Journal of Zhejiang University-SCIENCE A 2025 26(9):811-831
www.jzus.zju.edu.cn; www.springer.com/journal/11582
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Review

https://doi.org/10.1631/jzus.A2500054

Key factors influencing perovskite film crystallization in blade-coating processes

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Abstract: Perovskite films have fostered significant progress in the field of optoelectronic devices, particularly in solar cells, due to their excellent optoelectronic properties and cost-effective fabrication process. As a promising technique for large-scale industrial production of perovskite films, the blade-coating method has attracted wide attention because of its low cost, large-area coating capability, and simplicity. However, during the blade-coating process, perovskite films often present challenges such as poor film uniformity, high defect density, and uneven crystallization, which greatly affect the efficiency and stability of the devices. In this review, we summarize the application of blade-coating methods to the fabrication of perovskite films, with a focus on analyzing key factors affecting film quality, including precursor solution formulations, solvent characteristics, evaporation rate, crystallization kinetics, and film thickness. In particular, we discuss the impact of environmental factors on the perovskite crystallization process during blade-coating and explore how optimizing the blade-coating process and precursor solution composition can improve film uniformity and device performance. Additionally, we discuss the main challenges and shortcomings in the blade-coating preparation of perovskite films, including defects during large-area fabrication, differences in solvent evaporation rates, and their effects on crystallization quality. Strategies for addressing these issues are proposed. Finally, the prospects of the blade-coating method in large-scale production of perovskite films are outlined, emphasizing the importance of a deeper understanding of perovskite film crystallization mechanisms and the development of novel additives to enhance the performance of perovskite optoelectronic devices and accelerate their industrialization.

Key words: Perovskite thin films; Blade-coating; Crystal growth; Optoelectronic properties

1 Introduction

Perovskite materials have revolutionized optoelectronics due to their exceptional optoelectronic properties, including high absorption coefficients, long charge carrier diffusion lengths, and tunable bandgaps (Kojima et al., 2009; Kim et al., 2013; Dong et al., 2015; Saidaminov et al., 2015; Wang Z et al., 2017). As a disruptive photovoltaic technology, perovskite solar cells (PSCs) within decades have achieved a certified power conversion efficiency (PCE) of 26.95%. It is crucial to produce high-quality perovskite films that not only have controllable crystallinity but also maintain uniform morphology and minimized defect density. The crystallization process of the perovskite film formation directly affects the optoelectronic performance and long-term stability of the devices. Therefore, optimizing the crystallization process during film formation is the key to obtaining high-performance devices.

Essentially, the crystallization mechanism of perovskite thin films conforms to the theoretical framework established by the classical LaMer model (Whitehead et al., 2019), which delineates nucleation and subsequent crystal growth. The change in concentration of a precursor solution as a function of time can be illustrated qualitatively by a LaMer diagram (Fig. 1a). During solvent evaporation, the solute concentration reaches saturation concentration (C_s) at time t_1, yet nucleation remains inhibited due to the existing energy barrier. Upon surpassing the critical concentration (C_c)

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Received Feb. 24, 2025; Revision accepted May 1, 2025;
Crosschecked July 15, 2025

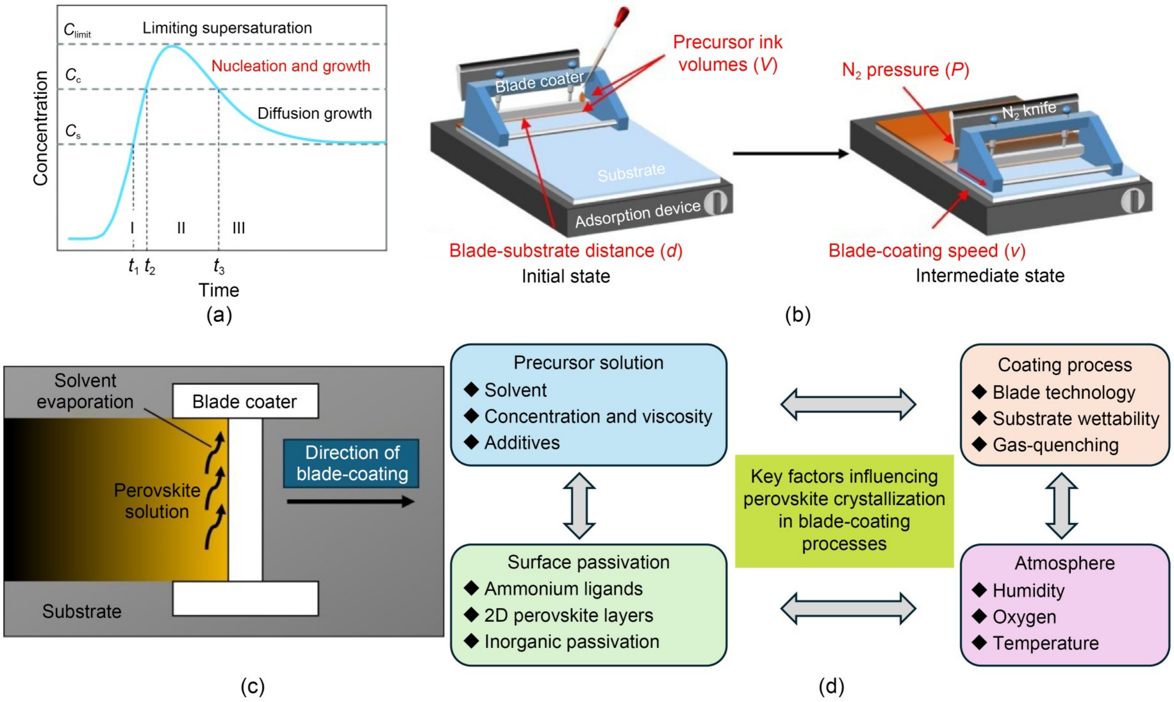

Fig. 1 (a) The LaMer model of nucleation and crystal growth (reprinted from (Zeng et al., 2020), Copyright 2020, with permission from Royal Society of Chemistry). C_{limit} is the concentration of critical limiting supersaturation; (b) Schematic illustration of the N_2 knife-assisted blade-coating process (reprinted from (Hu et al., 2025), Copyright 2025, with permission from Wiley); (c) Top-view schematic illustration of the blade-coating process; (d) Key factors influencing perovskite crystallization in the blade-coating processes. References to color refer to the online version of this figure

at time t_2, the system enters the primary nucleation phase (Stage I). When the concentration is higher than C_c (Stage II), both nucleation and crystal growth take place. Due to the competition between solvent evaporation and solute consumption by crystal growth, the concentration of the solution then starts to decrease and finally drops below C_c. As the concentration decreases below C_c at time t_3 (Stage III), nucleation ceases while existing grains continue growing until the system reaches sub-saturation concentration (C_s) (Zeng et al., 2020). Therefore, the perovskite film morphologies and properties obtained in this way are significantly determined by its crystallization (Xu et al., 2025).

Spin-coating is the most widely used technique for fabricating perovskite films, as it allows for rapid and uniform film deposition. However, the narrow time window for adding anti-solvent may result in very low tolerance during the device fabrication process, limiting the yield and reproducibility of perovskite devices, especially in large-scale production (Xiao et al., 2014; Yang MJ et al., 2015, 2016; Ge et al., 2016). Additionally, the powerful centrifugal force generated during spin-coating to apply the film and remove excess solution can lead to significant variation in the film thickness across different regions of the substrate (Heo et al., 2014; Ye et al., 2016; Chen et al., 2017). This is undesirable for fabricating large-area devices.

Blade-coating has emerged as a compelling alternative, offering high throughput and exceptional material utilization (Jeong et al., 2019; Park and Zhu, 2020). As illustrated in Figs. 1b and 1c, this technique uses a doctor blade to shear-align precursor solutions into uniform wet films, coupled with assisted methods like gas quenching (Huang et al., 2014; Gao et al., 2017a; Song S et al., 2017; Zheng et al., 2017) to modulate solvent evaporation kinetics. Gas quenching introduces a laminar airflow parallel to the substrate, enabling faster solvent extraction rates than natural evaporation (Kwon et al., 2007; Ghosh et al., 2008; Cho et al., 2009; Zhang et al., 2012). This rapid solvent depletion can potentially induce nucleation and directional crystal growth. Compared to spin-coated films, blade-coated films show enhanced grain uniformity, reduced defect density and low cost. Here, we review and summarize recent progress in blade-coated perovskite solar cells (Table 1).

Table 1 Literature survey and summary of recent progress in blade-coated perovskite solar cells. All the efficiency data collected are the highest values reported in the studies

Bandgap (eV)	Device type (rigid cell)	Area (cm^2)	PCE (%)	Strategy	Reference
1.53	p-i-n	0.09	24.31	Additives	Yang et al., 2025
~1.60	p-i-n	0.08	21.4	Additives	Feng et al., 2025
1.52	p-i-n	0.09	24.10	Additives	Wu et al., 2025
1.55	p-i-n	0.08	21.74	Solvent engineering	Hu et al., 2025
1.68	p-i-n	0.049	20.77	Solvent engineering	Zheng et al., 2024
1.78	p-i-n	1.05	19.6	Solvent engineering	Duan et al., 2025
1.68	p-i-n	1.05	21.5	Solvent engineering	Duan et al., 2025
1.68	p-i-n	N/A	21.31	Additives	Ge et al., 2025
1.77	p-i-n	0.07	19.45	Post-treatment	Pu et al., 2024
1.77	p-i-n	1	18.71	Post-treatment	Pu et al., 2024
1.70	n-i-p	0.1	19.05	Solvent engineering	Abate et al., 2024
1.77	p-i-n	0.09	19.28	Surface passivation	Zhang et al., 2024
1.77	p-i-n	1	18.08	Surface passivation	Zhang et al., 2024
1.67	p-i-n	0.07	22.06	Additives	Jia et al., 2024
1.67	p-i-n	1.02	19.63	Additives	Jia et al., 2024
1.68	p-i-n	0.07	19.92	Additives	Zhang et al., 2023
1.68	p-i-n	10	17.70	Additives	Zhang et al., 2023
1.80	p-i-n	0.09	18.92	Solvent engineering, surface passivation	Tang et al., 2023
1.65	p-i-n	0.06	21.90	Additives	Yang G et al., 2022
1.72	n-i-p	46.5	16.07	Solvent engineering, surface passivation	Tian et al., 2022
1.72	n-i-p	123.0	13.03	Solvent engineering, surface passivation	Tian et al., 2022
1.65	p-i-n	N/A	20.10	Additives	Chen et al., 2020

Furthermore, blade-coating is particularly advantageous for large-area perovskite module fabrication, as it enables scalable and continuous film deposition. However, achieving uniform crystallization across large-area substrates remains a significant challenge. Variation in the coating speed, solution wetting behavior, and drying conditions can lead to non-uniform thickness and defects such as pinholes and grain boundary discontinuities, which ultimately impact module efficiency. Recent studies have focused on optimizing solvent engineering, substrate pre-treatment, and blade-coating parameters to enhance the uniformity and reproducibility of large-area perovskite films. Addressing these challenges is crucial for improving not only module efficiency but also the overall production efficiency of perovskite photovoltaics.

Nevertheless, the crystallization dynamics in blade-coating still face several challenges. The crystallization process is highly sensitive to factors such as solution properties, process parameters, and environmental conditions. Specifically, variations in precursor formulations, solvent evaporation rates, coating speed, and post-treatment processes such as surface passivation can significantly affect crystallization behavior, leading to uneven crystallization, phase segregation, and defects (Yang et al., 2019; Park and Zhu, 2020; Han et al., 2025). These factors play crucial roles in nucleation and crystal growth, directly influencing the microstructure of the films, crystallization quality, and ultimately, the optoelectronic performance (Ding et al., 2019; Park and Zhu, 2020; Yin et al., 2025) (Fig. 1d). Therefore, systematically analyzing how these factors interact and their specific impacts on film quality is essential for achieving consistent crystallization and high-quality perovskite.

In this review, we summarize the key factors influencing the crystallization of perovskite films in blade-coating, focusing on the optimization of solution properties, process parameters, and environmental conditions to improve film quality. By delving into nucleation and crystal growth mechanisms, we aim to provide theoretical guidance for achieving controlled crystallization, uniform grain growth, high-quality films, and practical insights for the development of scalable, high-performance perovskite photovoltaics.

