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Thin Film Deposition Techniques for Photovoltaic Devices: Thermal Evaporation versus Spin Coating

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Abstract: This paper has critically discussed the two widely used thin-film deposition techniques which include thermal evaporation and spin coating and their merits and demerits as far as their capability to produce photovoltaic (PV) devices is concerned. When it comes to creating high purity of films, thermal vaporization under vacuum conditions has advantages in thermal evaporation [1]. Conversely, spin coating is characterized by the simplicity of operation, and the capacity to fabricate high quality films which may occur hence it finds application in laboratory research and small scale production projects [2]. The paper will focus on the methodology, materials used and end product of the films of each technique, their impact on device performance and the scalability of the devices in the solar energy solution. In particular, the thickness and uniformity of the films can be determined accurately by a physical vapor deposition method called thermal evaporation, which is particularly significant when dealing with large areas in industry [4], [5].

This method is adept at depositing multilayer structures and fast switching between layers, a vital characteristic to tandem solar cells, which frequently add layers of perovskites on various substrates including silicon [6]. Spin coating, on the other hand, is highly cost-effective and capable of using solution-processed materials and enables rapid screening of new material compositions and optimization of film properties to a variety of PV uses [7], [8]. The low-temperature processing capability has made this method especially desirable to reduce substrate oxidation and corrosion thereby enabling its use in a wide range of substrate materials such as insulators, semiconductors and metals [9]. Selection of these techniques is frequently determined by the material properties and the required film structure and the cost-effectiveness of large-scale manufacturing [10]. As an example, manufacturing of cadmium telluride thin films, which are commonly used as absorber layers, commonly involves thermal evaporation as it is effective in producing desired structural and electrical properties by controlling deposition [11]. On the other hand, perovskite solar cells, commonly explored due to their low-cost and high-efficiency, often use solution based processes, such as spin coating for their active layers [12].

Introduction

Though spin coating is commonly used to fabricate perovskite solar cells at laboratory scale because of its simplicity, low cost, and control over film thickness and uniformity, it cannot be easily scaled to large areas of industrial scale fabrication [13], [14]. The main problems that have led to these challenges are the uniform deposition on large substrates and the difficulties in balancing the complex interaction between the wetting behavior and solvent evaporation dynamics, which are key determinants of film quality and reproducibility [15]. As a result, other methods of deposition offering enhanced uniformity and use less material waste are being actively explored to create large-scale perovskite solar cell modules [16]. Indicatively, large-area perovskite film fabrication has been shown to be promisingly achieved by high-throughput (blade coating and vacuum deposition) techniques [17]. In the meantime, the development of solution-based processing, beyond the traditional spin coating, such as spray, gravure, knife/blade, and slot-die coating, is actively under development to be used in high-throughput, continuous deposition of flexible substrates [18].

These scalable solution-based technologies have tremendous benefits to the mass production of perovskite solar cells by being able to be deposited over large areas and are able to be integrated into roll-to-roll scale production processes [19], [20]. It is interesting to note that chemical vapor deposition and thermal vapor deposition are also feasible as viable routes to large-scale manufacturing, and both have high reproducibility despite the complexities of their technologies [21]. Even with these developments, majority of record efficiencies in perovskite solar cells are attained through spin coating on small scale applications and this highlights the current problem of ensuring that laboratory achievements can be translated into scalable manufacturing without loss of performance [22]. This drawback underscores the importance of further studies that would employ scalable coating methods capable of functioning with the same efficiency as spin-coated devices in the lab but able to maintain cost-efficiency and uniformity of the films on large substrates [23], [24], [25], [26]. One of the most significant issues that must be weighed concerning the extensive commercialization of perovskite photovoltaics is the replacement of spin coating in laboratories with industrial-scale deposition schemes that can preserve high power conversion efficiencies and stability of the devices [27], [28]. To deal with this, many industrial scale methodologies such as blade coating, slot-die coating and vacuum evaporation have been found to be essential in attaining high-quality perovskite films in large scale [29].

