**Perovskite Solution Mix and Fabrication Methods**

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**Perovskite Materials: Substrates and Precursors**

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Solar cells based on organic-inorganic lead halide perovskites are popular in the photovoltaic community due to their high efficiency, low cost, and solution processability. Understanding the fundamentals of metal halide perovskite and its interfaces is extremely important for achieving high-quality materials and developing efficient devices using these materials with the necessary properties. It is important to understand the entire solar cell manufacturing process in order to choose the right solvent, including knowing the initial structures of the solution, observing the dynamic processes during evaporation and checking the final structure of the solar cell film (Zhang et al., 2024A; Jowett, 2024D).

Material selection is of vital importance when choosing and creating perovskite substrates and precursors, as the formulation and deposition of the perovskite precursor on the substrate is a detailed step. The substrate is what the perovskite precursor solution is deposited on, using processing and manufacturing techniques such as solution-based deposition, printing methods, and optimized annealing processes. Solution-based deposition includes techniques such as spin coating, blade coating, or slot-die coating. Printing methods include inkjet printing or screen printing. And an optimized annealing process is where thermal annealing profiles are developed. To develop low-cost perovskite solar cells for large-scale production, researchers are focusing on utilizing readily available, inexpensive materials, and implementing scalable processing techniques like spin coating, blade coating, screen printing, or inkjet printing, while optimizing the perovskite precursor chemistry to achieve high efficiency with minimal processing steps and reduced waste.

The substrate may be made of metal, glass, or plastic. After the substrate has been chosen, we must choose affordable precursors, such as using readily available and inexpensive metal halides like lead iodide and organic cations like methylammonium or formamidinium as the primary building blocks of the perovskite material. After the precursors have been chosen, we can use additive engineering to Incorporate small amounts of additives to the precursor solution to control crystal growth, improve film morphology, and enhance device performance. An area of research is exploring the use of lead-free perovskite combinations to address environmental concerns while maintaining high efficiency. Scalable precursor synthesis is needed for mass production, as we must optimize the synthesis process to produce high-quality perovskite precursors in large quantities with consistent chemical properties. We must also develop cost-effective substrates, those materials that are compatible with large-scale manufacturing and can be readily recycled. In order to develop new low-cost perovskite materials with high stability, we can explore new organic cations, inorganic halide combinations, and incorporate functional additives to improve the stability of the perovskite material under environmental stress.

Areas of perovskite cell manufacturing which need to improve to bring perovskite to commercialization include: precursor synthesis, selection criteria for precursors based on chemistry, additive engineering, and deposition techniques. The perovskite fabrication process needs to be improved to commercialize, by selecting materials and methods to simplify and reduce the fabrication costs of PSCs, including the preparation and deposition methods of the perovskite layer, and selection of precursors, additives and solvents (Park et al., 2016; Niu et al., 2021; Kim et al., 2020A; Park, 2020; Seok et al., 2018; Lee et al., 2019A; Rong et al., 2018). The selection of precursors, for instance, directly affects the crystallization kinetics, film morphology and quality, and ultimately the photovoltaic performance of the PSCs (Lee et al., 2023; Halder et al., 2023; Chen et al., 2019; Liu et al., 2020; Ma et al., 2022A; Ma et al., 2023A). Additive engineering, on the other hand, can stabilize the perovskite phase, inhibition migration, and passivate defects, minimize recombination losses, and improve the overall stability and efficiency of the PSCs (Chen et al., 2020; Zhou et al., 2014; Graetzel et al., 2012; Cho and Park, 2017; Ma et al., 2023B).

The goal of current perovskite research is to produce high quality perovskite films that are efficient, stable, and reproducible, with a low-cost fabrication process.

**Perovskite Cell Creation Process**

To create the perovskite precursor solution, wet chemistry is utilized, where materials like methylammonium lead iodide, methylammonium halide, and other additives are mixed together in a solution. This precursor mixture is then deposited on a substrate like glass, metal oxide, flexible polymers, a silicon solar cell, or even transparent wood. Spin-coating is a popular perovskite solution deposition technique, which is a similar concept as the Spin-Art machines children use to make splotchy paintings on thick paper. In spin-coating, the solution is dripped or sprayed onto the substrate, which is then spun at a high enough speed to spread a thin layer of the solution across its surface. When the solvents in the mixture evaporate, they leave behind perovskite films; thin layers of perovskite crystals ready to be wired into a solar cell (Zientara, 2025).

***Precursor Creation***

The first step in the process is precursor salts are mixed to form a perovskite ink solution. If the material will be deposited as a vapor, the salts are not mixed until they are deposited together on a cell in the next step.

***Cell Fabrication***

To fabricate the perovskite cell, an ultra-thin layer of perovskite ink or powder is deposited onto the substrate, and the cell is heated to set the film. Other material layers are deposited surrounding the perovskite layer, such as charge transport layers (hole and electron), which help direct the flow of electrons.

***Module Completion***

To create a module, channels are laser scribed to separate the film into individual cells. Electrical contact channels are then scribed to wire those cells together, and edge sealant and encapsulant for weather proofing are added.

***Testing and Development***

Characterization analysis is performed on the cell or module to gauge its efficiency and stability.

**Perovskite Substrates**

Wang, Y., Lin, R., Wang, X. et al. Oxidation-resistant all-perovskite tandem solar cells in substrate configuration. Nat Commun 14, 1819 (2023). <https://doi.org/10.1038/s41467-023-37492-y>

In this work, we demonstrate the complete fabrication of p-i-n PSCs in substrate configuration using scalable vacuum-deposition processes (Paliwal et al., 2023).

This Review discusses the recent development of materials for fPSCs based on various flexible substrates, including plastic, metal, and other flexible substrates (Mishra et al., 2021)

PSCs are versatile and can be fabricated on flexible substrates, such as glass, metal, or plastic, depending on the application and desired flexibility of the solar cell. The substrate of a solar cell is the cell foundation or base layer or supporting material on which the active layers of the cell are deposited. The function of the substrate is to provide a stable surface to build the various layers of the solar cell upon, including the light-absorbing layer (perovskite absorber) and the electrodes. Substrate material selection depends on several factors, such as cost, desired flexibility, thermal expansion coefficient, and compatibility with the fabrication process. Glass is known for its transparency and stability, and is the most widely used. Metal foils can be used for flexible solar cells, offering durability and potential for lightweight applications. Plastics, like PET, can also be used for flexible solar cells, providing lightweight and conformability.

The highest PCEs obtained for p-i-n and n-i-p PSCs in substrate configuration are 16.4% and 15.9%, respectively, whereas PSCs manufactured in the superstrate configuration have achieved 25% PCEs (Feleki et al., 2022A; Feleki et al., 2022B; Yoo et al., 2021). The higher efficiency ratings of small-scale PSCs have been achieved by being fabricated on transparent conductive oxide (TCO)-coated glass substrates in the superstrate configuration (Cheng et al., 2022). However, it is more difficult to scale up for mass production superstrate devices that employ a TCO as the back or bottom contact (bottom-TCO), as the resistive losses of the TCO are greater than with small-area devices, limiting the current flow and the fill factor (FF) of the cell (Wilkinson et al., 2018). The best way to counter these TCO resistive losses in scaled up cells is to incorporate metal grids on the bottom-TCO, however, the metal grids would need to have a height of at least 1 μm to keep their width limited and still achieve a minimum cross-sectional area to conduct the required magnitude of current. This increased height of the metal grids would lead to deposition and uniformity issues with the deposited layers, including perovskite films, which would affect the performance of the cell (Werner et al., 2020; da Silva Filho et al., 2022). Conversely, positioning the transparent front electrode on top of the active stack in substrate configuration allows the area of the devices to be scaled with relative ease, as the metal gridlines can be placed on the top electrode, typically a TCO, without influencing the prior processing of the underlying device layers (Werner et al., 2020). Substrate configuration PSCs usually utilize the n-i-p configuration on titanium foils, as these foils have an intrinsically formed TiO2 layer on their surface that is a known electron-transporting layer (Lee et al., 2015B; Troughton et al., 2015; Heo et al., 2018; Han et al., 2018).

Perovskite solar cells can be fabricated using two primary configurations: superstrate and substrate. Cells formed with the superstrate configuration have achieved greater power operating efficiencies, but the substrate configuration is more conducive to scaling up for mass production. Superstrate configurations involve the transparent conducting oxide (TCO) layer being deposited on the substrate, followed by the active perovskite layers, and finally the top electrode. Substrate configurations involve illuminating the perovskite layer from the backside, with the bottom electrode (metal foil, for example) is deposited on the substrate, followed by the perovskite layers, and finally a transparent top electrode. Substrate configuration is commonly used for flexible all-perovskite tandem solar cells due to its ability to use a wider range of substrates. The lack of progress in researching PSCs in the substrate configuration could be due to the additional challenges associated with the processing of PSCs on metal thin films or foils compared with on bottom-TCOs or in the superstrate configuration and with the deposition of the top-TCO electrodes without damaging the underlying device layers (Aydin et al., 2021; Paliwal et al., 2023). Given the advantages of fabricating large-area devices in the substrate configuration and the large gap between the highest PCE values of PSCs in superstrate and substrate configuration, it is important to advance the development of PSCs in the substrate architecture. Superstrate configuration has higher reported efficiencies and a greater potential for low-cost production, however, it also limits substrate choices to transparent materials, and the first subcell (wide-bandgap) must be deposited first, which can be disadvantageous for all-perovskite tandem cells. Substrate configuration offers flexibility in substrate choice, potentially enabling the use of flexible and opaque substrates, and the narrow-bandgap subcell can be deposited first, which can improve stability; however, it may also have higher series resistance and lower shunt resistance, and reflection losses can affect the performance.