2 Precursor solution

2.1 Solvent

The choice of solvent not only regulates the crystallization process of the film by influencing the volatility, polarity, and boiling point of the solution, but also affects the solubility, nucleation, and crystal growth behavior of the perovskite precursor through its interaction with the precursor. The solvent's polarity and Gutmann donor number (DN) are key factors that influence the crystallization behavior of perovskite films. Studies have shown that the higher the DN value of a solvent, the stronger its coordination ability with metal ions in the perovskite precursor, thereby affecting the solubility and crystallization process of the solution (Hamill et al., 2018; Vidal et al., 2021; Wu et al., 2021; Lee et al., 2022). When the DN value of the solvent exceeds 18 kcal/mol, it can effectively dissolve lead halides, promoting the dissolution and crystallization of perovskite. Dimethyl sulfoxide (DMSO) and dimethylformamide (DMF) can effectively dissolve perovskite precursors due to their strong coordination with Pb^{2+}, facilitating crystal growth (Park et al., 2023). Although DMF has good dissolving ability, its high boiling point and toxicity pose challenges for large-scale fabrication (Abate et al., 2024). Therefore, researchers have begun exploring green solvent systems that do not contain DMF, such as acetonitrile (ACN) (Sun et al., 2021; Wu et al., 2021; Belay Adugna et al., 2022) and 2-methoxyethanol (2-ME) (Deng et al., 2019; Wang G et al., 2020; Wu et al., 2021; Lee et al., 2022), to optimize the crystallization process and reduce environmental pollution caused by solvents.

The physical properties of solvents, such as their volatility, vapor pressure, and boiling point, play a crucial role in the crystallization process of perovskite films. The evaporation rate of the solvent directly affects supersaturation during crystallization. Highly volatile solvents like ACN and 2-ME can evaporate quickly at room temperature. Due to their fast crystallization rates, they often promote nucleation and crystal growth of perovskite, resulting in a more uniform and dense film structure. However, for scalable processing techniques, such as slot-die coating of perovskite thin films (Fig. 2a), the coating window must be extended to deposit a uniform film, as the process involves key steps like precise control of precursor solution flow, coating speed, and substrate temperature, all of which ensure consistent film thickness and uniform crystallization (Whitaker et al., 2018). In contrast, solvents with lower volatility, such as DMSO, have lower vapor pressure and higher boiling points, which typically lead to slower nucleation and crystal growth rates. This can result in more defects in the film, such as pinholes or grain boundaries, negatively impacting the film's uniformity and density.

For large-area perovskite module fabrication, optimizing the solvent evaporation rate becomes even more critical. In large-scale processes, uniform crystallization across extensive substrates is required, and solvent properties need to be carefully controlled to achieve consistent film morphology. Efficient evaporation management, combined with solvent choice, can significantly improve the yield and uniformity of large-area perovskite films, a vital step toward the commercialization of perovskite-based devices.

Solvent mixtures provide an effective strategy to address this issue. By precisely controlling the evaporation rate of the solvent, a mixture of volatile non-coordinating solvents and non-volatile coordinating solvents can be used to adjust the solution's evaporation rate and colloid size distribution (Deng et al., 2019; Park, 2021). For example, mixing DMSO with ACN or 2-ME (Deng et al., 2019; Abate et al., 2024), or combining DMSO with ACN and ethanol (EtOH) (Duan et al., 2025), helps regulate the nucleation rate and crystal growth process, resulting in perovskite films with lower defect density and better optoelectronic properties. The use of EtOH, for example, induces a more uniform distribution of colloidal particles, promoting better film formation and reducing the occurrence of large, irregular crystallites that can impair device performance (Fig. 2b).

The polarity of the solvent and its coordination with the precursor directly influence the solubility and crystallization dynamics of perovskite (Abate et al., 2024). Solvents with low coordination abilities, like ACN, do not excessively coordinate with the perovskite precursor, helping to form smaller colloidal particles and promoting uniform crystal growth. On the other hand, high-coordination solvents such as DMF, while

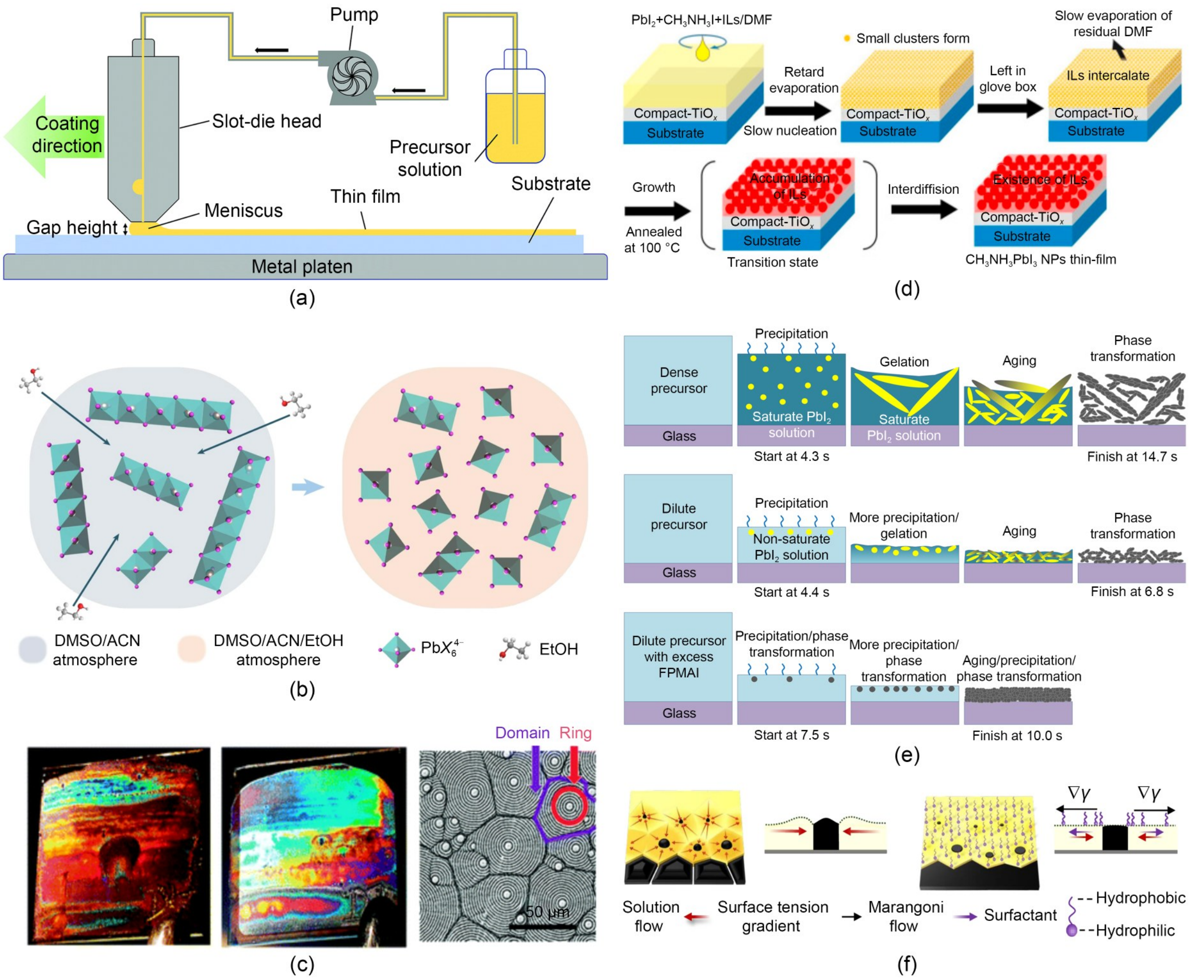

Fig. 2 (a) Schematic illustration of the key steps involved in slot-die coating of perovskite thin films (reprinted from (Whitaker et al., 2018), Copyright 2018, with permission from Royal Society of Chemistry); (b) Schematic illustration of the colloidal components after adding EtOH to the perovskite precursor solution (reprinted from (Duan et al., 2025), Copyright 2025, with permission from Springer Nature); (c) Photographs of the prepared colorful organometal trihalide perovskite (OTP) film and the complete device, and a plane view scanning electron microscope (SEM) image of a prepared colorful OTP film (reprinted from (Deng et al., 2015b), Copyright 2015, with permission from Royal Society of Chemistry); (d) Schematics of the formation mechanism of $CH_3NH_3PbI_3$ films with ionic liquids (reprinted from (Shahiduzzaman et al., 2017), Copyright 2017, with permission from Elsevier); (e) Schematics of the sol–gel stages using a dense precursor solution (0.8 mol/L), a dilute precursor solution (0.2 mol/L), and a dilute precursor solution with 50% molar excess 4-fluorophenylmethylammonium iodide (FPMAI) (reprinted from (Chu et al., 2021), Copyright 2021, with permission from Springer Nature); (f) Schematic illustration of the directional microscale solution flow towards a perovskite island during ink drying with and without surfactant (reprinted from (Deng et al., 2018), Copyright 2018, with permission from Springer Nature). $\nabla\gamma$ is the surface tension gradient. References to color refer to the version of this figure

more effective at dissolving the perovskite precursor, may cause excessive coordination, leading to rapid crystal growth and affecting the uniformity and optoelectronic properties of the film. Note that, in addition to the physical and chemical properties of the solvent itself, the interaction between the solvent and factors such as the substrate, environmental temperature, and humidity can further affect the final quality of the film. For instance, the matching of the solvent evaporation rate with the substrate surface temperature can affect the uniformity and compactness of the film, thereby impacting the crystallization process to variable degrees. Furthermore, while solvent mixtures offer an effective optimization strategy, balancing solvent environmental friendliness and cost-effectiveness while maintaining high-quality films remains a challenge that needs to be addressed. Future research should focus more on the development of green solvent systems and explore how the comprehensive regulation of factors such as solvent properties, solution concentration, and coating speed can further improve the film quality and device performance of perovskite thin films.

2.2 Concentration and viscosity

Variation in the solution concentration directly influences the thickness, uniformity, and final crystallization quality of the thin films. A low concentration solution accelerates the solvent evaporation process, causing the perovskite precursor to crystallize quickly during rapid evaporation, resulting in a more uniform film. Deng et al. (2015b) found that when the solution concentration is below a certain threshold, the perovskite thin film forms vibrant, multicolored patterns (Fig. 2c). Such a phenomenon is related to the photonic structures spontaneously formed by crystallizing grains. However, such films may have limitations in crystallization quality and grain size control, with the ‘coffee-ring’ effect potentially restricting optimization of their optoelectronic properties in practical applications. Nevertheless, low-concentration solutions offer certain advantages in specific applications, such as in flexible or small-area devices, particularly when balancing photoconversion efficiency with ease of preparation, which may provide researchers with new insights.

In contrast, when the solution concentration is high, the film thickness increases, providing more space for the full growth of perovskite crystals. High-concentration solutions help increase the wet film thickness, but this also means that the solvent overflow process becomes harder to control. Excessively high solution concentrations can lead to slower solvent evaporation, impacting the uniformity of the wet film during the drying process and ultimately affecting the crystal growth direction and film quality. Furthermore, high-concentration solutions have high viscosities, making it more complex to control the surface tension of the film and the liquid flow during coating. Finding a balance between concentration and viscosity becomes the key to improving film quality.

The viscosity of the solution not only affects the operability of the coating process but also determines how the solution is distributed on the substrate. Shahiduzzaman et al. (2017) found that the solution’s viscosity is closely related to the aggregation process of the perovskite precursor. In the absence of ionic liquids (ILs), the rapid evaporation of DMF during spin-coating causes fast crystallization, resulting in non-uniform morphology (Fig. 2d). However, ILs, with their high boiling points and low vapor pressures, slow down crystallization, leading to more controlled nucleation and uniform perovskite films. High viscosity solvents hinder the diffusion of the perovskite solute, whereas low viscosity solvents allow faster dispersion of solute, promoting collisions and aggregation between perovskite molecules, resulting in the formation of uniform nanoparticles and enhancing the crystallization quality of the film. During coating, the flowability and surface tension of the solution directly affect its spreading speed and uniformity on the substrate. Chen et al. (2022) suggested that high viscosity IL solvents improve the quality of blade-coating and printing because they limit the movement of the perovskite, thereby suppressing the deprotonation of methylamine/formamidinium (MA/FA) (Wang X et al., 2020).

The viscosity of the solution not only affects the thickness and uniformity of the film but also plays a crucial role in the grain morphology and growth direction. High viscosity solutions can effectively maintain a high concentration of perovskite solute, promoting crystal growth (Huang KW et al., 2024). However, how to avoid excessive aggregation leading to overgrowth of crystals, and how to adjust the grain size and morphology of the film through proper control of viscosity and concentration, remain challenges that need to be addressed.

