs. That is why, slot-die coating technique has been recommended as a roll-to-roll compatible process for the fabrication of PSCs in recent years by different researchers [12]. The basic illustration of the slot die coating technique as shown in **Figure 6**.

4.6 Spray coating

In brief, the ultrafine droplets of perovskite solution are sprayed from the nozzle and deposited on the target substrate which may be heated on a hotplate at certain temperature as demonstrated in **Figure 7**. After drying and annealing process, the perovskite film may be formed on the substrate.

Spray coating is a valuable low-temperature thin film deposition technique that allows a uniform, high coating rate applicable for various substrates. This method likewise draws great interest in the preparation of perovskite thin films [16]. But, little research on perovskite has been recorded employing the spray coating technique, maybe due to the instability of PSCs.

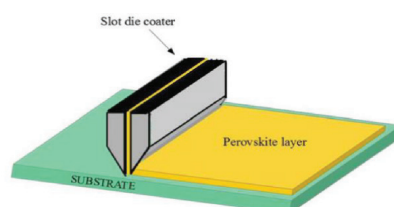


Figure 6.
The schematic illustration of the slot die technique for perovskite layer deposition [17].

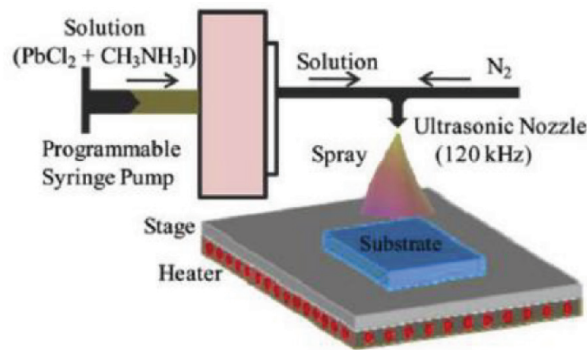


Figure 7.
Schematic diagram of ultrasonic spray-coating procedure [12].

In comparison with casting, spray coating has a better thickness control. In order to achieve a perovskite thin film with better quality by spray coating, the following should be considered; the perovskite solution concentration and viscosity, substrate temperature, the nozzle diameter and spray flow rate.

4.7 Ink-jet printing

An inkjet printing technique allows quick and material-conserving coating of thin films for the large-area preparation of photovoltaic thin films with the capacity to generate desired thin film as shown in **Figure 8**. However, to enhance the printing precision of the film the careful control of crystallization of the deposited wet films and solution properties is a fundamental condition. In this printing method, careful monitoring of the drop size is vital to obtain uniform thickness film. The ink properties take a leading role in assuring the stable droplets formation at the nozzle. Moreover, the fabricated film quality largely depends on the scattering of drops, coalescence, crystallization, and uniformity of the film during annealing. The parameters stated above are primarily influenced by the interaction of ink droplet with the substrate, for instance, the contact angle and surface roughness [20]. The astonishing success greatly promotes the application of this preparation method in perovskite devices.

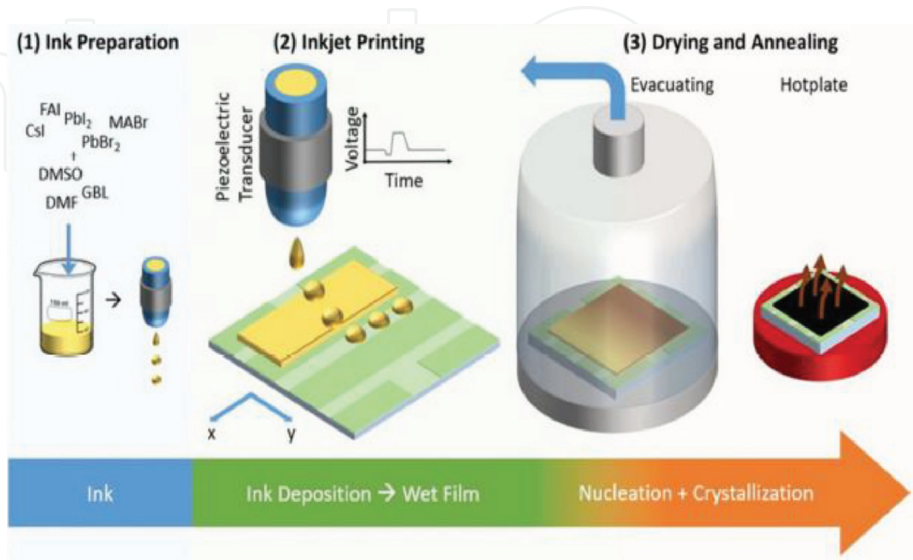


Figure 8.
Schematic illustration of the fabrication of perovskite material using ink-jet printing process [16].