According to Adolf and Uzorka (2025), a ground soil substrate achieves the highest efficiency on PV module performance of monocrystalline solar panels, at 21.1%, followed by grass (19.6%), wood (17.95%), concrete (16.2%), roof tiles (14.3%), and iron sheets (11.5%), and have found that substrates with lower thermal conductivity and higher albedo, like ground soil and grass, help the modules achieve higher efficiencies. The albedo effect, the measure of the reflectivity of a surface or material, or the ratio of reflected solar energy to the total incoming solar radiation, influences temperature and can have significant implications for solar panel efficiency and thermal management. Surfaces with a high albedo, like snow or white roofs, reflect more sunlight and absorb less heat, making them cooler. Conversely, surfaces with low albedo, such as asphalt or dark soil, absorb more sunlight, contributing to higher temperatures. Lower panel temperatures are critical for enhancing performance, while transpiration in natural substrates plays a significant role in heat dissipation, keeping panels cooler and improving efficiency during peak sunlight hours (Adolf and Uzorka, 2025; Kahana, 2025B).

A manufacturing and deposition process developed by Jeong et al. (2025) involves coating a polyimide layer onto a glass substrate, fabricating the perovskite-CIGS tandem solar cell on top of it, and then separating it from the glass. This method allows for more stable fabrication of the solar cells and more uniform layer deposition by utilizing the rigid glass as a supporting base, leading to improved device performance and higher reproducibility, as opposed to other methods that use flexible polyimide film directly as the substrate. Potassium diffusion from the glass substrate into the CIGS light-absorbing layer is avoided, which can create defects in the CIGS absorber, by coating the glass substrate with a polyimide layer (Jeong et al., 2025; Bellini, 2025Z).

ICO layers are particularly attractive for solar cell manufacturing due to their opto-electrical properties and room temperature deposition over indium tin oxide (ITO) counterparts (Özkol et al., 2025; Bellini, 2025). Özkol et al. (2025) developed a front-back contact silicon heterojunction (FBC-SHJ) solar cell with a transparent conductive oxide (TCO) based on cerium-doped indium oxide (ICO) with the aim of increasing the device's opto-electrical performance, using budget-friendly room temperature radio frequency (RF) sputtering (Özkol et al., 2025; Bellini, 2025).

Bellini,Emiliano (2025) PV Magazine, Heterojunction solar cell based on cerium-doped indium oxide TCO achieves 23.58% efficiency,

<https://www.pv-magazine.com/2025/05/20/heterojunction-solar-cell-based-on-cerium-doped-indium-oxide-tco-achieves-23-58-efficiency/?utm_source=Global+%7C+Newsletter&utm_campaign=612693e927-dailynl_gl&utm_medium=email&utm_term=0_6916ce32b6-612693e927-160603208>

Özkol, E., Magalhães, M.M.R., Zhao, Y., et al. (2025) Optimization and integration of room temperature RF sputtered ICO as TCO layers in high-performance SHJ solar cells, Solar Energy Materials and Solar Cells, Volume 288, 113637, <https://doi.org/10.1016/j.solmat.2025.113637>

**Perovskite Precursors**

Precursor selection (Park, 2020; Lee et al., 2019A; Yuan et al., 2024; Zhao et al., 2023)

Crystallization kinetics (Lu et al., 2020; Wu et al., 2024)

Film morphology ()

Film quality (Ma et al., 2023A; Ma et al., 2022B)

The properties of the precursor solution, including its concentration, solvent choice, and purity, significantly influence the final quality of the perovskite film, including optical and electrical properties, and thus the performance of the solar cell. When the precursor solution is deposited and heated, the chemical components react and rearrange to form the desired perovskite crystal structure. In the context of a solar cell, a "precursor" refers to a chemical compound that is used as a starting material to create the active material within the cell, usually a perovskite material, which then undergoes a reaction to form the final crystalline structure needed for efficient light absorption and charge generation; essentially, it's the initial chemical compound that is transformed into the desired material within the solar cell through a chemical process.

For perovskite solar cells (PSCs), common precursors include inorganic lead-based metal halide salts (like or ) and organic halide salts (like methylammonium iodide or formamidinium iodide ), which are dissolved in a protic, polar solvent to form a precursor solution before being deposited onto the solar cell substrate to form the perovskite film (Kim et al., 2012; Shin et al., 2020). Other metal halides include tin halides and bismuth halides, other organic salts include ethylammonium iodide

, and other inorganic salts include cesium iodide . A polar protic solvents is characterized by the presence of an acidic hydrogen atom that can act as a hydrogen bond donor, and examples include water , alcohols (methanol, ethanol), ammonia (NH₃), and carboxylic acids (acetic acid). The perovskite precursor solution is prepared by dissolving the metal halide salt and organic salt in the appropriate solvent. Protic, polar solvents like dimethylformamide , dimethyl sulfoxide , and N,N-dimethylacetamide are commonly used to dissolve the precursor materials. However, there is research into green solvents, such as ethanol.

The precise stoichiometric ratios of the precursor components are crucial for achieving high-efficiency PSCs and must be carefully controlled. The composition and crystallinity of the perovskite film is determined by the ratio of to , , or , and this ratio can be manipulated to improve cell performance. However, an imbalance in this ratio can also lead to the formation of undesired phases or defects (Kang et al., 2022). Zhang and Park (2024) note that when the precursor solution contains excess , a -rich phase within the perovskite film can form which can act as a passivation layer, potentially improving the film’s optoelectronic properties by reducing surface recombination. However, an incomplete conversion to the perovskite phase can result from too much , leading to degraded film quality and device inefficiency. There is also the ratio possibility of increasing the proportions of or , potentially leading to the creation of perovskite films with better coverage and reduced pinhole density. However, non-perovskite phases can form from too much Iodide, which affects film stability and efficiency.

To address the purity of the precursor materials and the balance of the stoichiometric ratio, Zhang and Park (2024) experimented with the purification of pre-synthesized perovskite microcrystal powders via crystallization, to serve as the precursors for perovskite film, using ambient-temperature stable δ-phase powder synthesized from low-grade (purity <99%) and FAI. Since α-phase needs a high temperature of over 150 °C, aqueous synthesis of δ-phase at room temperature is a cost-effective way for mass production of precursor material. The significant reduction of ions, the major impurity, decreased carrier trap states and greatly improved device performance and stability.

In evaluating the relationship between the molecular weight of the quenching gas and the morphology of perovskite films used in solar cells, including effects on perovskite film grain-size, crystallinity, surface roughness, and defects, researchers have found that argon and helium extend device lifetimes compared to using the more conventional nitrogen. Nitrogen is typically used as a low cost and large area compatible way of creating proper crystallization of the perovskite layer. However, in this experiment, perovskite films quenched with helium, as the lightest gas, and argon, as the heaviest, had larger grain sizes and were “very stable” under operational conditions compared to a device processed by nitrogen gas, which had a smaller grain size (Hadipour, 2025; Thompson, 2025I).

They introduced polyacrylic acid (PAA) into the inorganic CsPbI3 precursors consisting of CsI, PbI2 and DMAI. During the formation of CsPbI3 the PAA could form the hydrogen bonds with DMA, which accelerates the decomposition of DMAPbI3 and DMA extraction. The PAA-added sample exhibited relatively faster phase transformation and achieved the high-quality CsPbI3 film with no DMA residue. Systematic experimental and theoretical investigations revealed that the hydrogen bonding facilitated the DMA extraction by lowering the escaping energy barrier. DMAPbI3 (dimethylammonium [DMA]) or "HPbI3"-assisted crystallization is effective for the preparation of high-quality β- or γ-phase CsPbI3 films, but it unfortunately causes DMAPbI3 residue and the degradation of photovoltaic performance and stability (Li et al., 2023B; Bellini, 2023C, Jia, 2023).

When screen-printing flexible perovskite solar cells (f-PSCs), the defective and fragile contact at the buried interface seriously which restricts device performance must be accounted for. Herein, a series of siloxane coupling agents (SCAs) with different ending groups i.e., –SH, –NH2, and –CN were incorporated at the SnO2/perovskite interface, which can selectively interact with MA+ and Pb2+ via hydrogen and coordination bonding, respectively. It was revealed that the selection of (3-Cyanopropyl)Triethoxysilane (CN-PTES) can regulate perovskite crystallization with accelerated nucleation and retarded crystal growth, leading to improved crystallinity with released residual lattice strain. Moreover, the incorporated CN-PTES aligned the energy structure of the underlying SnO2 and boosted the interfacial adhesion between perovskite and SnO2, resulting in facilitated electron extraction and enhanced interfacial fracture energy. Consequently, the first screen-printed f-PSCs with improved mechanical resistance were finally obtained (Duan et al., 2025).