While many studies have revealed the effects of concentration and viscosity on film quality, how factors such as solution volatility, solvent polarity, and surface tension interact in the actual coating process still requires further investigation. Future research directions should focus on the systematic optimization of solution formulations, exploring new film-forming methods based on solution concentration and viscosity adjustment, especially in terms of achieving efficient and uniform coating in the blade-coating process to optimize the crystallization process of thin films.

2.3 Additives

In the process of preparing perovskite thin films by blade-coating, additives influence the crystallization process of the films through various mechanisms, including regulating the precursor solubility, extending crystallization time, controlling the nucleation process, improving the interface quality, and enhancing the stability of the films.

Solubility regulators, such as lead thiocyanate ($Pb(SCN)_2$) (Ke et al., 2016; Ding et al., 2019) and 1,8-diiodooctane (DIO) (Liang et al., 2014; Chueh et al., 2015; Yang ZB et al., 2015), can enhance the solubility of the perovskite precursor solution (Jang et al., 2022), extending the crystallization time. The prolonged crystallization time allows better control of the blade-coating process, avoiding issues caused by rapid crystallization, such as uneven crystallization, incomplete growth, and solvent residues. The increased solubility provides more time for the precursor molecules to arrange in an ordered manner, which helps achieve a smoother surface and improved crystal quality. In this way, additives can effectively regulate the solvent evaporation rate and solute migration, offering possibilities for optimizing the film's crystal morphology.

Nucleation regulators, especially organic ammonium halide additives (Chu et al., 2021), can effectively suppress excessive grain growth by increasing the density of nucleation centers in the precursor solution. After adding an appropriate amount of organic ammonium halides, the grains of the perovskite thin film typically change from rod-like to spherical, indicating that the grain growth has been effectively controlled, thus avoiding unevenness between grains (Fig. 2e) (Chu et al., 2021). These additives also shorten the film formation time, preventing excessive grain growth during film formation, further improving the uniformity and density of the film. This regulation of the nucleation process enhances not only the appearance of the film but also its optoelectronic performance.

The interface quality of the film plays a crucial role in its optoelectronic performance, especially at the buried interface of the perovskite layer (Chen et al., 2021a, 2021b; Ni et al., 2022; Zheng et al., 2022). To reduce issues such as non-radiative recombination at the interface, researchers have proposed using additives with strong coordination abilities. These additives accumulate at the interface during the film crystallization process, effectively suppressing harmful interfacial reactions. By adjusting the deprotonation of organic cations in the precursor solution, especially using additives with a pK_a value close to neutral, unordered crystallization can be avoided, thereby optimizing the interface quality of the film (Gao et al., 2024).

Surfactants (Deng et al., 2018; Liu et al., 2020) are another important class of additives. They improve the adhesion between the film and the underlying charge transport layer by altering the film's drying kinetics, thus enhancing the uniformity and smoothness of the film. The presence of surfactants can guide the solution flow in a more controlled manner, helping to prevent the formation of islands and promoting a more homogeneous film structure during the drying process (Fig. 2f). L-α-phosphatidylcholine (LP) is commonly used as a surfactant (Deng et al., 2018). It can effectively passivate charge traps and reduce the formation of island structures, making the film surface smoother and more uniform.

In addition to morphological and performance regulation, stability is also a key consideration in the preparation of perovskite thin films. By introducing stability-enhancing agents such as formamide and MACl (Jang et al., 2022), issues like voids and wrinkles in the film can be addressed. Formamide can slow the solvent evaporation rate, maintaining the uniformity of the solution and avoiding defects and non-uniformity caused by rapid crystallization of the film. However, due to formamide's high boiling point and its miscibility with DMSO, excessive use may lead to the formation of voids, so its amount must be precisely controlled. To further reduce voids, MACl as an additive can volatilize during annealing, promoting perovskite recrystallization and grain coarsening, ultimately resulting in a dense, void-free film (Williams et al., 2014; Zhao and Zhu, 2014; Zhou et al., 2015; Kim et al., 2019; Odysseas Kosmatos et al., 2019).

Furthermore, ammonium salt additives (Lu et al., 2017; Wang ZP et al., 2017; Zhang et al., 2017; Wu et al., 2019) not only improve grain growth and increase film density but also enhance the bending resistance and long-term stability of the film through hydrogen bonding interactions between the perovskite particles. Particularly in practical applications, bis-alkylamine (BAA) additives (Wu et al., 2019) can significantly enhance the durability of the film, providing greater assurance for the commercialization of perovskite thin films.

In the context of large-area perovskite module fabrication, additives also play a crucial role in ensuring uniform crystallization across large substrates. By tuning the crystallization rate and enhancing film uniformity, additives enable the production of high-quality, defect-free films that meet the stringent requirements for industrial-scale perovskite device manufacturing.

3 Coating process

3.1 Blade technology

The blade speed directly determines the crystallization behavior of perovskite and the final film structure by affecting the coating characteristics of the solution (Noblesse et al., 2006, 2008; Tsai et al., 2015). Figs. 3a and 3b show that two distinct deposition regimes are identified as a function of blade speed. At lower blade speeds (typically below 4 mm/s),

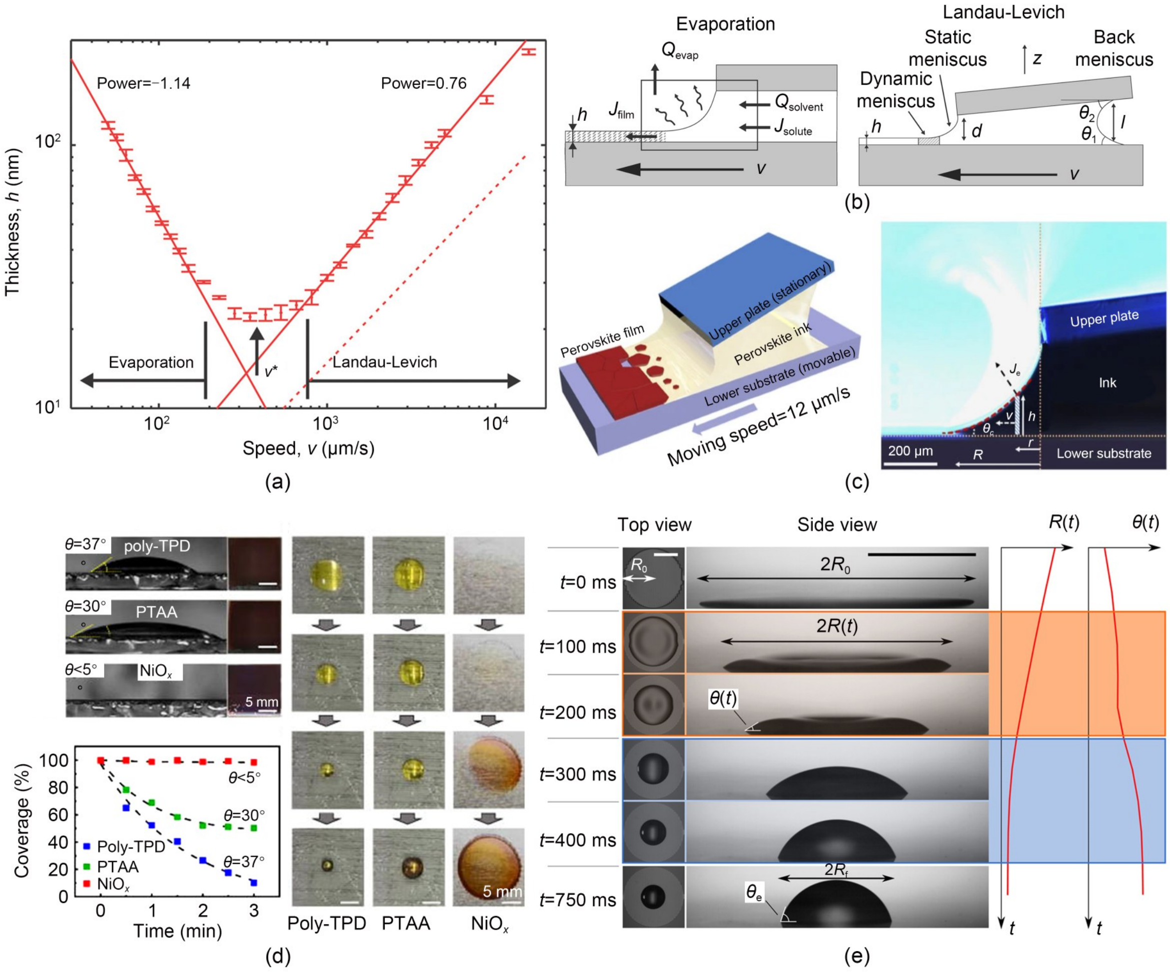

Fig. 3 (a) Measured film thickness *h* as a function of deposition speed *v*. Two regimes are identified as a function of *v*: the evaporation and Landau−Levich modes (reprinted from (le Berre et al., 2009), Copyright 2009, with permission from American Chemical Society); (b) Schematic of the two deposition regimes (reprinted from (le Berre et al., 2009), Copyright 2009, with permission from American Chemical Society). Q_{evap} is the flow rate of solvent leaving the box by evaporation, Q_{solvent} is the flow rate of solvent molecules entering the box, J_{film} is the outward mass flux of molecules in the film, J_{solute} is the inward flux of molecules in solution, *d* is the meniscus height, and θ_1, θ_2, and *l* are the geometric parameters defined in figure; (c) Schematic illustration of the meniscus-assisted solution printing (MASP) of large-grained perovskite films and optical micrograph of the side-view meniscus ink (reprinted from (He et al., 2017), Copyright 2017, with permission from Springer Nature). J_e is the evaporative flux of solvent, *r* is the horizontal distance of the meniscus surface away from the bulk ink, *h* is the height of the meniscus at *r*, *θ* is the contact angle, *v* is the velocity of outward convective flow, and *R* is the radius of curvature; (d) Contact angle of precursor solution on PFN-Br (poly[9,9-bis(3′-(N,N-dimethyl)-N-ethylammoinium-propyl-2,7-fluorene)-alt-2,7-(9,9-dioctylfluorene)]dibromide) treated poly-TPD (poly[N,N′-bis(4-butylphenyl)-N,N′-bisphenylbenzidine]), PTAA (poly[bis(4-phenyl) (2,4,6-trimethylphenyl) amine]), and NiO_x HTLs, and corresponding photographs of perovskite films. Evolution of precursor solution droplets on the three HTLs, and the corresponding coverage of droplets against time (reprinted from (Deng et al., 2022), Copyright 2022, with permission from American Institute of Physics); (e) Experimental imaging of the dewetting of a liquid droplet from a smooth solid surface (reprinted from (Edwards et al., 2016), Copyright 2016, with permission from AAAS); *R* is the radius of film. References to color refer to the version of this figure

the perovskite thin film enters the evaporation mode (le Berre et al., 2009; He et al., 2017; Deng et al., 2018). In this mode, the solution rapidly evaporates after coating, and the deposition process of the perovskite precursor is controlled mainly by solvent evaporation. This method effectively prevents excessive wetting of the film surface and solution flow. The lower supersaturation of the solution slows down the nucleation process and promotes grain growth (Lee et al., 2020), resulting in a higher quality perovskite thin film. However, due to the slower coating speed, this mode has low production efficiency and is not suitable for large-scale production (He et al., 2017).

As the blade speed increases (above 20 mm/s), the coating process enters the Landau-Levich mode (le Berre et al., 2009; Deng et al., 2018). In this mode, after the blade is lifted, the wet layer remains moist, and the solution does not dry quickly, leading to uneven crystallization and large "island" structures on the film surface. This structure not only affects the uniformity of the film but can also form pinholes and defects on the surface, reducing the overall performance of the film. Therefore, while increasing the blade speed can accelerate the coating process, it is crucial to strictly control the drying rate after coating to avoid excessive solution flow and a decline in film quality. During this process, optimizing the blade speed requires finding an appropriate balance between fast coating and film crystallization quality.

In blade-coating, if the solution does not dry immediately, it will flow in different modes driven by surface tension or evaporation, leading to unevenness and discontinuity in the film (Deng et al., 2019). As mentioned earlier (Deng et al., 2018), this solution flow can lead to defects on the film surface and uneven crystallization. To address this issue, one method is to significantly reduce the blade speed, allowing the solution to dry immediately after the blade is lifted. Although this method effectively prevents solution flow and film defects, it limits the coating speed of the blade, which impacts production efficiency (Deng et al., 2019). Alternatively, meniscus-assisted solution printing (MASP) (Fig. 3c) provides a solution to this challenge (He et al., 2017). This technique involves loading metal halide perovskite ink between two nearly parallel plates, with a fixed gap of 300 μm. The capillary forces at the meniscus edge assist in forming large perovskite grains.