Though, all these techniques are varying significantly from one to the other, but they have common goal of strengthen perovskite film formation so as to improve film quality and better device performance. The understanding of these mechanisms for creating new strategies is the key in producing top quality perovskite thin film. Further investigation of perovskite growth mechanism will be helpful in identifying opportunities for enhancement.

In consequence, optimizing processes will give more understanding into film formation, creating learning loops for developments in science.

5. Designing perovskite solar cells and modules

Perovskite thin films have yielded outstanding photovoltaic performance and are regarded compatible with low-cost, scalable fabrication. In spite of huge development in small-area PSCs’ photovoltaic performance, the large-area fabrication of uniform and top-quality perovskite films remained problematic coupled with cell instability and toxicity. But, researchers are making progress meaning that there is hope that all the challenges will be resolved in the foreseeable future.

In order to establish the possibility in the direction of commercialization, it is a definite measure for emerging PV technologies to show high efficiency at a module/mini module of minimum 10–100 cm² [16].

Table 1 shows the record of various scalable deposition strategies employed to develop large-area perovskite thin films and their roll-to-roll capabilities [16].

The simplicity of making PV cells through solution-based and vapor-based processes as well as deposition techniques such as spin coating, spraying, slot die, blade coating and ink-jet printing make it possible for PV cell manufacturers to ultimately replace clean rooms and complex industrial equipment with facile bench top procedures. The rapid development, which has propensity for more improvements, coupled with low-cost materials and simple preparation processes. This will prompt a novel design, new reports on working mechanism and applied perovskite materials that will emerge.

It is therefore relevant to explore the best mix of various deposition techniques forming hybrid techniques. Though, blended techniques may likely give rise to dissimilar film formation mechanisms as a result of different interfaces such as solid/vapor or solid/liquid interfaces in relation with liquid/liquid interface in a sequential solution method. This calls for thorough investigations in the nearest future. The aim is to merge the benefits of various coating techniques for superior film formation and utilizing the benefits for the fabrication of large scale perovskite thin film for light-harvesting devices.

Method	Material	Roll to roll	Largest coaling area (cm ²)	PCE (%) single cell area ≤ 1 (cm ²)	PCE (%) module area ≥ 10 (cm ²)
Blade coating	MAPbI ₃	yes	6 × 15	20.3	14.6
Slot die coating	MAPbI ₃	yes	12.5 × 13.5	~12	10
Spray coating	MAPbI ₃	yes	7.5 × 7.5	16.9	14.2
Ink jet printing	MAPbI ₃	yes	2.02	17.74	—

Table 1.
Record of various scalable deposition strategies employed to develop large-area perovskite thin films.

6. Conclusion

Due to their ‘adaptable’ low band gap, the perovskite thin films demonstrated better advantages over their counterparts by far more absorbing over a broader range, facilitating full light absorption in films as thin as 300–500 nm, which is favorable for the solid-state cells. Perovskite absorbers find application in tandem with other PV technologies: supplementing spectral absorption, bandgap tunability, and simple technique and process compatibility with silicon and CIGS technologies. Huge progress has been demonstrated in efficiency, stability, and scalability. To become a market-competitive technology, a few number of issues such as toxicity must be resolved alongside with the feedback between process development, scaling, efficiency and stability.

In sum, the performance of PSCs can be enhanced greatly via the optimization of the different materials composition and techniques entailed in their development process. Particularly, for the fabrication of scalable modules using commercial solution coating equipment, the incorporation of solvent engineering and chemical additives together with physical qualities in the precursor solution is very much needed. Additionally, perovskite is not just for PV panels. These perovskite materials are excellent nanomaterials with fascinating properties and provide themselves to numerous inventions for novel devices. In consequence, perovskite’s potential finds applications in the following: sensors, catalyst electrodes, fuel cells, lasers, sensors, memory devices and spintronic.

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