Literature Review

These auxiliary methods are to address the intrinsic weakness of spin coating including wastes of materials and non-uniformity on large substrates that hamper its practical use in the industrial settings [30], [31]. In particular, the methods of blade coating, slot-die coating, spray coating, screen printing, inkjet printing and gravure printing, as well as the methods of vacuum or vapor deposition, are under development to enable the upscale manufacturing of perovskite solar cells to module-scale performance [32], [33], [34]. In particular, slot-die coating has been a promising method to be integrated into roll-to-roll processes and has shown successful film formation on large substrates with efficiencies up to and above 18% [14]. In addition, the blade coating has the benefits of having a diverse compatibility with various fluid viscosities and low ink usage in small-scale batches, which is suitable to optimize at laboratory scale before expanding to industrial production [18]. These scalable solutions-based processes have strong benefits to the mass fabrication of perovskite solar cells because of the ability to deposit over large areas and the ability to integrate into roll-to-roll production systems [35], [36].

This method will improve not just the throughput but also greatly minimize the material waste as opposed to spin coating which is essential in making it economically viable [37], [38]. The feasibility regarding these scalable methods in damping bulk as well as interfacial defects, and, by extension, in enhancing the performance and long-term stability of devices is a major area of interest [39]. The homogeneous crystallization of the perovskite phase with large areas is also a serious challenge of such alternative processes, and it needs high level of control over the dynamics of solvent evaporation and film formation [40].In addition, the accurate control of precursor ink rheology and substrate surface energy gains importance to achieve a uniform film thickness and crystal growth when leaving laboratory-scale spin coating to large-scale deposition methods such as blade and slot-die coating [41]. This type of control is necessary to avoid such problems as pinholes and the non uniformthickness, which can significantly affect the work of the device and its efficiency [27], [42]. At that, screen printing can also be an attractive alternative of large-scale production since it can be functionally layered and allows a design to be flexible [43].

Methodology

In this paper, the efficiency of two widely used thin film deposition methods, thermal evaporation and spin coating and its process, material utilization efficiencies and the performance of the PV devices will be compared. It discusses the complex processes of film growth, crystallographic orientation and interface properties of each technique and compares the advantages and the disadvantages of the techniques in the context of future PV devices. This paper will examine the working principles of the techniques, factors such as the vacuum conditions, the rates of deposition, substrate temperature, concentration and spin rate of the solution and how it affects the morphology and optoelectronic properties of the films. This comparative study will enlighten the specific challenges in the uniform deposition of the films and reduction of defects in thermal evaporation and spin coating and will also guide future plans on cost-effective large-scale and high-efficiency PV devices.It will also examine how such deposition techniques affect the stability of these devices in the long run and the overall performance indicators of the final devices, which are vital in determining the commercial viability of the devices.

The environmental impact and waste of materials involved in each of the methods will also be analyzed and their appropriateness to sustainable manufacturing practices will be further evaluated. Although spin coating has played a key role in the optimization of devices in the laboratory scale, there are some fundamental weaknesses of the technique, including large amounts of material waste and the inability to process in large areas, which makes it necessary to consider other deposition techniques in making such devices commercially viable [44], [45]. As an example, screen printing has been shown to provide a viable route to silver electrode fabrication in organic photovoltaics, where comparable efficiencies can be made with screen printing as with thermal evaporation, and an all-solution coating process can be performed, suitable to mass-fabrication. But, scalability of such solution-based methods as spin-coating is usually constrained by inherent limitations such as high material waste and non-uniformity over larger substrates, which means that they are not as applicable to large-scale production as alternative methods, such as slot-die coating or thermal evaporation [47], [48].

Results

On the contrary, thermal evaporation, although purity and thickness control are high, is a process that is vacuum-based, limiting the high-throughput production and high cost [49], [50]. Nevertheless, recent progress in roll-to-roll vacuum processing, including that of Heliatek and the University of Southern Denmark, indicates that vacuum steps are not necessarily prohibitive to large-scale fabrication, particularly in relation to the efficiency gains which are typically achievable with vacuum-processed organic solar cells [51]. This subtle view disputes the mainstream belief that any vacuum-based technique cannot be adopted to large-scale production, and highlights that certain modifications can make them feasible in commercial production. Furthermore, the creation of fully roll-to-roll processes, which include such methods as flexographic printing, slot-die coating, and rotary screen printing, push the envelope of ambient condition production of organic PV devices even further [52]. Nevertheless, the energy requirements and environmental impact of the vacuum-based deposition processes are still significantly greater than those of the solution-processed ones, and roll-to-roll printing is the least environmentally impactful [53], [54].