Another possible solution is to lower the solution viscosity, as described in Section 2.2, to form a thinner coating film. By adjusting the coating speed and solution concentration, the film thickness can be increased (Deng et al., 2019). This approach makes the coating process more flexible and allows the optimal balance between crystallinity and film thickness to be found according to the needs of the film. Therefore, while focusing on the effects of blade speed and pressure on film crystallization, it is also important to explore the synergistic effects of the process. Optimizing the physical and chemical properties of the solution (such as viscosity and volatility) can help adjust the blade speed and pressure, ultimately achieving the best film quality.

3.2 Substrate wettability

The wettability of the substrate surface directly influences the spreading behavior of the liquid film, the diffusion of the solution, and the nucleation behavior of the thin film, thereby determining the uniformity and optoelectronic performance of the film. The tendency of the liquid film to dewet is closely related to the contact angle of the substrate (Deng et al., 2022). The evolution of the precursor solution droplets on these three hole transport layers (HTLs) shows how the contact angle influences the spreading behavior of the solution over time (Fig. 3d). This dynamic process further highlights how the interaction between the precursor solution and substrate determines the film's uniformity and coverage as the droplet spreads, affecting the final perovskite film morphology. The contact angle of the substrate determines how the liquid film spreads, which in turn affects the crystallization quality of the film. If the substrate has poor wettability (i.e., a high contact angle), the liquid film may dewet quickly (Vachaparambil and Einarsrud, 2018; Deng et al., 2022), leading to uneven films and impacting the uniformity of crystallization and the orientation of the grains. Changes in the contact angle significantly affect the rate at which the liquid film dewets. According to (Edwards et al., 2016), the rate of dewetting of the liquid film is sensitive to the equilibrium contact angle (Fig. 3e). In particular, under surface tension, substrates with poor wettability make it easier for the solution to dewet, causing unevenness during the crystallization process. Therefore, by adjusting the wettability of the substrate, the behavior of the liquid film during the coating process can be optimized, improving the uniformity and crystallization quality of the film.

During the coating process, the diffusion of the solution is closely related to the wettability of the substrate. For example, in large-area perovskite film preparation, especially on transparent conductive oxide (TCO) substrates, the solution often first fills the nanoscale valleys on the TCO surface, leading to multilayer stacking and affecting the uniformity of the coating (Phung et al., 2022; Ren et al., 2023). Wang et al. (2024) improved the wettability of the substrate using poly-DBPP and DBPP, enhancing the diffusion of the solution and improving the distribution of perovskite ink, which ultimately improved the uniformity and optoelectronic performance of the film. The strong bonding between poly-DBPP and the ITO substrate significantly reduced the contact angle, further enhancing the interaction between the substrate and the solution, thereby improving the crystallinity of the film. Note that substrate wettability can lead to the coffee-ring effect (Yu et al., 2019), which can impact the uniformity of the film and device performance. The coffee-ring effect is caused by capillary flow during the evaporation of a droplet, which typically leads to the accumulation of solutes at the edges of the film, forming a ring-shaped deposit. By improving the wettability of the substrate (Liu H et al., 2024), particularly using substrates with stronger hydrophilicity, this effect can be reduced, allowing solutes to be more evenly deposited on the substrate, thereby improving the uniformity of the film. The coffee-ring effect can also be suppressed by altering the solvent system and lowering the solution viscosity (Hu and Larson, 2005; Abo Jabal et al., 2017; Malinowski et al., 2018; Yu et al., 2019; Hu et al., 2020; Wilkinson et al., 2021; Yang XY et al., 2022).

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To further optimize the quality of perovskite thin films, researchers have recently proposed several methods to improve wettability through substrate surface treatments. Introducing self-assembled monolayers (SAMs) or other interface modification layers on the substrate can significantly adjust the substrate's wettability, thereby controlling the spreading and crystallization behavior of the liquid film. These surface modification techniques, by adjusting the surface energy of the substrate, can promote the oriented growth of perovskite crystals, reduce defects, and enhance the crystallization quality and device performance of the film.

3.3 Gas-quenching

The main challenge of the blade-coating method lies in the slow solvent evaporation rate, which prevents the solution from quickly reaching supersaturation and initiating crystallization (Yu et al., 2021). Auxiliary crystallization methods, such as anti-solvent quenching (Deng et al., 2015a; Zeng et al., 2020), vacuum flash evaporation (Li et al., 2016; Zeng et al., 2020), and gas-quenching, can rapidly remove solvents to reach supersaturation, thus promoting nucleation and crystal growth. Among these, gas-quenching, as a widely applied crystallization assistance method, has shown significant potential for industrial-scale production (Wu et al., 2018; Cheng et al., 2019; Sun et al., 2019; Zhang et al., 2019; Szostak et al., 2021). Gas-quenching induces nucleation and crystal growth by extracting solvents from the wet precursor film through strong convection. This method offers notable advantages, especially as it does not require complex equipment or toxic chemicals, showcasing good stability and reproducibility. After gas-quenching treatment, the blade-coated films exhibit a more uniform surface, larger grain size, and significantly reduced defect density, thereby greatly improving the film quality and optoelectronic performance (Razza et al., 2015; Ke et al., 2016; Song S et al., 2017; Deng et al., 2019; Ding et al., 2019).

The key to controlling gas-quenching crystallization lies in the distance between the air knife and the liquid film. If the air knife is too close to the liquid film, the solvent evaporation rate on the liquid film surface will be too fast, leading to an uneven perovskite film.

On the other hand, if the air knife is too far from the liquid film, solvent diffusion will be slow, causing the solution to reach supersaturation at a slower rate, and the liquid film may fail to dry completely (Yu et al., 2021). Therefore, optimizing the gas-quenching process depends on precisely controlling the airflow velocity and the distance between the air knife and the liquid film to achieve supersaturation in a short time, promoting high-quality nucleation and crystal growth. Gao et al. (2017a) used a multi-stream air knife (MAK) to compensate for the limitations of a single air knife. By optimizing the airflow velocity and temperature, they were able to obtain more uniform and dense perovskite films (Gao et al., 2017b). This improvement not only enhanced the quality of the films but also provided a more stable and efficient crystallization control method for industrial-scale production.

However, further research is needed to enhance the adaptability of the gas-quenching method to different solution formulations and substrate surfaces, as well as to optimize the film formation process by precisely controlling airflow parameters. For example, during the gas-quenching process, local over-drying or cooling may occur, affecting the overall film quality. To address this issue, future studies should focus on optimizing airflow distribution, temperature control, and airflow direction. Additionally, combining gas-quenching with other film formation methods (such as anti-solvent quenching or vacuum flash evaporation) may offer more effective strategies for improving the crystallization quality of perovskite films and their device performance.

4 Surface passivation

Passivation techniques play a crucial role in improving the crystallization quality of perovskite films, reducing surface defect densities, and enhancing their overall stability. The effects of passivation are not limited to increasing grain size but extend to optimizing the film structure by reducing surface defects, improving crystal order, and minimizing non-radiative recombination losses (Stolterfoht et al., 2019; Wang et al., 2019; Caprioglio et al., 2023). In the blade-coating method, surface passivation of perovskite films does not necessarily require the development of a specific passivation technique for the fabrication process.

One of the main approaches to tuning energy levels in perovskites is the incorporation of lithium fluoride (LiF) or magnesium fluoride (MgF_x) into both the perovskite and the electron transport layers (ETLs), which helps reduce non-radiative recombination (Stolterfoht et al., 2018; Peña-Camargo et al., 2020; Liu et al., 2022). This approach effectively aligns the energy levels between the perovskite and the ETL, facilitating better charge extraction and reducing recombination losses (Fig. 4a). Interfacial capping layers, such as ammonium ligands or functional reactive compounds, are commonly used to passivate surface defects of perovskite films (Li FZ et al., 2020; Li Z et al., 2022; Zhang et al., 2022; Chen et al., 2023; Zhou et al., 2023; Huang ZX et al., 2024; Liu J et al., 2024). These capping layers serve to protect the surface, effectively mitigating defect-related issues that could negatively impact device performance.

For enhancing the humidity stability of perovskite films, passivating agents like the MABr/MACl dual-passivation system (Kim et al., 2023) have shown significant effects. This dual-passivation system notably suppresses interfacial defects, especially in environments with fluctuating humidity levels, and effectively reduces the negative impact of humidity on the film. It also plays a role in improving the interface stability, which is essential for enhancing the overall longevity and performance of perovskite-based devices.

Introducing two-dimensional (2D) perovskite layers onto the surface of the film, especially to passivate the surface defects of three-dimensional (3D) perovskite layers, can further enhance both the stability and optoelectronic performance of the film (Tian et al., 2022; Teale et al., 2024). The formation of 2D perovskite layers can either directly or indirectly cover the surface of the 3D perovskite. Through passivation, this process reduces the surface defect density, thereby improving the film's stability and photonic response. Two common methods for 2D perovskite layer passivation include direct and indirect approaches (Teale et al., 2024). The direct method typically involves physically stacking or using solvent-selective dissolution techniques to transfer the 2D perovskite layer onto the surface of the 3D perovskite. The indirect method, on the other hand, involves applying passivating ligands to the surface of the perovskite, followed by an annealing process that gradually forms the 2D perovskite layer (Quan et al., 2016). This method allows for the

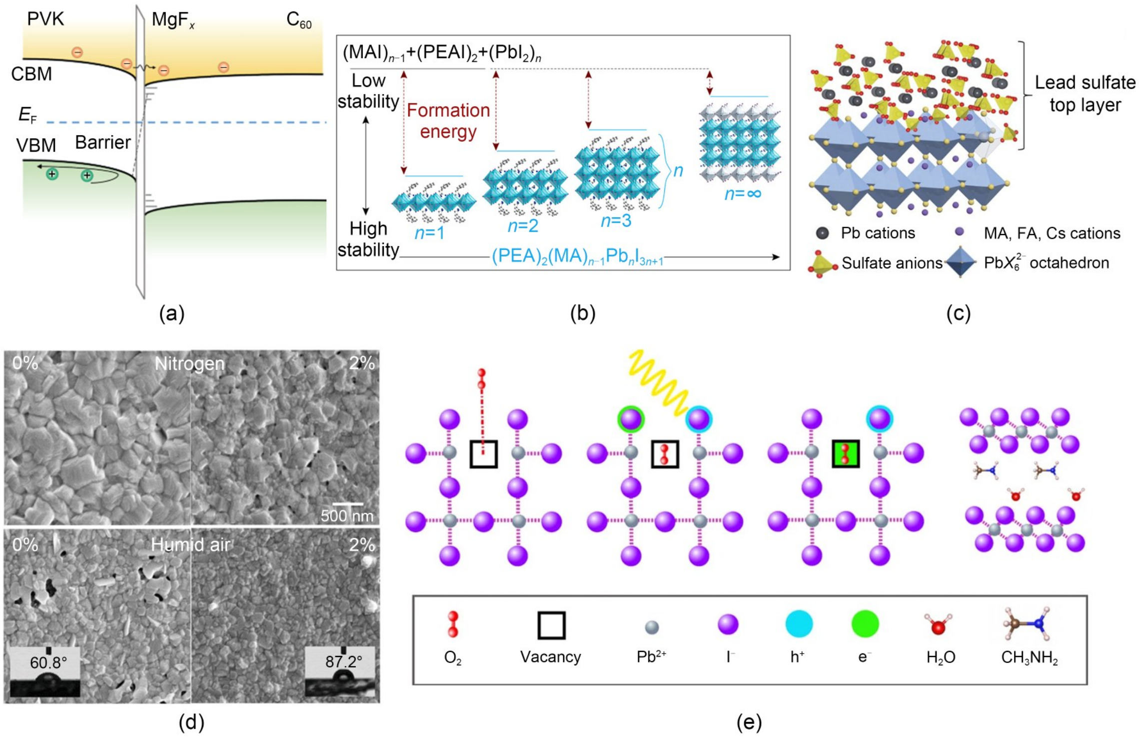

Fig. 4 (a) Energy level diagram of the perovskite/C_{60} interface with an MgF_x insertion layer (reprinted from (Liu et al., 2022), Copyright 2022, with permission from AAAS). PVK: perovskite; CBM: conduction band minimum; E_F: Fermi level; VBM: valence band maximum; (b) Unit cell structure of perovskites with different *n* values (reprinted from (Quan et al., 2016), Copyright 2016, with permission from American Chemical Society). PEA: phenethylammonium; (c) Schematic illustration of the protection of perovskites through in situ formation of a lead sulfate top layer on the perovskite surface (reprinted from (Yang et al., 2019), Copyright 2019, with permission from Springer Nature); (d) SEM images of perovskite films with 0% and 2% [bvbim]Cl (1,3-bis(4-vinylbenzyl)imidazolium chloride, a polymerizable ionic liquid) molar content prepared in nitrogen or humid air conditions, and contact angle measurement observed for films prepared in humid air (reprinted from (Xia et al., 2020), Copyright 2020, with permission from Wiley); (e) Schematic representation of the reaction steps of O_2 with $CH_3NH_3PbI_3$ (reprinted from (Aristidou et al., 2017), Copyright 2017, with permission from Springer Nature)

continuous adjustment and formation of a more ordered 2D perovskite layer at the surface of the perovskite's dimensionality by varying the *n* value (Fig. 4b). This effectively reduces surface defects and improves film quality thereby enhancing the stability and optoelectronic properties of the material.