Duan, M., Yang, J., Li, T. et al. (2025) Mechanically stable screen-printed flexible perovskite solar cells via selective self-assembled siloxane coupling agents, npj Flex Electron 9, 30, <https://doi.org/10.1038/s41528-025-00407-6>

**Lead Free Perovskites**

Perovskite devices are more sustainable to produce than silicon-based solar cells, and when tin is used instead of toxic lead, we get cells that are home and human friendly. Tin halide perovskite (THP) solar cells are being explored due to their potential for improved stability and to avoid lead toxicity concerns. Sn-based perovskite has similar properties to lead-based perovskite, however, their photovoltaic performance is considerably lower than that of lead-based perovskite, due to the oxidation of Sn2+ to form Sn4+.

Because of lead toxicity issues, there is an imperative to find lead-free perovskite materials with comparable performance to lead-based perovskites. However, the PCE of tin-based devices is poor (PCE ~13%) (Cao and Yan, 2021). In perovskite-perovskite tandems, the low band gap perovskites typically incorporate tin, which reacts rapidly with oxygen, presenting stability issues. Lead-free perovskites exhibit lower efficiency and have stability issues when compared to lead-based perovskites.

Alternatives to lead perovskite solar cells include: tin (Sn), germanium (Ge), bismuth (Bi), antimony (Sb), silver (Ag), and copper (Cu). These elements can potentially maintain the perovskite crystal structure while offering lower toxicity levels, however, they face challenges regarding stability and achieving comparable efficiency to lead-based perovskites. Tin (Sn) is often considered the most promising replacement due to its similar chemical properties to lead, but shows instability under ambient conditions. Germanium (Ge) is a good candidate for its suitable bandgap, but has low stability and high cost. Bismuth (Bi) offers good stability and lower toxicity, but its efficiency is currently lower than lead-based perovskites. Antimony (Sb) shows promise for high stability and good optoelectronic properties. Tin and germanium are in the same column as lead in the periodic table and therefore share the same electron coordination number in their outer shells. Tin even has a similar ionic size to lead.

Research directions to improve lead-free perovskites include compositional engineering, surface passivation, and device architecture optimization. Compositional engineering involves exploring different combinations of cations and anions to optimize the optoelectronic properties of lead-free perovskites. Surface passivation involves utilizing surface treatments to enhance stability and prevent degradation. Device architecture optimization involves modifying the device structure to improve charge carrier collection and transport in lead-free perovskites.

Methylammonium tin iodide (CH3NH3SnI3) could be used to replace lead due to its narrower band gap, eco-friendliness, wider visible absorption spectrum, and excellent mobility (Ahmad et al., 2022). However, Sn is also toxic and is not stable in its 2+ oxidation state as it can readily oxidize to 4+ upon exposure to moisture or oxygen (leading to a severe self-doping mechanism, which decreases carrier lifetimes) (Leijtens et al., 2015).

The crystalline silicon photovoltaics industry is moving toward Pb-free soldering[[1]](#footnote-0) due to the mounting pressure from the European Union's RoHS2 directive,[[2]](#footnote-1) which states that the maximum concentration for the value of lead tolerated by weight in homogeneous electronic materials is 0.1%. Unfortunately the concentration is >10 wt% for the most effective photovoltaic devices based on perovskites demonstrated so far (Abate, 2017).

From the perspective of cost, developing monolithic tandem cells is potentially more valuable. However, one main limitation for relatively low PCE of perovskite monolithic tandem solar cells comes from the poor semiconducting properties of Sn-based narrow-bandgap (NBG) perovskites. Till now, Sn substitution in Pb-perovskites is the only approach to reduce the bandgap to as narrow as 1.20 eV. However, compared to Pb-perovskites, Sn-containing NBG perovskites are reported to have higher trap density of states (tDOS) (Chung et al., 2012), shorter carrier recombination lifetime (Ma et al., 2016), larger Urbach energy (Yang et al., 2017), higher background carrier concentration due to oxidization of Sn2+ ions (Nowel et al., 2014), resulting in a high VOC deficit, and lower absorption coefficient in near infrared region (Yang et al., 2017) and low short-circuit current density (JSC). The smaller absorption coefficient in near infrared region than in visible range in Sn containing NBG perovskites makes the problem even worse, because a much thicker perovskite film is needed to fully absorb the infrared part of sunlight.

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**Lead Halide Perovskites**

CaTiO3 (calcium titanate), a true perovskite mineral, is a non-halide perovskite. Methylammonium lead triiodide CH3NH3PbI3 is a common example of a halide perovskite, or a more complex one like (Cex, Fa+1-x)Pb(Iy, Br1-y)3. German researchers concluded that only lead perovskites can achieve high efficiencies, as opposed to non-toxic, lead-free alternatives (Jowett, 2024B). Lead halide perovskites are an optoelectronic material that show potential for solar cells and electronic devices due to their properties and low-cost fabrication, but their long-term stability is a problem because the ions inside can move around, known as ion migration, which negatively affects their performance (Liang et al., 2025; Foley, 2025). Lead halide perovskites are composed of halide anions, organic cations (usually MA or FA), and lead cations. Lead halide perovskites have a direct band gap and its density of state is much larger than that of gallium arsenide (GaAs), which correlates to a high light absorption coefficient. They also show high defect-tolerance, which means they tend to form shallow traps rather than deep traps, leading to a high open circuit voltage (Tao, 2022). Pb-based perovskites have high defect-tolerance to reduce recombination loss, high absorption coefficient, and high charge carrier mobility. Lead-based perovskites have toxicity concerns induced by the irreversible degradation of Pb2+, though the release of lead into the environment can be minimized by properly encapsulating the PSC device or module.

Leaded gasoline has been removed from the market as lead is a cause of neurological, reproductive, and physical disorders such as memory or learning problems in adults and children, reduced fertility in men, miscarriages or stillbirths in women, along with general mood disorders, and digestive issues. However, lead is used in perovskite cells due to some of its fundamental atomic characteristics, such as large ionic size and a coordination number of six. Perovskites require elements with a specific electron coordination number in the B position of the ABX3 structure to maintain the octahedra of halides. Due to the size of most of the organic molecules used in the A positions, having a large B component is beneficial to make sure there is enough room in the crystal for the A components. If lead has to be used in perovskite cells we must prevent the lead from entering the environment via proper encapsulation of the solar cells. After designing an effective solar cell encapsulation, methods must also be implemented to capture any lead that might get released should the cell or panel get damaged enough to breach the encapsulation.[[3]](#footnote-2)

Excellent Optoelectronic Properties: Lead perovskites are semiconductors with a range of desirable characteristics for optoelectronic devices:

Tunable band gaps: Their absorption and emission energies can be varied, spanning the UV-visible to near-infrared regions.

High absorption coefficients: They efficiently absorb sunlight.

Low exciton binding energies: This allows for easy separation of electron-hole pairs, crucial for efficient charge generation in solar cells.

Long exciton diffusion lengths: Charges can travel further before recombining.

High dielectric constants.

High defect tolerance: Unlike many other semiconductors (like silicon), lead perovskites can still function well even with imperfections in their crystal structure.

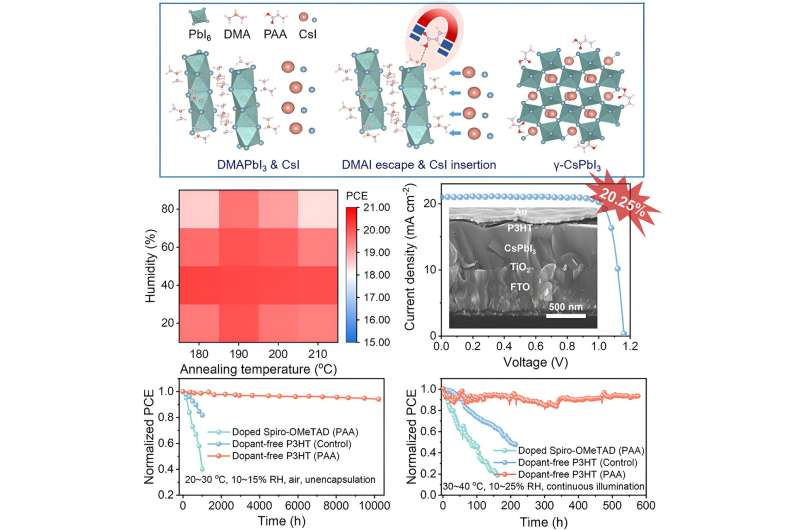
**Methylammonium Lead Triiodide CH3NH3PbI3, MAPbI3**

**Formamidinium Lead Triiodide CH(NH2)2PbI3, FAPbI3**

As an absorber, formamidinium lead triiodide (FAPbI3) possesses desirable photovoltaic properties, low cost, and thermal stability, but has challenges in crystallization kinetics quality and thermodynamic metastability at room temperature. While alloying strategies such as adding methylammonium hydrochloride and Cs+ can effectively control the crystallization process and photoelectric properties of formamidinium-based perovskites films, it may leave behind residual compositional additives that often lead to cation-anion separation, thermal decomposition and potential nucleophilic reactions, complicating the preparation of high quality, non-alloyed α-FAPbI3 perovskite films. An iodine intercalation-decalation strategy can be used to produce high-quality, nonalloyed α-FAPbI3 perovskite films. The strong bonding between cogenetic iodine (I2) and I− forms polyiodide ions, which changes the original FAI+PbI2→FAPbI3 reaction path to FAI3+PbI2→FAPbI3+I2, which is conducive to overcoming the barrier in α-FAPbI3 formation. Furthermore, owing to its volatility property, I2 is removed from the lattice during annealing, ensuring the absence of any extrinsic residue on the high-quality, nonalloyed α-FAPbI3 film. The nonalloyed α-FAPbI3 film produced from the iodine intercalation-decalation reaction demonstrates a substantial improvement in the crystal quality and uniformity, while enhanced thermal stability of the film inhibits ion migration (Zhang et al., 2025B; Peking University, 2025).

