

Innovation To Industry: Roadblocks In Perovskite Solar Cell Commercialization

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Abstract - Perovskite solar cells (PSCs) have emerged as a promising technology for future energy solutions, demonstrating high power conversion efficiencies and cost-effectiveness. However, the transition from laboratory innovation to commercial viability faces several critical challenges. This review examines the key roadblocks hindering PSC commercialization and explores potential solutions. The primary obstacles include scaling up perovskite technologies, developing industry-compatible manufacturing processes, and selecting appropriate functional materials and solvents for mass production. Additionally, the stability of cells and modules remains a crucial concern, with special attention needed to identify specific aspects differentiating module stability from individual cell stability. Environmental considerations, particularly lead toxicity, also pose significant challenges to widespread adoption. To address these issues, researchers are exploring various strategies, including the use of plasmonic nanostructures to enhance photovoltaic performance, application-driven development approaches, and the implementation of graphene-based composites to improve stability. Furthermore, advanced techniques such as machine learning and autonomous experimentation are being employed to accelerate PSC screening, development, and stability testing. As the field progresses, a comprehensive approach addressing efficiency, stability, and cost – the 'golden triangle' parameters – will be crucial for overcoming the distinct contradictions impeding rapid commercialization

Keywords: - Perovskite solar cells, Solar energy commercialization, Photovoltaic technology, Renewable energy barriers, Solar cell efficiency, Manufacturing scalability

I. INTRODUCTION

Perovskite solar cells have emerged as a promising technology in the field of photovoltaics, offering the potential for high efficiency, low-cost production, and versatile applications. Since their introduction in 2009, these devices have demonstrated rapid progress in laboratory settings, with power conversion efficiencies now comparable to those of established silicon-based solar cells. However, the transition from innovative research to large-scale commercial production has been impeded by several critical challenges. This paper examines the key obstacles hindering the commercialization of perovskite solar cells, focusing on three primary areas: material stability, manufacturing scalability, and economic viability. We analyze the current state of perovskite technology, highlighting recent advancements and persistent issues in each of these domains. Additionally, we explore the environmental and regulatory considerations that influence the industry-wide adoption of perovskite solar cells. By identifying and discussing these obstacles, we aim to provide a comprehensive overview of the challenges facing perovskite solar cell commercialization. This analysis will serve as a valuable resource for researchers, industry professionals, and policymakers working towards the successful integration of perovskite technology into the global solar energy market. Understanding these challenges is crucial for developing targeted solutions and strategies to accelerate the transition of perovskite solar cells from laboratory innovation to commercial viability.

Although their widespread commercial use is currently hampered by concerns regarding long-term stability issues, a perovskite solar cell is a type of photovoltaic device that uses a special material called a "perovskite" as its light-absorbing layer, capable of converting sunlight into electricity with high efficiency due of their unique crystal structure [1-14].



Fig 1: Perovskite Solar Cell

II. METHODOLOGY

(1) Device Configurations And Performance

PSCs have a layered device structure that includes a glass substrate coated with transparent conductive oxide (TCO), an n-type semiconductor as the electron-transport layer (ETL), a perovskite absorber layer, a p-type semiconductor as the hole-transport layer (HTL), and a back-contact (metal, TCO, or carbon) (Fig. 1B). The perovskite absorber sensitizes a mesoporous metal oxide layer (e.g., meso-TiO₂) employed as a scaffold in mesoscopic PSCs established following dye-sensitized solar cell studies (3,8). The perovskite layer is sandwiched between a planar ETL [e.g., compact TiO₂ (c-TiO₂), SnO₂, or C₆₀ and its variants] and an HTL [e.g., poly (3, 4-ethylenedioxythiophene)-poly(styrene-sulfonate) (PEDOT:PSS)]. (9-12). Depending on the sequence of depositing the ETL and HTL, the structure can be split into formal (conventional) or inverted designs. Notably, the design and manufacture of inverted devices is not a simple reversal of the formal device structure, and the two device topologies often necessitate the systematic construction of acceptable ETLs and HTLs, particularly given the limitations in the suitability of processing solvents. The perovskite in triple mesoscopic PSCs is deposited on a three-layer scaffold composed of a screen-printed mesoporous TiO₂ layer, a ZrO₂ spacer layer, and a carbon electrode. Such devices employ carbon electrode store place than noble metal back-contacts and do not require a hole-conducting layer.