The passivation of perovskite films using inorganic materials such as phosphate and sulfate ions has also been shown to be crucial in improving film quality (Yang et al., 2019). The in-situ formation of a lead sulfate ($PbSO_4$) top layer on the perovskite surface plays a key role in protecting the material (Fig. 4c). This inorganic passivation layer stabilizes the surface of the perovskite by reacting with it, reducing defect densities, and significantly enhancing the film's resistance to moisture and chemical degradation in humid environments. As a result, these inorganic passivation layers contribute to the long-term stability of the films, making them more suitable for practical applications.

In conclusion, passivation remains one of the most effective strategies for enhancing the performance and durability of perovskite films. By carefully selecting and applying passivating agents, the structural and functional properties of the films can be optimized, leading to higher-quality, more stable perovskite-based devices that are better suited for large-scale, commercial applications.

5 Atmosphere

The blade-coating method for perovskite film preparation in industrial-scale production is typically carried out in ambient conditions, as solution processing within a glovebox is not feasible for commercial applications (Ko et al., 2015; Yang ZB et al., 2015; Lee et al., 2017; Song ZN et al., 2017; Fu et al., 2022). However, environmental factors such as humidity, temperature, and oxygen levels can significantly influence both the crystallization quality of the perovskite films and the performance of the resulting devices. Therefore, extra attention must be given to the impact of these environmental conditions on the crystallization process during blade-coating.

Perovskite materials, especially organic halides like methylammonium iodide (MAI) and formamidinium iodide (FAI), are highly hygroscopic (Bass et al., 2014; Christians et al., 2015; Leguy et al., 2015; Yang JL et al., 2015; Zhang et al., 2015; Wang et al., 2016; Niu et al., 2017; Xu et al., 2018). In the blade-coating process, variations in humidity directly affect the stability of the perovskite precursor solution. When humidity is high, moisture can promote hydrolytic reactions of the perovskite, leading to the degradation of organic halides and the formation of PbI_2 (Niu et al., 2014, 2015; Yang ZB et al., 2015; Huang et al., 2017; Xia et al., 2020). Fig. 4d shows the impact of humidity on the film morphology. Films exposed to humid air show increased defects and uneven grain structures, which negatively affect the crystallization quality. In particular, during the crystallization process, the presence of water can cause volume defects in the perovskite crystals (Jang et al., 2022), which compromises the film's crystallization quality. The impact of water causes instability in the crystallization speed, leading to smaller grain sizes and an increase in defect density within the perovskite films.

Humidity is closely linked to the evaporation rate of the solvent during the blade-coating process. In a high-humidity environment, the slower evaporation of the solvent results in uneven crystallization on the surface of the perovskite film. This unevenness can create defects such as pinholes and bubbles in the film, which further degrade its optoelectronic performance. In contrast, in low humidity conditions, blade-coated perovskite films generally exhibit better uniformity and low surface defect densities, leading to improved crystallization quality and device efficiency (Yang ZB et al., 2015).

Temperature is another critical factor influencing perovskite film crystallization during the blade-coating process. Elevated temperatures generally aid in the evaporation of the solvent, thereby accelerating the crystallization process of the film. However, if the temperature is too high, it can lead to rapid solvent evaporation, causing the solid-liquid interface to form prematurely at the solution's surface, which results in uneven vertical growth of the film. Additionally, this can leave solvent residues behind, negatively affecting the crystallization quality of the film. Therefore, precise temperature control is essential to ensure uniform grain growth, particularly during the blade-coating process, where managing temperature is vital to reduce crystallization defects.

Light exposure and the presence of oxygen also affect the crystallization of perovskite films during blade-coating. Perovskite materials are highly sensitive to light and oxygen, especially methylammonium-based perovskites ($MAPbI_3$), which are prone to degradation under the combined effects of light and oxygen (Aristidou et al., 2015; O'Mahony et al., 2015; Bryant et al., 2016). When films are exposed to strong light or oxygen during the blade-coating process, the perovskite material may undergo photooxidative degradation, forming peroxides, which can further deteriorate the quality of the material (Bryant et al., 2016). Particularly during the crystallization of the precursor solution, oxygen and light can facilitate the deprotonation of the organic cations in the perovskite, leading to the formation of PbI_2 and consequently compromising the integrity and stability of the perovskite crystals (Fig. 4e).

To mitigate the negative impact of these environmental factors on the crystallization process, many researchers are exploring controlled environment blade-coating methods. For instance, performing blade-coating in a dry atmosphere can effectively prevent degradation due to moisture. Additionally, using UV-blocking materials to shield the perovskite film from direct light exposure can significantly improve the crystallization quality and stability of the films. These measures help create a more stable environment for the perovskite crystallization process, ensuring better film quality and enhanced device performance in industrial applications.

In conclusion, understanding and controlling environmental factors during the blade-coating process are essential for improving the crystallization quality and stability of perovskite films. By mitigating the effects of humidity, temperature, and light exposure, it is possible to achieve high-quality films with better long-term performance and reliability, paving the way for large-scale industrial production of perovskite-based devices.

6 Conclusions and perspective

Blade-coating, holds significant potential as a promising large-scale and low-cost technique for fabricating perovskite films but faces several key challenges, particularly in controlling the crystallization process and ensuring uniform film quality. As discussed in this review, various factors that influence perovskite film crystallization—such as the precursor solution, coating process, substrate conditions, and environmental factors—need to be optimized to minimize defect density and achieve uniform and consistent film morphology on large-area substrates.

During blade-coating, the crystallization of perovskite films is affected by multiple parameters, with uneven evaporation rate being one of the main issues. Differences in evaporation rates across different areas can lead to non-uniform film thickness and may result in island-like perovskite growth (Deng et al., 2015a; Han et al., 2025). If not properly controlled, these islands can cause pinholes that allow direct contact between the ETL and HTL, which in turn generates leakage currents and degrades device performance (Ye et al., 2016; Hu et al., 2017; Deng et al., 2018; Rong et al., 2018). The crystallization dynamics vary significantly between perovskites with different compositions, such as $MAPbI_3$ and FACs perovskites. $MAPbI_3$-based films are relatively more mature for large-area coating, but $MAPbI_3$ is more sensitive to environmental factors. In contrast, FACs perovskites, where the iodide (I^-) is partially replaced by bromide (Br^-), have a higher diffusion rate of Br^- in solvents than that of I^- (Park, 2016), which leads to different crystallization rates and phase segregation, affecting the stability and long-term performance of the films.

As the size of perovskite solar cell modules increases, efficiency losses are influenced by multiple factors, including the increase in series resistance, decrease in shunt resistance, large-area coating non-uniformities, and dead zones (non-active areas) in busbars and interconnection electrodes (Li et al., 2018). During large-area coating, variations in precursor solution concentration, differences in solvent evaporation rates, and temperature gradients further exacerbate non-uniformities in the crystallization process, making it increasingly difficult to prepare high-quality films.

The main factors influencing perovskite film crystallization include solvent properties, solution concentration, viscosity, and the use of additives. Solvents, through their polarity and volatility, regulate the crystallization dynamics, affecting nucleation and grain growth. Solution concentration and viscosity impact film thickness, uniformity, and grain morphology. High-concentration solutions promote thicker films but may result in slower evaporation and more defects, while low-concentration solutions offer better control over crystallization but can lead to insufficient film formation. Additives are also critical in modulating the crystallization process, controlling nucleation rates, improving film morphology, and enhancing stability by regulating solubility, interface quality, and grain size. A balanced combination of these factors is essential to achieve optimal perovskite film quality and long-term performance.

Despite these challenges, significant progress has been made in recent years in enhancing the scalability and uniformity of perovskite films. By optimizing precursor solution formulations, including the use of additives and solvent combinations, researchers have been able to exert more control over the crystallization process, improving film morphology, reducing defect density, and enhancing the stability of perovskite films. However, the selection and concentration of ideal additives remain heated topics in current research, as the effects of additives can vary depending on the solvent system and perovskite composition.

The key to improving blade-coating technology lies in a deeper understanding of the crystallization mechanism of perovskite films. Future research should focus on revealing the kinetics of perovskite film formation, particularly how solvent evaporation and precursor concentration gradients affect the crystallization process. In addition, developing advanced in-situ monitoring techniques to track the crystallization process in real-time will be critical for optimizing blade-coating processes and achieving more reproducible results. Research into novel perovskite compositions, such as mixed-cation or mixed-halide systems, may also help develop films with superior crystallization characteristics and stability, which is crucial for advancing the commercialization of perovskite solar cells.

Moreover, transitioning to more stable and efficient perovskite compositions still requires further optimization of the blade-coating process to develop universal coating methods that can adapt to their different crystallization dynamics and solvent requirements. Precisely controlling the crystallization and growth of these perovskite films on large-area substrates will be a key step toward achieving commercial viability.

In addition to improving film quality, developing reliable post-treatment techniques such as annealing and drying strategies and passivation can effectively reduce solvent residues, minimize defects, and ensure the long-term stability of perovskite solar cells. As blade-coating technology continues to evolve, integrating these advancements with large-scale, automated production lines to achieve competitive manufacturing of high-quality perovskite films will be a crucial area for future research.

In conclusion, the blade-coating method holds immense potential for the fabrication of perovskite films, especially in large-scale production. However, to successfully realize this potential, several key challenges, including film uniformity, defect control, and scalability, must be addressed. With continued advancements in solution chemistry, process optimization, and a deeper understanding of crystallization mechanisms, the efficiency and stability of blade-coated perovskite photovoltaics will significantly improve, paving the way for the large-scale application of perovskite solar cells and other perovskite-based optoelectronic devices.

Acknowledgments

This work is supported by the Natural Science Foundation of Zhejiang Province of China (Nos. LR24F040001, LDG25E020001, and LD24E020001), the National Natural Science Foundation of China (No. 62274146), and the Fundamental Research Funds for the Central Universities (No. 226-2022-00200), China.

Author contributions

Jingyi SUN and Borui LEI wrote the first draft of the manuscript. Jingjing XUE, Jingyi SUN, and Borui LEI revised and edited the final version. All authors approved the final manuscript. Jingyi SUN and Borui LEI contributed equally to this work.

Conflict of interest

Jingyi SUN, Borui LEI, and Jingjing XUE declare that they have no conflict of interest.