**Black Perovskite, Inorganic Cesium Lead Triiodide () Perovskite**

Cesium-lead iodide (CsPbI3) perovskite, also known as black perovskite, was used as the absorber material by Li et al. (2023B) in an inorganic solar cell with a dopant-free hole transport layer based on the P3HT polymer which utilzied a hydrogen-bonding-facilitated DMA extraction strategy. This perovskite material has an energy bandgap of approximately 1.7 eV and, according to several scientists, is an ideal solution for single-junction and wide-band-gap sub-cells in tandem PV devices (Li et al., 2023B; Bellini, 2023C, Jia, 2023).



*Image: Credit: Li, M.H., Wang, S., Ma, X., et al.,* *Joule (2023). DOI: 10.1016/j.joule.2023.09.009*

[*https://www.cell.com/joule/pdfExtended/S2542-4351(23)00399-9*](https://www.cell.com/joule/pdfExtended/S2542-4351(23)00399-9)

<https://phys.org/news/2023-11-stable-efficient-inorganic-cspbi3-solar.html>

**Cesium Lead Bromide (CsPbBr3)**

A common all-inorganic lead perovskite, particularly favored for its high photoluminescence quantum yield and stability, making it excellent for LEDs and display applications.

**Mixed-halide perovskites (e.g., MAPbI3−x​Brx​ or CsPb(Brx​I1−x​)3​)**

By mixing different halide anions (I, Br, Cl), the bandgap and emission color can be precisely tuned, allowing for optimization in various optoelectronic devices.

**Mixed-cation perovskites (e.g., (FAx​MA1−x​)PbI3​ or (Csx​FA1−x​)PbI3​)**

Combining organic and inorganic cations can further enhance stability and tailor properties for specific applications.

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Table 1. Additives in absorber layer of PSC (Khatoon et al., 2023A)[[4]](#footnote-3)

| **Additive in PSC** | **Composition** | **Efficiency (%)** | **Voc (V)** | **Jsc(mA/cm2)** | **FF (%)** | **Stability** |
| --- | --- | --- | --- | --- | --- | --- |
| Sm3+ | FTO/c-TiO2/m-TiO2/  CsPb0.97Sm0.03Br3/carbon  (Duan et al., 2018) | 10.14 | 1.594 | 7.48 | 85.1 | 90% eff remains @80% RH & 25◦C without encapsulation for 110d |
| Eu | FTO/c-TiO2/m-TiO2/CsPb1-xEuxI2Br/  Spiro-OMeTAD/Au  (Xiang et al., 2018) | 13.71 | 1.22 | 14.63 | 76.6 | 93% eff remains after 370 hr |
| KI | FTO/C-TiO2/m-TiO2/  (CsFAMA)Pb(I0.85Br0.15)3/Au  (Abdi-Jalebi et al., 2018) | 21.5 | 1.17 | 23.2 | 73 | Over 80% of initial PCE after 300 h under  continuous operation at MPPT |
| NaF | ITO/CsMAFAPb(IBr)3/  Spiro-OMeTAD/Au  (Li et al., 2019A) | 21.92 | 1.126 | 24.23 | 80.35 | 90% eff remains after 1000 h without encapsulation at MPP |
| ZnCl2 | FTO/C-TiO2/ MAI(PbI2)1 − x(ZnCl2)x/  spiro-OMeTAD/Au  (Jin et al., 2017) | 18.2 | 1.09 | 22.04 | 75.76 | 93% eff remains after 3o days in ambient env |
| PCBSD | ITO/PEDOT:PSS/MAPbI3/PC61BM/  Bphen/Ag  (Li et al., 2016C) | 17.21 | 0.98 | 22.81 | 77 | 84.6% of initial PCE after 720 h in  RH 40 ± 5% under dark |
| Caffeine | (Wang et al., 2019) | 19.87 | 1.134 | 22.77 | 76.9 | 1300 hr @ 85◦C |
| Thiourea | FTO/-TiO2/m-TiO2/MAPbI3/  Spiro-OMeTAD/Au  (Fei et al., 2017) | 18.46 | 1.1 | 22.49 | 75 | 85% initial eff after 1200 h under dark |
| bis-PCBM + BrPh-ThR | FTO/c-TiO2/m-TiO2/(FAI)0.81(PbI2)0.85  (MABr)0.15(PbBr2)0.15/spiro-OMeTAD/Au  (Zhang et al., 2018D) | 21.7 | 1.12 | 23.93 | 78 | 93% of initial PCE after 3600 h with RH10–20% at 20–25 °C |
| SP3 | FTO/c-TiO2/m-TiO2/MAPbI3/  spiro-OMeTAD/Au  (Wu et al., 2019) | 20.43 | 1.146 | 22.88 | 78.55 | 86% of initial PCE after 720 h with RH 30% under dark) |
| PVP | ITO/SnO2/MAPbI3/spiro-OMeTAD/Au  (Zuo et al., 2017) | 20.2 | 1.15 | 21.74 | 80.9 | 85% of initial PCE after 2500 h under dark of RH 25–40% |
| ZnP | FTO/c-TiO2/m-TiO2/MAPbI3/Co (II)- and Co (III)-based porphyrins/Au  (Li et al., 2019B) | 18.26 | 1.09 | 22.64 | 73.66 | 90% of initial PCE after 1000 hwith RH 45% at 85 °C |
| Butylphosphonic acid  4-ammonium chloride(4-ABPACl) | FTO/c-TiO2/MAPbI3/spiro-OMeTAD/Au  (Li et al., 2015A) | 16.55 | 1 | 22.05 | 75 | Over 80% of initial PCE after 360 h at 85 °C under dark |
| alkylamine ligands (AALs) | ITO/PTAA/CSFAMA/C-60/BCP/Cu  (Zheng et al., 2020A) | 23 | 1.17 | 24.1 | 81.6 | 1000 h at MPP at 1.5G illumination without any loss in efficiency |
| PEAI | ITO/SnO2/FAMAPbI3/PEAI/spiro-OMeTAD/Au  (Jiang et al., 2019) | 23.32 | 1.18 | 24.9 | 81.4 | 500 h stability at 85 °C |
| 6-aminoquinoline monohydrochloride (AQCl) | Cs0.05(MA0.12FA0.88)0.95Pb (I0⋅88Br0.12)3  (Zhang et al., 2021) | 21.66 | 1.18 | 22.74 | 80.73 | – |
| 2-hydroxyethyl methacrylate (HEMA) | CsPbI2Br  (Fu et al., 2021) | 16.13 | 1.23 | 15.81 | 82.98 | PCE of 16.13% and could retain 78% of its initial efficiency after 1000 h (RH of 30%). |
| 1-propionate-4-amino-1,2,4-triazolium tetrafluoroborate (PATMBF4) | Cs0.05(FA0.85MA0.15)0.95Pb (I0.85Br0.15)  (Li et al., 2021B) | 21.35 | 1.11 | 23.74 | 81.02 | PCE can sustain over 85% after exposure to air for 4000 h with a relative humidity of 40 ± 5% |

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**Perovskite Additive Engineering**

Additive engineering for solar cells encompasses solvents, functional additives, facets engineering, dopants, and interface engineering. Solvent selection influences the wettability of the substrate, precursor dissolution, and evaporation rate during the process (Chao et al., 2021; Cao et al., 2019). Functional additives can be used to modify the properties of the perovskite crystals (Bai et al., 2022), including the orientation and homogeneity of the perovskite films (Ma et al., 2022A; Ma et al., 2022B). Dopants are a type of additive that can be used to modify the electronic properties of perovskite films (Lee et al., 2022A). Interface regulation is a device architecture optimization technique, along with inverted cell structures.

Here we report a reactive surface engineering approach based on a simple post-growth treatment of 3-(aminomethyl)pyridine (3-APy) on top of a perovskite thin film. First, the 3-APy molecule selectively reacts with surface formamidinium ions, reducing perovskite surface roughness and surface potential fluctuations associated with surface steps and terraces. Second, the reaction product on the perovskite surface decreases the formation energy of charged iodine vacancies, leading to effective n-type doping with a reduced work function in the surface region (Jiang et al., 2022).