The environmental sustainability of such processes is also improved by decreasing or removing the use of toxic substances, like lead and silver, and the use of encapsulation techniques that increase the longevity of the device and reduce its overall environmental impact [52], [56]. Moreover, the creation of alternative drying and annealing systems, including photonic flash annealing or NIR curing, may also lead to further energy savings in the processing of films during solution-based processing and towards more environmentally-friendly manufacturing processes [57]. As an example, vacuum flash evaporation has demonstrated itself as potentially useful in regulating solvent evaporation dynamics in perovskite films, allowing high-efficiency devices and potentially simplifying processing [58]. This methodology is consistent with the overall goal of creating lab-to-fab systems to move laboratory scale studies closer to the needs of industry in commercial production, and increase the commercialization of high-performance PV systems [59].

Discussion

This part is a synthesis of the results of the comparative study of thermal evaporation and spin coating, which determines the important aspects that should be considered when choosing the correct deposition method depending on the particular PV material systems and the desired architecture of the device. It also examines the new trends and combinations of the two methodologies that bring together the best features of the two, providing the avenues to greater performance and manufacturability of future generation solar cells. This is further discussed in the context of assessing their relative strengths and weaknesses in regard to economic viability and the environmental cost, especially with regard to material waste and energy usage [60]. The main feature of this assessment is that it incorporates the life cycle assessment methodologies in order to quantify the total environmental footprint, including the extraction of raw materials through to end-of- life disposal, of each deposition method. Such a holistic view allows considering the sustainability implications of different manufacturing routes to perovskite solar cells [61], [62].

These tests are important to inform future research on green solvents and methods of fabrication that reduce the environmental impact and high power conversion efficiencies and scalability [63]. In addition, further developments in in-situ characterization methods, in combination with computational modeling, are offering a better understanding of the film formation processes during deposition, allowing the optimization of these processes to achieve high-quality materials and device performance [64]. This is specifically relevant to the perovskite solar cells, in which crystallization kinetics and morphology are critical factors in determining a high efficiency and long-term stability, although various methods are used [65]. The intrinsic problems of perovskite materials such as reproducibility problems require ongoing development of deposition methods [66]. In particular, whereas in small-scale perovskite deposition various approaches were employed such as the dual-source vapor deposition, one-step solution deposition, scalable methods such as inkjet printing and slot-die coating are required in large-scale application to overcome commercialization challenges that associated with chemical stability [67].

Conclusions

The present review highlights the complexity of the trade-off between process scalability, material stability and environmental considerations in the identification and optimization of thin-film deposition methods to photo-voltaic devices. Although thermal evaporation is best at making high-purity and uniform films, its vacuum requirements hinder high-throughput, economical scale manufacturing; spin coating, on the other hand, is simple and accessible in the laboratory scale, but does not scale to large-area uniformity and material waste. Thus, using green solvents and anti-solvent-free fabrication for large scale perovskite layers is essential in improving the overall sustainability of the solution-processable methods [68]. Future research activities will be more concerned with the complexity of the interaction between solution compositions and deposition parameters to optimize the process of film drying hence enabling the shift to scalable manufacturing [69].

This encompasses high-technology drying dynamics studies that deal with the difficulties of having thicker and less uniform solution films in scalable deposition techniques, which are usually associated with such problems as the coffee ring effect and non-uniform growth of crystals [70]. Designing accurate control over the solvent removal kinetics and film solidification when operating scaled solution processing is thus a vital move to obtain the required morphological and microstructural features in high-performance perovskite solar cells [71].

Besides, spin coating is only commonly utilized in early research and development due to its convenience, but scalability in industries needs alternative approaches such as chemical vapor deposition or thermal vapor deposition due to its high repeatability and scalability to mass production [72]. The advantages of these methods include uniformity and control of stoichiometry in films, which is crucial in maintaining efficiency and stability of devices at larger scales [30]. The in-situ monitoring and real time control of the process in the vapor phase deposition techniques will be important in streamlining these mass production processes to ensure that the quality of the film as well as the performance of the devices is uniform [73].

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