References

Abate SY, Qi YF, Zhang QQ, et al., 2024. Eco-friendly solvent engineered $CsPbI_{2.77}Br_{0.23}$ ink for large-area and scalable high performance perovskite solar cells. *Advanced Materials*, 36(11):2310279. https://doi.org/10.1002/adma.202310279

Abo Jabal M, Homede E, Pismen LM, et al., 2017. Controlling Marangoni flow directionality: patterning nano-materials using sessile and sliding volatile droplets. *The European Physical Journal Special Topics*, 226(6):1307-1324. https://doi.org/10.1140/epjst/e2016-60404-x

Aristidou N, Sanchez-Molina I, Chotchuangchutchaval T, et al., 2015. The role of oxygen in the degradation of methylammonium lead trihalide perovskite photoactive layers. *Angewandte Chemie International Edition*, 54(28):8208-8212. https://doi.org/10.1002/anie.201503153

Aristidou N, Eames C, Sanchez-Molina I, et al., 2017. Fast oxygen diffusion and iodide defects mediate oxygen-induced degradation of perovskite solar cells. *Nature Communications*, 8:15218. https://doi.org/10.1038/ncomms15218

Bass KK, McAnally RE, Zhou SL, et al., 2014. Influence of moisture on the preparation, crystal structure, and photophysical properties of organohalide perovskites. *Chemical Communications*, 50(99):15819-15822. https://doi.org/10.1039/C4CC05231E

Belay Adugna G, Yimer Abate S, Tao YT, 2022. High-efficiency and scalable Solution-sheared perovskite solar cells using green solvents. *Chemical Engineering Journal*, 437:135477. https://doi.org/10.1016/j.cej.2022.135477

Bryant D, Aristidou N, Pont S, et al., 2016. Light and oxygen induced degradation limits the operational stability of methylammonium lead triiodide perovskite solar cells. *Energy & Environmental Science*, 9(5):1655-1660. https://doi.org/10.1039/C6EE00409A

Caprioglio P, Smith JA, Oliver RDJ, et al., 2023. Open-circuit and short-circuit loss management in wide-gap perovskite p-i-n solar cells. *Nature Communications*, 14(1):932. https://doi.org/10.1038/s41467-023-36141-8

Chen B, Yu ZJ, Manzoor S, et al., 2020. Blade-coated perovskites on textured silicon for 26%-efficient monolithic perovskite/silicon tandem solar cells. *Joule*, 4(4): 850-864. https://doi.org/10.1016/j.joule.2020.01.008

Chen CS, Chen JX, Han HC, et al., 2022. Perovskite solar cells based on screen-printed thin films. *Nature*, 612(7939): 266-271. https://doi.org/10.1038/s41586-022-05346-0

Chen H, Ye F, Tang WT, et al., 2017. A solvent- and vacuum-free route to large-area perovskite films for efficient solar modules. *Nature*, 550(7674):92-95. https://doi.org/10.1038/nature23877

Chen H, Maxwell A, Li CW, et al., 2023. Regulating surface potential maximizes voltage in all-perovskite tandems. *Nature*, 613(7945):676-681. https://doi.org/10.1038/s41586-022-05541-z

Chen SS, Xiao X, Chen B, et al., 2021a. Crystallization in

one-step solution deposition of perovskite films: upward or downward? *Science Advances*, 7(4):eabb2412.
https://doi.org/10.1126/sciadv.abb2412

Chen SS, Dai XZ, Xu S, et al., 2021b. Stabilizing perovskite-substrate interfaces for high-performance perovskite modules. *Science*, 373(6557):902-907.
https://doi.org/10.1126/science.abi6323

Cheng R, Chung CC, Zhang H, et al., 2019. An air knife–assisted recrystallization method for ambient-process planar perovskite solar cells and its dim-light harvesting. *Small*, 15(8): 1804465.
https://doi.org/10.1002/smll.201804465

Cho TS, Kwon YD, Kwon SB, 2009. A study of the influence of air-knife tilting on coating thickness in hot-dip galvanizing. *Journal of Thermal Science*, 18(3):262-267.
https://doi.org/10.1007/s11630-009-0262-7

Christians JA, Miranda Herrera PA, Kamat PV, 2015. Transformation of the excited state and photovoltaic efficiency of $CH_3NH_3PbI_3$ perovskite upon controlled exposure to humidified air. *Journal of the American Chemical Society*, 137(4):1530-1538.
https://doi.org/10.1021/ja511132a

Chu SL, Chen WJ, Fang ZB, et al., 2021. Large-area and efficient perovskite light-emitting diodes via low-temperature blade-coating. *Nature Communications*, 12(1):147.
https://doi.org/10.1038/s41467-020-20433-4

Chueh CC, Liao CY, Zuo F, et al., 2015. The roles of alkyl halide additives in enhancing perovskite solar cell performance. *Journal of Materials Chemistry A*, 3(17):9058-9062.
https://doi.org/10.1039/C4TA05012F

Deng W, Wan F, Peng XX, et al., 2022. Super hydrophilic, ultra bubble repellent substrate for pinhole free Dion–Jacobson perovskite solar cells. *Applied Physics Letters*, 121(23): 233902.
https://doi.org/10.1063/5.0127262

Deng YH, Peng E, Shao YC, et al., 2015a. Scalable fabrication of efficient organolead trihalide perovskite solar cells with doctor-bladed active layers. *Energy & Environmental Science*, 8(5):1544-1550.
https://doi.org/10.1039/C4EE03907F

Deng YH, Wang Q, Yuan YB, et al., 2015b. Vividly colorful hybrid perovskite solar cells by doctor-blade coating with perovskite photonic nanostructures. *Materials Horizons*, 2(6):578-583.
https://doi.org/10.1039/C5MH00126A

Deng YH, Zheng XP, Bai Y, et al., 2018. Surfactant-controlled ink drying enables high-speed deposition of perovskite films for efficient photovoltaic modules. *Nature Energy*, 3(7):560-566.
https://doi.org/10.1038/s41560-018-0153-9

Deng YH, van Brackle CH, Dai XZ, et al., 2019. Tailoring solvent coordination for high-speed, room-temperature blading of perovskite photovoltaic films. *Science Advances*, 5(12):eaax7537.
https://doi.org/10.1126/sciadv.aax7537

Ding J, Han QW, Ge QQ, et al., 2019. Fully air-bladed high-efficiency perovskite photovoltaics. *Joule*, 3(2):402-416.
https://doi.org/10.1016/j.joule.2018.10.025

Dong Q, Fang Y, Shao Y, et al., 2015. Electron-hole diffusion lengths >175 μm in solution-grown $CH_3NH_3PbI_3$ single crystals. *Science*, 347(6225):967-970.
https://doi.org/10.1126/science.aaa5760

Duan CY, Gao H, Xiao K, et al., 2025. Scalable fabrication of wide-bandgap perovskites using green solvents for tandem solar cells. *Nature Energy*, 10(3):318-328.
https://doi.org/10.1038/s41560-024-01672-x

Edwards AMJ, Ledesma-Aguilar R, Newton MI, et al., 2016. Not spreading in reverse: the dewetting of a liquid film into a single drop. *Science Advances*, 2(9):e1600183.
https://doi.org/10.1126/sciadv.1600183

Feng YM, Mallo N, Lindsay O, et al., 2025. Enhanced efficiency and stability in blade-coated perovskite solar cells through using 2,3,4,5,6-pentafluorophenylethylammonium halide additives. *ACS Applied Materials & Interfaces*, 17(5): 7670-7678.
https://doi.org/10.1021/acsami.4c18413

Fu F, Li J, Yang TCJ, et al., 2022. Monolithic perovskite-silicon tandem solar cells: from the lab to fab? *Advanced Materials*, 34(24):2106540.
https://doi.org/10.1002/adma.202106540

Gao H, Xiao K, Lin RX, et al., 2024. Homogeneous crystallization and buried interface passivation for perovskite tandem solar modules. *Science*, 383(6685):855-859.
https://doi.org/10.1126/science.adj6088

Gao LL, Li CX, Li CJ, et al., 2017a. Large-area high-efficiency perovskite solar cells based on perovskite films dried by the multi-flow air knife method in air. *Journal of Materials Chemistry A*, 5(4):1548-1557.
https://doi.org/10.1039/C6TA09565H

Gao LL, Zhang KJ, Chen N, et al., 2017b. Boundary layer tuning induced fast and high performance perovskite film precipitation by facile one-step solution engineering. *Journal of Materials Chemistry A*, 5(34):18120-18127.
https://doi.org/10.1039/C7TA05012G

Ge QQ, Ding J, Liu J, et al., 2016. Promoting crystalline grain growth and healing pinholes by water vapor modulated post-annealing for enhancing the efficiency of planar perovskite solar cells. *Journal of Materials Chemistry A*, 4(35):13458-13467.
https://doi.org/10.1039/C6TA05288F

Ge X, Huang ZX, Shi B, et al., 2025. Crystallization control of blade-coated wide bandgap FACs-based perovskite. *Advanced Functional Materials*, 35(12):2417493.
https://doi.org/10.1002/adfm.202417493

Ghosh AK, Jeong BH, Huang XF, et al., 2008. Impacts of reaction and curing conditions on polyamide composite reverse osmosis membrane properties. *Journal of Membrane Science*, 311(1-2):34-45.
https://doi.org/10.1016/j.memsci.2007.11.038

Hamill JC, Schwartz J, Loo YL, 2018. Influence of solvent coordination on hybrid organic–inorganic perovskite formation. *ACS Energy Letters*, 3(1):92-97.
https://doi.org/10.1021/acsenergylett.7b01057

Han JY, Park K, Tan S, et al., 2025. Perovskite solar cells. *Nature Reviews Methods Primers*, 5(1):3.
https://doi.org/10.1038/s43586-024-00373-9

He M, Li B, Cui X, et al., 2017. Meniscus-assisted solution printing of large-grained perovskite films for high-efficiency solar cells. *Nature Communications*, 8:16045. https://doi.org/10.1038/ncomms16045

Heo JH, Song DH, Im SH, 2014. Planar $CH_3NH_3PbBr_3$ hybrid solar cells with 10.4% power conversion efficiency, fabricated by controlled crystallization in the spin-coating process. *Advanced Materials*, 26(48):8179-8183. https://doi.org/10.1002/adma.201403140

Hu GH, Yang LS, Yang ZY, et al., 2020. A general ink formulation of 2D crystals for wafer-scale inkjet printing. *Science Advances*, 6(33):eaba5029. https://doi.org/10.1126/sciadv.aba5029

Hu H, Larson RG, 2005. Analysis of the effects of marangoni stresses on the microflow in an evaporating sessile droplet. *Langmuir*, 21(9):3972-3980. https://doi.org/10.1021/la0475270

Hu Q, Zhao LC, Wu J, et al., 2017. In situ dynamic observations of perovskite crystallisation and microstructure evolution intermediated from $[PbI_6]^{4-}$ cage nanoparticles. *Nature Communications*, 8:15688. https://doi.org/10.1038/ncomms15688

Hu ZH, Cai HK, Luo XG, et al., 2025. Nonvolatile and strongly coordinating solvent enables blade-coating of efficient FACs-based perovskite solar cells. *Small Methods*, in press. https://doi.org/10.1002/smtd.202402177

Huang FZ, Dkhissi Y, Huang WC, et al., 2014. Gas-assisted preparation of lead iodide perovskite films consisting of a monolayer of single crystalline grains for high efficiency planar solar cells. *Nano Energy*, 10:10-18. https://doi.org/10.1016/j.nanoen.2014.08.015

Huang JB, Tan SQ, Lund PD, et al., 2017. Impact of H_2O on organic–inorganic hybrid perovskite solar cells. *Energy & Environmental Science*, 10(11):2284-2311. https://doi.org/10.1039/C7EE01674C

Huang KW, Li MH, Chen YT, et al., 2024. Fast fabrication of μm-thick perovskite films by using a one-step doctor-blade coating method for direct X-ray detectors. *Journal of Materials Chemistry C*, 12(4):1533-1542. https://doi.org/10.1039/D3TC02736H

Huang ZX, Ge X, Liu Z, et al., 2024. Highly efficient blade-coated 1.67 eV p-i-n perovskite solar cells enabled by a hybrid self-assembled monolayer and surface passivation. *ACS Applied Energy Materials*, 7(24):11683-11690. https://doi.org/10.1021/acsaem.4c01080

Jang GS, Kim Y, Kim YY, et al., 2022. Ambient air-processed wide-bandgap perovskite solar cells with well-controlled film morphology for four-terminal tandem application. *Solar RRL*, 6(8):2200252. https://doi.org/10.1002/solr.202200252

Jeong DN, Lee DK, Seo S, et al., 2019. Perovskite cluster-containing solution for scalable D-bar coating toward high-throughput perovskite solar cells. *ACS Energy Letters*, 4(5): 1189-1195. https://doi.org/10.1021/acsenergylett.9b00042

Jia P, Chen GY, Li G, et al., 2024. Intermediate phase suppression with long chain diammonium alkane for high performance wide-bandgap and tandem perovskite solar cells. *Advanced Materials*, 36(25):2400105. https://doi.org/10.1002/adma.202400105

Ke WJ, Xiao CX, Wang CL, et al., 2016. Employing lead thiocyanate additive to reduce the hysteresis and boost the fill factor of planar perovskite solar cells. *Advanced Materials*, 28(26):5214-5221. https://doi.org/10.1002/adma.201600594

Kim HS, Mora-Sero I, Gonzalez-Pedro V, et al., 2013. Mechanism of carrier accumulation in perovskite thin-absorber solar cells. *Nature Communications*, 4:2242. https://doi.org/10.1038/ncomms3242

Kim M, Kim GH, Lee TK, et al., 2019. Methylammonium chloride induces intermediate phase stabilization for efficient perovskite solar cells. *Joule*, 3(9):2179-2192. https://doi.org/10.1016/j.joule.2019.06.014

Kim SW, Moon SJ, Kim SH, et al., 2023. Reducing humidity dependency of ambient-air-processed wide-bandgap inverted perovskite solar cells. *ACS Energy Letters*, 8(11): 4777-4781. https://doi.org/10.1021/acsenergylett.3c01952