Jiang, Q. et al. (2022) Surface reaction for efficient and stable inverted perovskite solar cells. Nature 611, 278–283

Other Additives:

Tartaric Acid: Can be added to the precursor solution to modulate crystal growth and improve charge transport.

Aminoacetamide Hydrochloride (AAH): Can be added to the precursor to increase the processing window and facilitate the fabrication of high-quality perovskite films.

N-Acetyl-L-Cysteine (NALC): Can be used as a reductive agent to stabilize the precursor solution and improve device stability

Additive engineering (Zhang and Zhu, 2020)

Additive engineering (Ma et al., 2023B; McMeekin et al., 2023; Tan et al., 2023; Ding et al., 2024; Zhang and Park, 2023)

Here we report a synergistic dopant-additive combination strategy using methylammonium chloride (MACl) as the dopant and a Lewis-basic ionic-liquid additive, 1,3-bis(cyanomethyl)imidazolium chloride ([Bcmim]Cl). This strategy effectively inhibits the degradation of the perovskite precursor solution (PPS), suppresses the aggregation of MACl and results in phase-homogeneous and stable perovskite films with high crystallinity and fewer defects (Ding et al., 2024).

Carbonyl functional materials as additives are extensively applied to reduce the defects density of the perovskite film (Jiang et al., 2023)

***Solvents***

Chao, L., Niu, T., Gao, W., et al. (2021) Solvent Engineering of the Precursor Solution toward Large-Area Production of Perovskite Solar Cells. Adv. Mater., 33, 2005410. <https://doi.org/10.1002/adma.202005410>

In perovskite solar panels, dimethylformamide (DMF) is commonly used as a solvent to dissolve the perovskite precursor materials, allowing for the creation of a smooth and uniform perovskite film during the fabrication process; however, due to its potential toxicity, researchers are actively exploring alternative solvents with less harmful properties while still achieving high solar cell efficiency. DMF's high polarity enables it to effectively dissolve lead halide salts, which are key components of perovskite materials, allowing for the formation of a solution that can be deposited onto the solar cell substrate using techniques like spin-coating. The choice of solvent, like DMF, significantly impacts the morphology of the resulting perovskite film, with proper solvent selection leading to well-crystallized and uniform films with minimal defects. Researchers are actively exploring alternative solvents like gamma-butyrolactone (GBL) and dimethyl sulfoxide (DMSO) to potentially mitigate the toxicity issues associated with DMF while maintaining high solar cell performance.

Among the various polar solvents commonly used, such as dimethyl sulfoxide (DMSO), dimethylformamide (DMF), γ-butyrolactone, N-methyl-2-pyrrolidone, tetrahydrofuran, dimethylacetamide, only DMSO was evaluated as a non-toxic green solvent by measuring disability-adjusted life years (Vidal et al., 2021; Park, 2021). A method was reported for synthesizing stable α-FAPbI3 that is insensitive to temperature and humidity variations and compatible with large-scale fabrication. This method involves utilizing a vertically aligned PbI2 thin film grown from an ionic liquid green solvent, methylammonium formate. This kind of PbI2 film facilitates the rapid infiltration and full reaction of FAI through its nanoscale ionic channels to form α-FAPbI3. Environmentally benign biomass-derived green solvents, specifically γ-valerolactone (GVL) and n-butyl acetate, were reported98. Compared to traditional reagents (DMF and DMSO) that might cause instability of FA+ in the precursor, GVL not only exhibits a strong interaction with FA+, stabilizing it and promoting the formation of high-valence [PbIx]2–x complexes (Hui et al., 2021).

The annual production of DMSO is ~100,000 tons. Industrial-grade DMSO costs approximately 1 USD per kilogram. For 3500 L (3.85 tons), the cost would be ~3850 USD. When scaled to the overall cost of producing 1 GW of solar capacity, this represents a minor fraction of the total production costs. Therefore, eco-friendly and low-cost fabrication of PSCs should primarily focus on DMSO as the main solvent, or alternatively, efforts should be made to develop more green solvents for the preparation of high-quality perovskite thin films (Yun et al., 2022; Chen et al., 2022A; Hui et al., 2021; Miao et al., 2023).

Water has been established as a suitable solvent in forming 4-terminal CsPbBr3 perovskite solar cells based on the appropriateness of its donor number and dielectric constant, two important characteristics for solvents, but also has shortcomings at the level of film quality and device performance. Using density functional theory (DFT) calculations and Tyndall effect analysis, Shao et al. (2025) have developed a dual-solvent engineering strategy incorporating N-dimethylformamide (DMF) as a co-solvent along with water. Screen printing was used to fabricate the all-inorganic carbon-based mesoscopic perovskite solar cells (Shao et al., 2025; Thompson, 2025O).

It was reported that highly crystalline, highly oriented, and scalable smooth thin films were fabricated under ambient conditions at room temperature by utilizing a high-concentration precursor solution and low-boiling point solvents such as a 10% w/w mixture solvent of methylamine in ACN (Dou et al., 2018).

Solvent engineering was also employed to modulate perovskite crystallization and interface quality. Particularly, the conventional precursor solvents of N, N-dimethylformamide (DMF) and dimethyl sulfoxide (DMSO) were likely remained within the perovskite films on account of their strong coordination with PbI2. Accordingly, the substitution of the DMSO by n-methylpyrrolidone or n-Butanol, which manifested weaker coordination ability with PbI2, leading to the ease of solvent evaporation and high crystal quality at the buried interface (Huang et al., 2024; Wang et al., 2021; Zheng et al., 2024).

Huang, C. et al. Meniscus-modulated blade coating enables high-quality α-phase formamidinium lead triiodide crystals and efficient perovskite minimodules. Joule 8, 1–15 (2024).

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***Functional Additives***

Additives are used in small quantities to improve the efficiency and stability of the perovskite solar cell. Zhang and Park (2024) showed that additives being capable of hydrogen bonding with iodide species in precursor solution lead to the creation of polyhedral single crystals with distinct facets (Ma et al., 2022B), and that facets with different atomic densities exert a significant influence on the chemical and electronic environments of the perovskite surface, consequently affecting the performance of the final device. For instance, the (100) and (111) facets exhibited comparable carrier mobility and photocurrent, both of which were notably superior to the (110) facet. By increasing the proportion of both (100) and (111) facets among all facets, the corresponding PSC demonstrated a quasi-steady-state PCE as high as 24.6%. Furthermore, the moisture stability of perovskite crystals was discovered to strongly depend on the perovskite facets (Ma et al., 2023A).

In terms of the homogeneity of perovskite composition across the layer, FA-rich composition was formed on the perovskite film surface, while Cs-rich composition was dominant at the bottom of the film (Liang et al., 2023). This inhomogeneity is one of the origins of instability and lower efficiency in PSCs. 1-(phenylsulfonyl)pyrrole was developed as an additive to homogenize cation distribution within the perovskite films, where the difference in crystallization kinetics and phase transition kinetics between FA cation and Cs cation was overcome.

During thermal annealing of 3D perovskites, the encapsulated DMSO leaves the bulk film, causing dissolution and recrystallization. This process, balanced by DMSO evaporation, leads to crystal volume collapse and voids at grain boundaries. The use of amidino-based Dion-Jacobson 2-dimensional (2D) perovskite assists in the nucleation and growth of 3D perovskite, reducing voids and bulk defects in the film. This results in efficient charge transport and significantly improved stability.

Furthermore, additive engineering can be extended to the Sn-Pb alloyed perovskite, where the utilization of the narrow bandgap Sn-Pb perovskite can replace crystalline Si to make a perovskite-perovskite tandem solar cell. However, unlike the single lead ion, nonuniform nucleation and rapid crystallization are often observed in this binary system, which impedes film quality and overall device performance. By introducing aminoacetamide hydrochloride (AAH) into the precursor, the processing window was significantly increased from 10 s to 100 s, thereby facilitating the easier fabrication of high-quality perovskite films without pinholes (Gao et al., 2024). AAH was found to be primarily distributed at the bottom interface of the final perovskite film, serving the additional function of passivating the buried interface.

It should be emphasized that the additive engineering discussed above can be extended not only to the preparation of Sn-Pb perovskites but also to other types of perovskites in general, such as Pb-free, wide-bandgap, and 2-dimensional (2D) perovskites.

Using pyrrodiazole (PZ) as an additive in formamidinium iodide (FAI)-based inverted perovskite solar cells enables larger area devices made with industry-compatible slot die coating and allows the scalable preparation of homogeneous structure perovskite films via regulating the crystallization process of perovskite through immobilizing strategy. Yuan et al. (2025) noted that both lead iodide (PbI2) and formamidinium iodide (FAI) benefitted from the PZ immobilization strategy, enabling the formation of high-quality perovskite films for the cells. The immobilization effect, driven by the formation of Lewis acid-base pairs (PZ-PbI2) and hydrogen bonds (PZ-FAI), not only improves the colloidal size distribution uniformity in the perovskite precursor solution but also enhances the stability of the wet film by inhibiting colloid agglomeration (Yuan et al., 2025; Thompson, 2025J).

***Facets Engineering***

In the context of solar cells, "facets" refer to the different flat surfaces or crystal planes that make up the crystal structure of a semiconductor material, like perovskite, within the cell, and the specific arrangement of these facets can significantly impact the solar cell's efficiency and stability due to their varying electronic and physical properties depending on their atomic arrangement; essentially, different facets interact with light and charge carriers differently, allowing for targeted manipulation to optimize solar cell performance through "facet engineering.”

Different crystal facets have distinct atomic arrangements, leading to varied electronic properties like carrier mobility and defect density. By selectively passivating specific facets through facet-dependent passivation, with appropriate materials, researchers can improve the performance of solar cells by addressing potential recombination sites. Facet engineering is particularly important in perovskite solar cells due to their complex crystal structure and the potential for tuning the facet distribution to enhance efficiency and stability. Some frequently studied facets in perovskite solar cells include (100), (111), and (110), each with unique characteristics regarding charge carrier transport and stability. By controlling crystal growth, researchers can promote the formation of desired facets on the perovskite film, maximizing desirable properties. In interface engineering, heterojunctions are created between different facets with tailored electronic properties, which can improve charge carrier separation and collection. Passivation strategies include applying specific materials to selectively passivate certain facets, which can mitigate charge recombination at the surface.

***Dopants***

By incorporating dopants into the perovskite, α-phase perovskite can be stabilized (Lu et al., 2020), strain can be regulated (Kim et al., 2020B), ion migration is able to be mitigated (Zhao et al., 2022; Chen et al., 2022B), defects can be passivated (Chen et al., 2022B; Jeong et al., 2021), and thereby the overall stability of the materials and PSCs can be enhanced (Lee et al., 2022A; Zhao et al., 2022; Jeong et al., 2021). For instance, the black α-phase of often suffers from its intrinsic instability at room temperature due to transition into the inactive non-perovskite yellow δ-phase. Consequently, stabilization of the α-phase at ambient conditions is critical and can be possible by doping. A method utilizing vapour-assisted doping with formamidinium thiocyanate or methylammonium thiocyanate containing ions has been reported to effectively facilitate the conversion of the yellow phase to the black phase (Lu et al., 2020). The presence of ions in the perovskite is helpful to maintain the long-term stability of the generated black phase perovskite.

To further maximize the performance of PSCs, anion engineering was proposed. Formate () as a pseudo-halide anion was investigated (Jeong et al., 2021), where it was found that the presence of formate suppresses common anion vacancy defects at the grain boundaries and surfaces of the perovskite films.

**Perovskite Deposition Techniques for Large-Area Fabrication**

Parashar, M., Singh, R., and Shukla, V.K. (2021) Fabrication of perovskite solar cells in ambient conditions, Materials Today: Proceedings, Volume 34, Part 3, Pages 654-657, <https://doi.org/10.1016/j.matpr.2020.03.182>

Mass production of perovskites (Lee et al., 2019B; Chao et al., 2021; Zhang et al., 2024A; Kim et al., 2020C)

We are aware that while scaling up in the area, the efficiency of the lab-scale devices decreases at a very high rate (1.4 × 10−2% cm−2) in comparison to crystalline silicon technology (1.7 × 10−4% cm−2) and other thin-film technologies (4 × 10−3 % cm−2) (Lee et al., 2018A; Khatoon et al. 2023A).

Processing costs can be reduced in perovskite cells because they align and join multiple layers without requiring the high energy costs of thermal diffusion or high vacuum of ion implantation doping of a silicon cell.[[5]](#footnote-4)

Producing uniform, high-performance perovskite material in a large-scale manufacturing environment is difficult, and there is a substantial difference in small-area cell efficiency and large-area module efficiency. While the methods used to produce the best lab-scale perovskite devices are not easy to scale up, there are significant efforts to apply scalable approaches to perovskite fabrication. For thin-film technologies, these can be split into two major production types: If high-efficiency, durable perovskite modules can be made reliably using either of these scalable fabrication approaches, they have the potential to scale rapidly because existing knowledge and supply chains could be leveraged. Achieving uniform and consistent film quality across large areas is crucial for high efficiency and scalability. Selecting suitable and compatible materials for charge transport layers and electrodes that are compatible with the perovskite layer is important. Ensuring consistent and uniform film quality and device performance across large areas during large-scale production. Additionally, the choice of solvents presents a certain level of complexity, as different large-area deposition methods typically require distinct solvent combinations. Therefore, the introduction of various deposition techniques is usually accompanied by the optimization of solvent selection.

Flexible perovskite cells can be printed on long continuous rolls of flexible plastic film, where the solar films are thin, lightweight, portable and semi-transparent, making them suitable for various applications including construction, space, defence, mining, emergency management, disaster relief, and wearables. For example, printed PV films can be laminated onto windows or other glazing or incorporated into tents or sails for recreational or emergency purposes (Foley, 2024B).

As for the manufacturing process for tandem cells, it starts with silicon wafers, and the wafers pass through a series of chambers resembling conjoined refrigerators. Inside, clouds of ions build up layers of the cell in a process called physical vapor deposition. It’s slower than solution-based methods, but produces extremely high-quality films. A similar process creates the perovskite cell (Peplow, 2023).

***2 Major Production Types for Halide Perovskite Cells***

1. Sheet-to-Sheet: Device layers are deposited on a rigid base, which typically acts as the front surface of the completed solar module. This approach is commonly used in the cadmium telluride (CdTe) thin-film industry. Sheet-to-Sheet: Device layers are deposited on a rigid base, which typically acts as either the front or rear surface of the completed solar module. This approach is commonly used in the cadmium telluride (CdTe) thin-film industry.
2. Roll-to-Roll: Device layers are deposited on a flexible base, which can then be used as either an interior or exterior portion of the completed module. Researchers have tried this approach for other PV technologies, but roll-to-roll processing did not gain commercial traction because of the performance limitations of these technologies. However, it is widely used to produce photographic and chemical film and paper products such as newspapers. Roll-to-Roll: Device layers are deposited on a flexible base, which can then be used as either an interior or exterior portion of the completed module. Researchers have previously tried this approach for other thin-film PV technologies, but roll-to-roll processing did not gain commercial traction because of the performance limitations of these technologies and the need for additional rigid encapsulation layers to ensure multi-decadal lifetimes. However, the roll-to-roll approach is widely used to produce photographic and chemical film and paper products such as newspapers. Cost-effective and high-speed roll-to-roll (R2R) fabrication methods are regarded as the key deposition technique. These methods require accurate control over the formation of the intermediate phase and their conversion into the perovskite structure (Li et al., 2021A; Park and Zhu, 2020; Kim et al., 2021). fPSCs are lightweight, bendable, and suitable for roll-to-roll industrial production and can be integrated easily over any surface (Mishra et al., 2021). Considered a leading method for large-scale production as it enables continuous deposition of the perovskite layer on a flexible substrate, significantly increasing production speed and lowering costs. Investigating novel fabrication techniques like roll-to-roll processing for flexible perovskite modules. R2R gravure printing is highly scalable and flexible but struggles with uniformity and solvent control, limiting PCE due to film defects and crystallization issues. Blade coating is simple and cost-effective, yet maintaining uniform film quality and environmental sensitivity can hinder performance. To overcome the challenges encountered, a short processing window and uneven crystallization, a green antisolvent combination consisting of tert-butyl alcohol and ethyl acetate (EA) was introduced into R2R-compatible gravure printing with specific printing patterns. This solvent blend was found to improve the perovskite processing window, facilitating the deposition of uniform and high-crystalline films without PbI2 traces (Kim et al., 2020C). A German company has created roll-to-roll product lines for flexible organic, perovskite, and dye-sensitized solar cells (DSSC) technologies, with working web widths of up to 1,000 mm, as well as a smaller tool for sheet-to-sheet setups used. There are 20 modules available for coating,including gravure, doctor blade, slot die coating, rotary screen, curtain coating, and screenprinting. Drying choices include hot air, infrared, UV crosslinking, and jet drying. They also want to integrate inline laser scribing and quality control systems within the roll-to-roll process, for use in an automated module assembly line (Thompson, 2024F).

Wet chemical methods involve solution processing under ambient conditions, while gas phase methods utilize vacuum processes. Many methods also involve heating to crystallize the perovskite and remove solvents. Printing methods: Exploring inkjet printing or screen printing for precise pattern deposition and potential for high-throughput manufacturing. mass production of perovskite solar cells, the most promising methods include solution-based deposition techniques like spin coating, blade coating, slot-die coating, spray coating, and particularly roll-to-roll processing which allows for continuous production on flexible substrates, alongside other methods like screen printing and inkjet printing, depending on the desired level of precision and throughput needed for large-scale manufacturing; all aiming to achieve high-quality perovskite films while maintaining cost-effectiveness.

**Wet Chemical Methods (Solution Processing)**

Generally, films fabricated using solution process methods are associated with pinholes and cracks, which decrease the shunt resistance resulting in leakage current (Boro et al., 2022). Solution-based deposition: Utilizing techniques like spin coating, blade coating, or slot-die coating to deposit the perovskite film on substrates, enabling large-area coverage and uniform thickness. This is preferred due to its potential for low cost and scalability, where a liquid precursor solution containing the perovskite materials is deposited onto a substrate using various techniques. Optimizing solution-based deposition methods like spin coating, spray coating, and blade coating for large-scale production.