Ko HS, Lee JW, Park NG, 2015. 15.76% Efficiency perovskite solar cells prepared under high relative humidity: importance of PbI_2 morphology in two-step deposition of $CH_3NH_3PbI_3$. *Journal of Materials Chemistry A*, 3(16): 8808-8815. https://doi.org/10.1039/C5TA00658A

Kojima A, Teshima K, Shirai Y, et al., 2009. Organometal halide perovskites as visible-light sensitizers for photovoltaic cells. *Journal of the American Chemical Society*, 131(17): 6050-6051. https://doi.org/10.1021/ja809598r

Kwon SB, Lee DW, Kwon YD, 2007. Experimental and computational studies on Coanda nozzle flow for the air knife application. *Journal of Thermal Science*, 16(2):164-169. https://doi.org/10.1007/s11630-007-0164-5

le Berre M, Chen Y, Baigl D, 2009. From convective assembly to landau−levich deposition of multilayered phospholipid films of controlled thickness. *Langmuir*, 25(5):2554-2557. https://doi.org/10.1021/la803646e

Lee HS, Kim MK, Pae SR, et al., 2020. Tuning the wettability of the blade enhances solution-sheared perovskite solar cell performance. *Nano Energy*, 74:104830. https://doi.org/10.1016/j.nanoen.2020.104830

Lee J, Kang H, Kim G, et al., 2017. Achieving large-area planar perovskite solar cells by introducing an interfacial compatibilizer. *Advanced Materials*, 29(22):1606363. https://doi.org/10.1002/adma.201606363

Lee SH, Hong S, Kim HJ, 2022. Selection of a suitable solvent additive for 2-methoxyethanol-based antisolvent-free perovskite film fabrication. *ACS Applied Materials & Interfaces*, 14(34):39132-39140. https://doi.org/10.1021/acsami.2c10171

Leguy AMA, Hu YH, Campoy-Quiles M, et al., 2015. Reversible hydration of $CH_3NH_3PbI_3$ in films, single crystals, and solar cells. *Chemistry of Materials*, 27(9):3397-3407. https://doi.org/10.1021/acs.chemmater.5b00660

Li FZ, Deng X, Qi F, et al., 2020. Regulating surface termination for efficient inverted perovskite solar cells with greater

than 23% efficiency. *Journal of the American Chemical Society*, 142(47):20134-20142.
https://doi.org/10.1021/jacs.0c09845

Li X, Bi DQ, Yi CY, et al., 2016. A vacuum flash–assisted solution process for high-efficiency large-area perovskite solar cells. *Science*, 353(6294):58-62.
https://doi.org/10.1126/science.aaf8060

Li Z, Klein TR, Kim DH, et al., 2018. Scalable fabrication of perovskite solar cells. *Nature Reviews Materials*, 3(4):18017.
https://doi.org/10.1038/natrevmats.2018.17

Li Z, Li B, Wu X, et al., 2022. Organometallic-functionalized interfaces for highly efficient inverted perovskite solar cells. *Science*, 376(6591):416-420.
https://doi.org/10.1126/science.abm8566

Liang PW, Liao CY, Chueh CC, et al., 2014. Additive enhanced crystallization of solution-processed perovskite for highly efficient planar-heterojunction solar cells. *Advanced Materials*, 26(22):3748-3754.
https://doi.org/10.1002/adma.201400231

Liu H, Shi GY, Khan R, et al., 2024. Large-area flexible perovskite light-emitting diodes enabled by inkjet printing. *Advanced Materials*, 36(8):2309921.
https://doi.org/10.1002/adma.202309921

Liu J, de Bastiani M, Aydin E, et al., 2022. Efficient and stable perovskite-silicon tandem solar cells through contact displacement by MgF_x. *Science*, 377(6603):302-306.
https://doi.org/10.1126/science.abn8910

Liu J, He YC, Ding L, et al., 2024. Perovskite/silicon tandem solar cells with bilayer interface passivation. *Nature*, 635(8039):596-603.
https://doi.org/10.1038/s41586-024-07997-7

Liu K, Liang Q, Qin MC, et al., 2020. Zwitterionic-surfactant-assisted room-temperature coating of efficient perovskite solar cells. *Joule*, 4(11):2404-2425.
https://doi.org/10.1016/j.joule.2020.09.011

Lu JF, Jiang LC, Li W, et al., 2017. Diammonium and monoammonium mixed-organic-cation perovskites for high performance solar cells with improved stability. *Advanced Energy Materials*, 7(18):1700444.
https://doi.org/10.1002/aenm.201700444

Malinowski R, Volpe G, Parkin IP, et al., 2018. Dynamic control of particle deposition in evaporating droplets by an external point source of vapor. *The Journal of Physical Chemistry Letters*, 9(3):659-664.
https://doi.org/10.1021/acs.jpclett.7b02831

Ni ZY, Jiao HY, Fei CB, et al., 2022. Evolution of defects during the degradation of metal halide perovskite solar cells under reverse bias and illumination. *Nature Energy*, 7(1):65-73.
https://doi.org/10.1038/s41560-021-00949-9

Niu GD, Li WZ, Meng FQ, et al., 2014. Study on the stability of $CH_3NH_3PbI_3$ films and the effect of post-modification by aluminum oxide in all-solid-state hybrid solar cells. *Journal of Materials Chemistry A*, 2(3):705-710.
https://doi.org/10.1039/C3TA13606J

Niu GD, Guo XD, Wang LD, 2015. Review of recent progress in chemical stability of perovskite solar cells. *Journal of Materials Chemistry A*, 3(17):8970-8980.
https://doi.org/10.1039/C4TA04994B

Niu GD, Li WZ, Li JW, et al., 2017. Enhancement of thermal stability for perovskite solar cells through cesium doping. *RSC Advances*, 7(28):17473-17479.
https://doi.org/10.1039/C6RA28501E

Noblesse F, Hendrix D, Faul L, et al., 2006. Simple analytical expressions for the height, location, and steepness of a ship bow wave. *Journal of Ship Research*, 50(4):360-370.
https://doi.org/10.5957/jsr.2006.50.4.360

Noblesse F, Delhommeau G, Guilbaud M, et al., 2008. Simple analytical relations for ship bow waves. *Journal of Fluid Mechanics*, 600:105-132.
https://doi.org/10.1017/S0022112008000220

Odysseas Kosmatos K, Theofylaktos L, Giannakaki E, et al., 2019. Methylammonium chloride: a key additive for highly efficient, stable, and up-scalable perovskite solar cells. *Energy & Environmental Materials*, 2(2):79-92.
https://doi.org/10.1002/eem2.12040

O'Mahony FTF, Lee YH, Jellett C, et al., 2015. Improved environmental stability of organic lead trihalide perovskite-based photoactive-layers in the presence of mesoporous TiO_2. *Journal of Materials Chemistry A*, 3(14):7219-7223.
https://doi.org/10.1039/C5TA01221J

Park J, Kim J, Yun HS, et al., 2023. Controlled growth of perovskite layers with volatile alkylammonium chlorides. *Nature*, 616(7958):724-730.
https://doi.org/10.1038/s41586-023-05825-y

Park NG, 2016. Crystal growth engineering for high efficiency perovskite solar cells. *CrystEngComm*, 18(32):5977-5985.
https://doi.org/10.1039/C6CE00813E

Park NG, 2021. Green solvent for perovskite solar cell production. *Nature Sustainability*, 4(3):192-193.
https://doi.org/10.1038/s41893-020-00647-6

Park NG, Zhu K, 2020. Scalable fabrication and coating methods for perovskite solar cells and solar modules. *Nature Reviews Materials*, 5(5):333-350.
https://doi.org/10.1038/s41578-019-0176-2

Peña-Camargo F, Caprioglio P, Zu FS, et al., 2020. Halide segregation versus interfacial recombination in bromide-rich wide-gap perovskite solar cells. *ACS Energy Letters*, 5(8):2728-2736.
https://doi.org/10.1021/acsenergylett.0c01104

Phung N, Verheijen M, Todinova A, et al., 2022. Enhanced self-assembled monolayer surface coverage by ALD NiO in p-i-n perovskite solar cells. *ACS Applied Materials & Interfaces*, 14(1):2166-2176.
https://doi.org/10.1021/acsami.1c15860

Pu DX, Zhou S, Guan HL, et al., 2024. Enhancing efficiency and intrinsic stability of large-area blade-coated wide-bandgap perovskite solar cells through strain release. *Advanced Functional Materials*, 34(17):2314349.
https://doi.org/10.1002/adfm.202314349

Quan LN, Yuan MJ, Comin R, et al., 2016. Ligand-stabilized reduced-dimensionality perovskites. *Journal of the American Chemical Society*, 138(8):2649-2655.
https://doi.org/10.1021/jacs.5b11740

Razza S, di Giacomo F, Matteocci F, et al., 2015. Perovskite solar cells and large area modules (100 cm^2) based on an

air flow-assisted PbI_2 blade coating deposition process. *Journal of Power Sources*, 277:286-291.
https://doi.org/10.1016/j.jpowsour.2014.12.008

Ren ZJ, Cui ZW, Shi XY, et al., 2023. Poly(carbazole phosphonic acid) as a versatile hole-transporting material for p-i-n perovskite solar cells and modules. *Joule*, 7(12): 2894-2904.
https://doi.org/10.1016/j.joule.2023.10.014

Rong YG, Hu Y, Mei AY, et al., 2018. Challenges for commercializing perovskite solar cells. *Science*, 361(6408): eaat8235.
https://doi.org/10.1126/science.aat8235

Saidaminov MI, Abdelhady AL, Murali B, et al., 2015. High-quality bulk hybrid perovskite single crystals within minutes by inverse temperature crystallization. *Nature Communications*, 6:7586.
https://doi.org/10.1038/ncomms8586

Shahiduzzaman M, Yamamoto K, Furumoto Y, et al., 2017. Viscosity effect of ionic liquid-assisted controlled growth of $CH_3NH_3PbI_3$ nanoparticle-based planar perovskite solar cells. *Organic Electronics*, 48:147-153.
https://doi.org/10.1016/j.orgel.2017.06.001

Song S, Hörantner MT, Choi K, et al., 2017. Inducing swift nucleation morphology control for efficient planar perovskite solar cells by hot-air quenching. *Journal of Materials Chemistry A*, 5(8):3812-3818.
https://doi.org/10.1039/C6TA09020F

Song ZN, McElvany CL, Phillips AB, et al., 2017. A techno-economic analysis of perovskite solar module manufacturing with low-cost materials and techniques. *Energy & Environmental Science*, 10(6):1297-1305.
https://doi.org/10.1039/C7EE00757D

Stolterfoht M, Wolff CM, Márquez JA, et al., 2018. Visualization and suppression of interfacial recombination for high-efficiency large-area pin perovskite solar cells. *Nature Energy*, 3(10):847-854.
https://doi.org/10.1038/s41560-018-0219-8

Stolterfoht M, Caprioglio P, Wolff CM, et al., 2019. The impact of energy alignment and interfacial recombination on the internal and external open-circuit voltage of perovskite solar cells. *Energy & Environmental Science*, 12(9):2778-2788.
https://doi.org/10.1039/C9EE02020A

Sun B, Wang WW, Lu H, et al., 2021. Tuning the interactions of methylammonium acetate with acetonitrile to create efficient perovskite solar cells. *The Journal of Physical Chemistry C*, 125(12):6555-6563.
https://doi.org/10.1021/acs.jpcc.0c10805

Sun R, Guo J, Sun CK, et al., 2019. A universal layer-by-layer solution-processing approach for efficient non-fullerene organic solar cells. *Energy & Environmental Science*, 12(1): 384-395.
https://doi.org/10.1039/C8EE02560F

Szostak R, Sanchez S, Marchezi PE, et al., 2021. Revealing the perovskite film formation using the gas quenching method by in situ GIWAXS: morphology, properties, and device performance. *Advanced Functional Materials*, 31(4): 2007473.
https://doi.org/10.1002/adfm.202007473

Tang Y, Zhang YC, Zhou XM, et al., 2023. Solvent engineering of scalable deposited wide-bandgap perovskites for efficient monolithic perovskite-organic tandem solar cells. *Nano Energy*, 114:108653.
https://doi.org/10.1016/j.nanoen.2023.108653

Teale S, Degani M, Chen B, et al., 2024. Molecular cation and low-dimensional perovskite surface passivation in perovskite solar cells. *Nature Energy*, 9(7):779-792.
https://doi.org/10.1038/s41560-024-01529-3

Tian CC, Gao XF, Li J, et al., 2022. Scalable growth of stable wide-bandgap perovskite towards large-scale tandem photovoltaics. *Solar RRL*, 6(7):2200134.
https://doi.org/10.1002/solr.202200134