1. Spin coating: A rapid and cost-effective method where a substrate is rapidly spun while a precursor ink is applied. This allows for the creation of thin films with controlled thickness. Spin coating: A common method for laboratory-scale production, where the precursor solution is spun on a substrate to create a thin film, but may not be as suitable for large-area manufacturing. Usually, the perovskite layer is spin-coated on the substrate via either a single-step or two-step process. In the single-step process, perovskite precursor (a mixture of dissolved in DMF:DMSO) is spin-coated onto the FTO substrate in one step and kept at 1000 C to achieve a uniform perovskite film. In recent times, an anti-solvent method is effective, in which the perovskite precursor solution is prepared in the polar solvent and quenched during the process of spin coating by a non-polar solvent. It is often observed that precise control over the volume of quenching solvent and timing is very much essential to achieve uniform morphology and optimal device performance. In the two-step process, lead iodide was the first to be spin-coated and then transferred into a vessel where 1 molar CH3NH3I was dissolved in isopropanol. Other than these two frequently used methods, organic-inorganic hybrid perovskites (OIHPs) can also be deposited via a ‘vacuum-assisted solution process’ (VASP) in which perovskite films are coated and annealed in a chamber filled with the organic component vapor (Mohamad et al., 2021). Spin coating faces scalability issues due to limited throughput.
2. Blade coating: A blade is used to spread a chemical solution on a substrate, forming a wet thin film. This method can be adapted for roll-to-roll manufacturing, similar to newspaper printing, and is more efficient than spin coating in terms of ink usage. Blade coating: A more scalable method where a blade is used to spread the perovskite precursor solution across the substrate, offering better control over film thickness compared to spin coating. The Me-4PACZ film was coated on the NiOx film surface with blade coating in air. “After that, the prepared perovskite precursor solution with different concentrations of additives were deposited in air by slot-die coating technology (Yuan et al., 2025; Thompson, 2025J).
3. Slot-die coating: A reservoir supplies the precursor ink, which is then applied over the substrate. This method is well-suited for roll-to-roll manufacturing due to its better reproducibility when the ink is well-developed. Slot-die coating: A precise method for depositing uniform films by dispensing the precursor solution through a narrow slit. Slot-die coating offers high throughput and precision but requires costly equipment and precise solution viscosity management, with defect formation and drying dynamics as key PCE limits. South Korean researchers have proposed slot die coating (SDC) to make uniform high-quality perovskite films as a step towards large-area perovskite device manufacturing, as SDC increased the roughness of the hole transport layer (HTL) interface, which improved the wettability of the surface, enabling a high-quality perovskite film without bubbles or pinholes. Self-assembled monolayer (SAM), such as Me-4PACz are excellent materials for the HTL in perovskite solar cells, but they have poor wettability, which has slowed progress so far. Using a nickel oxide (NiOx) and Me-4PACz combination, the researchers found that the use of SDC improved the roughness of the HTL interface, resulting in improved wettability. The SDC-based NiOx/Me-4PACz hole transport layer suppressed energy losses at the HTL/perovskite interface (Sangale et al., 2024; Thompson, 2024I).
4. Ink-jet printing: Small nozzles disperse the precursor ink onto the substrate, a technique used to create small-scale solar cells, but its scalability for large-area production depends on printing speed and device structure. Inkjet printing: Offers high precision and potential for complex patterns by precisely depositing small droplets of the perovskite precursor solution onto the substrate. German and Indian researchers have developed an inkjet printing method to fabricate formamidinium tin-lead (SN-Pb) perovskite solar cells, achieving 10.26% power conversion efficiency and a 1.25 eV energy bandgap, meaning it can narrow the bandgap subcell of all-perovskite tandem solar cells. Inkjet-printing was chosen for the combinatorial mixed formamidinium tin-lead (Sn-Pb) film due to its “flexibility in design” and ability to “precisely adjust the crystallization properties of organohalogen perovskite layers,” in addition to a high degree of control. Inkjet-printing is also considered to be a high-throughput manufacturing methodology as opposed to spin coating, which has enabled high-performing lab-sized devices but lacks the scaling potential. Further research is to develop large-area inkjet printed tin-lead perovskite solar cells and finally to integrate them as bottom cells in all-perovskite tandem solar cells (Tara et al., 2024; Thompson, 2024E).
5. Spray coating: A spray nozzle deposits the perovskite material onto the substrate. Spray coating: A method where the precursor solution is sprayed onto the substrate, allowing for large-area deposition and potential for flexible substrate applications. Spray coating is versatile and scalable but faces challenges in achieving uniform coverage and environmental sensitivity, affecting PCE through particle size and film defects. This mixture allows the high-concentration solution to rapidly transition into a supersaturated state, enabling the rapid preparation of a high-quality . High-speed in situ XRD monitoring demonstrates that the precursor film can rapidly crystallize within one second at room temperature, achieving a relative crystallinity of over 98%. The method is compatible with various deposition techniques, including blade coating (PCE of 19.6%) (Fig. 6d) and slot-die coating (PCE of 17.3%) (Fig. 6e). Spray-coating is also regarded as an alternative deposition technology, which can be applied to various substrate materials with micro-scale roughness. For instance, CsPbI2Br was prepared by ultrasonic-assisted spray coating (Fig. 6f) (Lee et al., 2022B) where other components or layers were also tried to deposit via spray coating. Recently, a detachable, reassemblable tandem perovskite/silicon solar cell has been reported. This modular cell incorporates a spray-coated single-walled carbon nanotube film between the top perovskite cell and the bottom silicon cell. This advancement not only simplifies the assembly, disassembly, and maintenance of the tandem solar cell but also effectively addresses the issue of resource wastage caused by mismatched lifetimes of the top and bottom cells (Zhang et al., 2024B).
6. Drop casting: A droplet of the precursor solution is deposited onto the substrate and then dried.
7. Sol-gel method: A two-step process where a solution of perovskite precursors is coated onto a substrate, followed by heating to remove the solvent and form a perovskite film. This method offers advantages like low reaction temperatures, precise composition control, and suitability for large-area applications.

**Gas Phase Methods (Vacuum Processes)**

1. Chemical Vapor Deposition (CVD): A vaporized precursor is deposited onto a substrate in a vacuum chamber.
2. Thermal Vapor Deposition: Material is heated and evaporated, then condensed onto the substrate.
3. Physical Vapor Deposition (PVD): Includes sputtering and evaporation, which can be used to deposit thin films with specific properties. To construct this electrode, the IIT team employed a technique called low-energy physical vapor deposition. In this process, materials are vaporized in a vacuum chamber and then condensed onto a surface, forming thin, uniform layers (Rani et al., 2025).
4. Atomic Layer Deposition (ALD): A layer-by-layer deposition process that can be used to create highly precise and uniform films.
5. Castro-Méndez et al. (2025) have found a way to make spiro-OMeTAD, a popular perovskite solar cell hole transport layer, less prone to heat-induced crystallization. They used vapor phase infiltration (VPI) to embed titanium oxide/hydroxide (TiOx) into spiro-OMeTAD, a typical organic HTL material, to make the film more resilient to heat, and in turn more stable. VPI is a deposition technique related to atomic layer deposition (ALD) that can form organic-inorganic hybrid materials with unique properties. The researchers observed that the perovskite layer in a PSC stack can endure temperatures as high as 120 C, but the spiro-OMeTAD HTL may start crystallizing after multiple heating cycles at only 70 C (Castro-Méndez et al., 2023; Thompson, 2025M).