Tsai PT, Yu KC, Chang CJ, et al., 2015. Large-area organic solar cells by accelerated blade coating. *Organic Electronics*, 22:166-172.
https://doi.org/10.1016/j.orgel.2015.03.001

Vachaparambil KJ, Einarsrud KE, 2018. Explanation of bubble nucleation mechanisms: a gradient theory approach. *Journal of The Electrochemical Society*, 165(10):E504-E512.
https://doi.org/10.1149/2.1031810jes

Vidal R, Alberola-Borràs JA, Habisreutinger SN, et al., 2021. Assessing health and environmental impacts of solvents for producing perovskite solar cells. *Nature Sustainability*, 4(3):277-285.
https://doi.org/10.1038/s41893-020-00645-8

Wang F, Ma JL, Xie FY, et al., 2016. Organic cation-dependent degradation mechanism of organotin halide perovskites. *Advanced Functional Materials*, 26(20):3417-3423.
https://doi.org/10.1002/adfm.201505127

Wang FF, Liu TX, Liu YY, et al., 2024. A polymeric hole transporter with dual-interfacial interactions enables 25%-efficiency blade-coated perovskite solar cells. *Advanced Materials*, 36(52):2412059.
https://doi.org/10.1002/adma.202412059

Wang G, Liao LP, Chen LJ, et al., 2020. Perovskite solar cells fabricated under ambient air at room temperature without any post-treatment. *Organic Electronics*, 86:105918.
https://doi.org/10.1016/j.orgel.2020.105918

Wang J, Fu WF, Jariwala S, et al., 2019. Reducing surface recombination velocities at the electrical contacts will improve perovskite photovoltaics. *ACS Energy Letters*, 4(1):222-227.
https://doi.org/10.1021/acsenergylett.8b02058

Wang X, Fan YP, Wang L, et al., 2020. Perovskite solution aging: what happened and how to inhibit? *Chem*, 6(6): 1369-1378.
https://doi.org/10.1016/j.chempr.2020.02.016

Wang Z, Shi ZJ, Li TT, et al., 2017. Stability of perovskite solar cells: a prospective on the substitution of the A cation and X anion. *Angewandte Chemie International Edition*, 56(5):1190-1212.
https://doi.org/10.1002/anie.201603694

Wang ZP, Lin QQ, Chmiel FP, et al., 2017. Efficient ambient-air-stable solar cells with 2D–3D heterostructured butylammonium-caesium-formamidinium lead halide perovskites. *Nature Energy*, 2(9):17135.
https://doi.org/10.1038/nenergy.2017.135

Whitaker JB, Kim DH, Larson BW, et al., 2018. Scalable slot-die coating of high performance perovskite solar cells. *Sustainable Energy & Fuels*, 2(11):2442-2449. https://doi.org/10.1039/C8SE00368H

Whitehead CB, Özkar S, Finke RG, 2019. LaMer's 1950 model for particle formation of instantaneous nucleation and diffusion-controlled growth: a historical look at the model's origins, assumptions, equations, and underlying sulfur sol formation kinetics data. *Chemistry of Materials*, 31(18):7116-7132. https://doi.org/10.1021/acs.chemmater.9b01273

Wilkinson J, Tam C, Askounis A, et al., 2021. Suppression of the coffee-ring effect by tailoring the viscosity of pharmaceutical sessile drops. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 614:126144. https://doi.org/10.1016/j.colsurfa.2021.126144

Williams ST, Zuo F, Chueh CC, et al., 2014. Role of chloride in the morphological evolution of organo-lead halide perovskite thin films. *ACS Nano*, 8(10):10640-10654. https://doi.org/10.1021/nn5041922

Wu CC, Wang K, Li J, et al., 2021. Volatile solution: the way toward scalable fabrication of perovskite solar cells? *Matter*, 4(3):775-793. https://doi.org/10.1016/j.matt.2020.12.025

Wu JJ, Liu ZK, Yang YR, et al., 2025. Regulating precursor viscosity with inert solvent additives for efficient blade-coated perovskite solar cells. *Small Methods*, in press. https://doi.org/10.1002/smtd.202500129

Wu WQ, Wang Q, Fang YJ, et al., 2018. Molecular doping enabled scalable blading of efficient hole-transport-layer-free perovskite solar cells. *Nature Communications*, 9(1): 1625. https://doi.org/10.1038/s41467-018-04028-8

Wu WQ, Yang ZB, Rudd PN, et al., 2019. Bilateral alkylamine for suppressing charge recombination and improving stability in blade-coated perovskite solar cells. *Science Advances*, 5(3):eaav8925. https://doi.org/10.1126/sciadv.aav8925

Xia R, Gao XX, Zhang Y, et al., 2020. An efficient approach to fabricate air-stable perovskite solar cells via addition of a self-polymerizing ionic liquid. *Advanced Materials*, 32(40):2003801. https://doi.org/10.1002/adma.202003801

Xiao MD, Huang FZ, Huang WC, et al., 2014. A fast deposition-crystallization procedure for highly efficient lead iodide perovskite thin-film solar cells. *Angewandte Chemie International Edition*, 53(37):9898-9903. https://doi.org/10.1002/anie.201405334

Xu F, Bao Z, Tu YG, et al., 2025. Blade-coated mixed-halide wide-bandgap perovskite photovoltaics: progress and challenges. *Advanced Materials Technologies*, 10(8):2401434. https://doi.org/10.1002/admt.202401434

Xu XW, Ma CQ, Xie YM, et al., 2018. Air-processed mixed-cation $Cs_{0.15}FA_{0.85}PbI_3$ planar perovskite solar cells derived from a PbI_2–CsI–FAI intermediate complex. *Journal of Materials Chemistry A*, 6(17):7731-7740. https://doi.org/10.1039/C8TA01049H

Yang G, Ni ZY, Yu ZJ, et al., 2022. Defect engineering in wide-bandgap perovskites for efficient perovskite–silicon tandem solar cells. *Nature Photonics*, 16(8):588-594. https://doi.org/10.1038/s41566-022-01033-8

Yang JL, Siempelkamp BD, Liu DY, et al., 2015. Investigation of $CH_3NH_3PbI_3$ degradation rates and mechanisms in controlled humidity environments using in situ techniques. *ACS Nano*, 9(2):1955-1963. https://doi.org/10.1021/nn506864k

Yang MJ, Zhou YY, Zeng YN, et al., 2015. Square-centimeter solution-processed planar $CH_3NH_3PbI_3$ perovskite solar cells with efficiency exceeding 15%. *Advanced Materials*, 27(41):6363-6370. https://doi.org/10.1002/adma.201502586

Yang MJ, Zhang TY, Schulz P, et al., 2016. Facile fabrication of large-grain $CH_3NH_3PbI_{3-x}Br_x$ films for high-efficiency solar cells via CH_3NH_3Br-selective Ostwald ripening. *Nature Communications*, 7:12305. https://doi.org/10.1038/ncomms12305

Yang S, Chen SS, Mosconi E, et al., 2019. Stabilizing halide perovskite surfaces for solar cell operation with wide-bandgap lead oxysalts. *Science*, 365(6452):473-478. https://doi.org/10.1126/science.aax3294

Yang XY, Wu MM, Doi M, et al., 2022. Evaporation dynamics of sessile droplets: the intricate coupling of capillary, evaporation, and marangoni flow. *Langmuir*, 38(16):4887-4893. https://doi.org/10.1021/acs.langmuir.2c00130

Yang YR, Wu JJ, Zhang K, et al., 2025. Tailored colloidal shapes in precursor solutions for efficient blade-coated perovskite solar modules. *Advanced Materials*, 37(9): 2418790. https://doi.org/10.1002/adma.202418790

Yang ZB, Chueh CC, Zuo F, et al., 2015. High-performance fully printable perovskite solar cells via blade-coating technique under the ambient condition. *Advanced Energy Materials*, 5(13):1500328. https://doi.org/10.1002/aenm.201500328

Ye F, Chen H, Xie FX, et al., 2016. Soft-cover deposition of scaling-up uniform perovskite thin films for high cost-performance solar cells. *Energy & Environmental Science*, 9(7):2295-2301. https://doi.org/10.1039/C6EE01411A

Yin RY, Wu YT, Huang ZJ, et al., 2025. Fabricating perovskite films for solar modules from small to large scale. *Advanced Functional Materials*, 35(24):2419184. https://doi.org/10.1002/adfm.202419184

Yu XH, Xing RB, Peng ZX, et al., 2019. To inhibit coffee ring effect in inkjet printing of light-emitting polymer films by decreasing capillary force. *Chinese Chemical Letters*, 30(1):135-138. https://doi.org/10.1016/j.cclet.2018.09.007

Yu Y, Zhang F, Hou T, et al., 2021. A review on gas-quenching technique for efficient perovskite solar cells. *Solar RRL*, 5(10):2100386. https://doi.org/10.1002/solr.202100386

Zeng LX, Chen S, Forberich K, et al., 2020. Controlling the crystallization dynamics of photovoltaic perovskite layers on larger-area coatings. *Energy & Environmental Science*, 13(12):4666-4690.

https://doi.org/10.1039/D0EE02575E

Zhang AF, Li MY, Dong C, et al., 2024. π–π stacking at the Perovskite/C_{60} interface enables high-efficiency wide-bandgap perovskite solar cells. *Small*, 20(35):2401197. https://doi.org/10.1002/smll.202401197

Zhang F, Park SY, Yao CL, et al., 2022. Metastable Dion-Jacobson 2D structure enables efficient and stable perovskite solar cells. *Science*, 375(6576):71-76. https://doi.org/10.1126/science.abj2637

Zhang M, Bing JM, Cho Y, et al., 2019. Synergistic effect of potassium and iodine from potassium triiodide complex additive on gas-quenched perovskite solar cells. *Nano Energy*, 63:103853. https://doi.org/10.1016/j.nanoen.2019.06.049

Zhang TY, Dar MI, Li G, et al., 2017. Bication lead iodide 2D perovskite component to stabilize inorganic α-$CsPbI_3$ perovskite phase for high-efficiency solar cells. *Science Advances*, 3(9):e1700841. https://doi.org/10.1126/sciadv.1700841

Zhang W, Pathak S, Sakai N, et al., 2015. Enhanced optoelectronic quality of perovskite thin films with hypophosphorous acid for planar heterojunction solar cells. *Nature Communications*, 6:10030. https://doi.org/10.1038/ncomms10030

Zhang Y, Cui QP, Shao FQ, et al., 2012. Influence of air-knife wiping on coating thickness in hot-dip galvanizing. *Journal of Iron and Steel Research International*, 19(6):70-78. https://doi.org/10.1016/S1006-706X(12)60130-7

Zhang ZY, Shang JH, Ge HH, et al., 2023. Suppressing halide phase segregation in wide-bandgap perovskite film by co-doping strategy for high-performance and stable perovskite solar cells. *Materials Today Physics*, 37:101187. https://doi.org/10.1016/j.mtphys.2023.101187

Zhao YX, Zhu K, 2014. CH_3NH_3Cl-assisted one-step solution growth of $CH_3NH_3PbI_3$: structure, charge-carrier dynamics, and photovoltaic properties of perovskite solar cells. *The Journal of Physical Chemistry C*, 118(18):9412-9418. https://doi.org/10.1021/jp502696w

Zheng JH, Zhang M, Lau CFJ, et al., 2017. Spin-coating free fabrication for highly efficient perovskite solar cells. *Solar Energy Materials and Solar Cells*, 168:165-171. https://doi.org/10.1016/j.solmat.2017.04.029

Zheng XT, Kong WC, Wen J, et al., 2024. Solvent engineering for scalable fabrication of perovskite/silicon tandem solar cells in air. *Nature Communications*, 15(1):4907. https://doi.org/10.1038/s41467-024-49351-5

Zheng ZH, Li FM, Gong J, et al., 2022. Pre-buried additive for cross-layer modification in flexible perovskite solar cells with efficiency exceeding 22%. *Advanced Materials*, 34(21):2109879. https://doi.org/10.1002/adma.202109879

Zhou XM, Lai HW, Huang T, et al., 2023. Suppressing nonradiative losses in wide-band-gap perovskites affords efficient and printable all-perovskite tandem solar cells with a metal-free charge recombination layer. *ACS Energy Letters*, 8(1):502-512. https://doi.org/10.1021/acsenergylett.2c02156

Zhou ZM, Wang ZW, Zhou YY, et al., 2015. Methylamine-gas-induced defect-healing behavior of $CH_3NH_3PbI_3$ thin films for perovskite solar cells. *Angewandte Chemie International Edition*, 54(33):9705-9709. https://doi.org/10.1002/anie.201504379