**Other Techniques**

1. Electrodeposition: A process where the perovskite material is deposited onto a substrate using an electric current.
2. Screen printing: A printing method where a stencil is used to deposit the perovskite material onto the substrate. Copper metallization methods to avoid using silver for tandem silicon-perovskite cells compatible with either TOPCon or heterojunction bottom cells include screen printing, FlexTrail printing and rotary printing (flexographic printing and indirect gravure printing) (Thompson, 2024B). Screen printing: A relatively low-cost method for depositing thick perovskite films by using a screen with a desired pattern to transfer the ink onto the substrate.
3. Vacuum deposition: Includes methods like co-evaporation, where two or more materials are evaporated simultaneously onto the substrate
4. Optimized annealing process: Developing thermal annealing profiles to achieve high-quality perovskite crystallization with minimal energy consumption. Passivation is when defects are controlled, or modulated, in the deposition process through annealing, or heat treating the device, in a hydrogen-containing atmosphere (Wang et al., 2025C; Carroll, 2025).
5. LIDE technology, a two-step process that creates deep structures in thin glass with a high aspect ratio in the range of over 1:10 at a high processing speed, can be used with glass stencils in a low temperature metallization process to produce ultra-fine line metal contact fingers for solar cells, which can lead to reduced front-side shading in solar cells (Schweigstill et al., 2024; Bellini, 2025E). LIDE technology, a two-step process that creates deep structures in thin glass with a high aspect ratio in the range of over 1:10 at a high processing speed, can be used with glass stencils in a low temperature metallization process to produce ultra-fine line metal contact fingers for solar cells, which can lead to reduced front-side shading in solar cells. Finger width has decreased from 120 μm in 2005 to less than 20 μm in 2024. This process allows for the production of dot- or line-shaped structures down to 5 μm and less. In their experiment, Schweigstill et al. (2024) used the LIDE technique to initially modify a 400 μm thick sheet of 10 cm x 10 cm AF 32 eco glass, and then used wet chemical etching to remove the laser-modified glass at a faster rate than the unmodified areas, which resulted in highly precise microstructures. A lasering process was then used to structure the glass for the opening of the final aperture channel at the opposite side of the glass foil (Schweigstill et al., 2024; Bellini, 2025E).
6. In gettering, the impurities are initially released into a solid solution, then undergo diffusion through the silicon, and then they are trapped in an area away from the active circuit regions of the wafer. Gettering is already embedded in most of the current solar cells, through phosphorus diffusion in PERC or PERx devices, as well as in Al-BSF cells. It is also embedded in TOPCon solar cells, although its effectiveness varies a lot, and in silicon heterojunction cells it can be used as a pre-treatment to improve the quality of silicon substrates (Kamphues et al., 2025; Bellini, 2025O).
7. A lift-off process has been developed for tandem cells that involves coating a polyimide layer (flexible plastic) onto a rigid glass substrate, fabricating the perovskite-CIGS tandem solar cell on top of it, and then separating the glass from the final flexible solar cell. The new cell consists of a top layer of perovskite and a bottom based on copper, indium, gallium and diselenide (CIGS) technology. Conventional methods use flexible polyimide film directly as the substrate. The use of a flat, rigid glass substrate also ensures uniform layer deposition, leading to improved device performance and higher reproducibility. Potassium diffusion from the glass substrate into the CIGS light-absorbing layer, which introduces defects into the CIGS absorber, is avoided with this method (Jeong et al., 2025; McFadden, 2025).

**Solar Cell Grading**

Our main focus is to design and propose tandem solar cell devices in perovskite/perovskite and perovskite-silicon configurations with high efficiency and stability, including linear and parabolic grading strategies in the cell devices. "linear and parabolic grading strategies" refer to methods of varying the composition or properties of materials within a cell's layers to optimize performance and stability, such as by using a linear or parabolic distribution of a material or property. Grading refers to intentionally creating a gradient or variation in the properties of a material or layer within a cell device. Instead of having uniform properties across the entire layer, grading allows for a controlled change in properties, often to match the requirements of different regions or functions within the cell. This can be achieved by varying the composition of the material or by modifying other parameters like bandgap or doping levels. Linear grading involves a gradual, straight-line change in material properties or composition across a layer. Parabolic grading Involves a curved, parabolic change in material properties or composition across a layer. These grading strategies are often used to optimize the performance of solar cells by improving the efficiency and stability. For example, in perovskite solar cells, researchers have used linear and parabolic grading to enhance efficiency and stability. According to pv magazine International, "Our main focus is to design and propose tandem solar cell devices in perovskite/perovskite and perovskite-silicon configurations with high efficiency and stability, including linear and parabolic grading strategies in the cell devices,”. By optimizing the distribution of materials and properties, grading can lead to better charge transport and absorption of light, resulting in higher efficiency. Grading can help reduce stress and improve the long-term stability of the device, which is crucial for practical applications. Grading allows for the design of devices with specific performance characteristics, such as optimized voltage or current output.

**Methods**

Zhao, D. et al. Low-bandgap mixed tin–lead iodide perovskite absorbers with long carrier lifetimes for all-perovskite tandem solar cells. Nat. Energy 2, 17018 (2017).

***Low-bandgap perovskite film preparation.***

The (FASnI3)0.6(MAPbI3)0.4 precursor solution was obtained by mixing stoichiometric amounts of FASnI3 and MAPbI3 perovskite precursors in mixed N,N-dimethylmethanamide (DMF)/dimethyl sulfoxide (DMSO). More details can be found in the Supplementary Methods. Different thicknesses of the (FASnI3)0.6(MAPbI3)0.4 layers were realized by varying the precursor concentration, leading to the approximate thickness of 400, 510, 620 and 1,010 nm. The (FASnI3)0.6(MAPbI3)0.4 precursors were spin-coated onto ITO/PEDOT:PSS at 5,000 r.p.m. for 60 s. Diethyl ether was applied to conduct solvent engineering. All perovskite films were annealed at 100 ∘C for 7 min. The samples for SEM and UV–Vis measurements were prepared on ITO/PEDOT:PSS and glass/PEDOT:PSS. The samples for TRPL were deposited on bare glass and covered by a 30-nm-thick film of poly(methyl methacrylate) (PMMA).

***Wide-bandgap perovskite film preparation.***

For 1.58 eV FA0.3MA0.7PbI3 perovskite, the precursor solution with 45 wt% concentration was prepared by dissolving PbI2, MAI, FAI and Pb(SCN)2 (molar ratio = 1:0.7:0.3:0.02) in a mixed DMF/DMSO (volume ratio = 9:1). The perovskite layer was fabricated by spin-coating 70 μl precursor solution on the substrate followed by quickly dripping 0.75 ml diethyl ether on the film. The resulting film was then annealed at 100 ∘C for 5 min.

***Device fabrication.***

For low-bandgap (1.25 eV) bottom cells, PEDOT:PSS films were coated on the pre-patterned and cleaned ITO substrates at 4,000 r.p.m. for 50 s and then dried at 175 ∘C for 30 min. The (FASnI3)0.6(MAPbI3)0.4 perovskite films were deposited by spin-coating onto PEDOT:PSS film at 5,000 r.p.m. for 60 s and annealed at 100 ∘C for 7 min. Finally, C60(20 nm)/BCP(5 nm)/Ag(75 nm) were sequentially deposited by thermal evaporation to complete the fabrication. Devices were encapsulated with cover glass and UV-curable epoxy. More details can be found in the Supplementary Methods.

For 1.58 eV semi-transparent top cells, the SnO2 ESLs were deposited onto pre-patterned and cleaned FTO substrates by plasma-enhanced atomic layer deposition (Ensure Scientific Group AutoALD-PE V2.0) following the process and treatment described in our earlier work2. A C60-SAM layer passivating the ESLs, FA0.3MA0.7PbI3 perovskite films, and spiro-OMeTAD as hole-selective layers were deposited following a previously reported method2. Finally, 10 nm MoOx, 8.5 nm Au and 10 nm MoOx were thermally evaporated sequentially through a patterned mask onto the hole-selective layers. The active area of each device ranged from 0.085 to 0.12 cm2 and was defined by a mask. More details can be found in the Supplementary Methods.

***Film and device characterization.***

High-resolution field emission top-view and cross-sectional SEM images of (FASnI3)0.6(MAPbI3)0.4 perovskite films with the thickness of 400, 510, 620 and 1,010 nm were taken with Hitachi S-4800. The crystal structure of different thick (FASnI3)0.6(MAPbI3)0.4 films was examined by X-ray diffraction (RigakuUltima III) with Cu Kα radiation under operation conditions of 40 kV and 44 mA excitation. The absorption spectra were measured by UV–Vis spectrophotometer (PerkinElmer Lambda 1050). All layer thicknesses were determined using a Dektak surface profiler and cross-sectional SEM images. TRPL measurements were conducted similarly as described in our earlier work2,16. Photoluminescence decay curves were biexponential in nature and fitted by iterative re-convolution with the measured system response function. Mean photo-generated carrier lifetimes (see Supplementary Table 3) for the biexponential fit are calculated by the weighted average method2. The Urbach energy was measured on the basis of the equation of

, where η(hν) is the EQE value and EUrbach is the Urbach energy37. J–V curves were measured in air under 100 mW cm−2 AM1.5G solar irradiation (PV Measurements) with a Keithley 2400 Source Meter. The incident light was controlled by a shutter. The light intensity for J–V measurements was calibrated by a standard Si solar cell and our perovskite solar cells certified by Newport. The steady-state efficiencies were obtained by tracking the maximum output power point. EQE spectra were performed from 300 to 1,150 nm on a QE system (PV Measurements, model IVQE8-C QE system without bias voltage). All characterizations and measurements were performed in the ambient. One of our (FASnI3)0.6(MAPbI3)0.4 devices was sent to an accredited PV laboratory of Newport Corporation for PCE certification. More details can be found in the Supplementary Methods.

***4-terminal tandem cell measurements.***

The J–V curves of semi-transparent top cells were measured in air under 100 mW cm−2 AM1.5G solar irradiation, and their steady-state efficiency was obtained at the maximum power point for over a period of 100 s. EQE spectra were performed on a QE system. The top cell with an active area of 0.10 cm2 as defined by the mask and the bottom cell with a masked area of 0.105 cm2 are measured, separately. Each semi-transparent wide-bandgap top-cell sample consists of multiple subcells with small and large active areas as defined by the areas of the metal electrodes. The small subcells have similar active areas as the bottom cells and are used for J–V measurements. The large subcells are used to filter the bottom cells for easy cell alignment. The J–V curves, steady-state efficiency, and EQE spectrum of 1.25 eV bottom cells were taken by putting such a semi-transparent wide-bandgap top cell with a large active area on top as a filter.

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