The potential of PSCs as a top-cell for constructing tandem solar cells with other PV devices, such as silicon, copper indium gallium selenide (CIGS), and low-bandgap perovskites, has been reviewed elsewhere. Collaboration with current mature PV technologies not only increases efficiency beyond the Shockley-Queasier limit of single-junction devices but also offers access to established market channels.

Figure (2) summarizes the progress in the efficiency of single-junction PSCs. Spin coating is generally used to deposit the perovskite layer and charge-transporting layers in small-area lab cells (<1.0 cm²). Enlarging the device area using existing fabrication processes for PSC modules reduces the PCE of all device architectures. Screen printing, slot-die coating, spray coating, and soft-cover coating technologies have been developed to produce intermediate-sized PSC modules measuring tens of square centimetres. Alternative processing procedures must be investigated in order to achieve large-area homogenous films and efficient resource consumption.

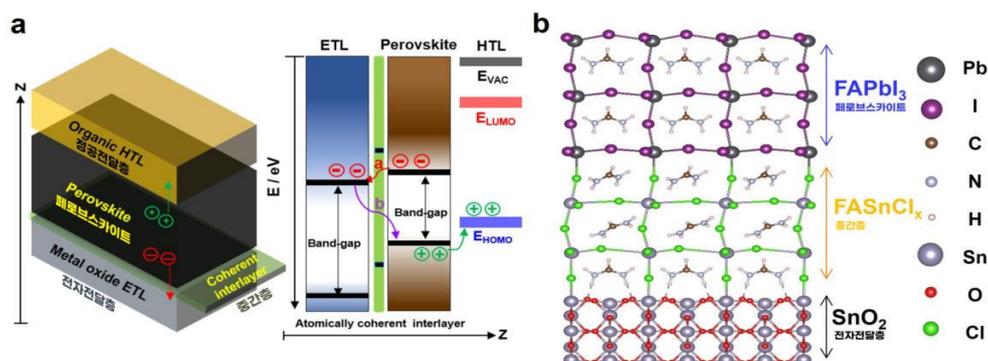


Fig 2: Single Junction PSCs

(2) Stability of PSC

Scalable manufacture of efficient PSMs is crucial for commercialization. The crucial aspect for this approach is the creation of pinhole-free and homogenous large-area perovskite film, which demands precision processing techniques. Spin coating is the most commonly used technique for small-area PSCs due to its ability to deposit high-quality perovskite films with defined thicknesses and compositions, resulting in efficient PSMs with a certified PCE of 22.87% (active area, 24.63 cm²). However, this approach is limited to the substrate size and waste of 90% of perovskite ink, and it is particularly unsuitable for high-throughput roll-to-roll (R2R) or sheet-to-sheet (S2S) manufacturing processes. The vacuum evaporation deposition approach may deposit perovskite films up to 600 cm². However, the high cost of large-scale vacuum equipment may limit commercialization of perovskite photovoltaics, resulting in fewer reports of PSMs derived from this process.

Scalable deposition technologies should be low-cost and compatible with high throughput production processes (R2R, S2S). Blade coating, slot-die coating, inkjet printing, and spray coating are promising alternatives for scalable manufacturing of perovskite films. Blade-coating is the most widely investigated process for creating large-area perovskite films, resulting in a high PCE of 20.4% (active area, 29.25 cm²) [29]. However, this approach has restrictions on substrate size as the film thickness gradually decreases along the coating direction due to non-continuous ink supply. Minimizing efficiency loss becomes difficult when the active area surpasses 30 cm². The slot-die coating method is similar to blade coating, but it overcomes the thickness variation issue because the slot diehead allows for continuous ink supply. PSMs using large-area film processes including inkjet printing, spray coating, and vacuum evaporation are slower. Inkjet printing is a non-contact manufacturing approach that can prepare patterned perovskite films. However, delayed drying of inkjet inks is necessary for high processing stability and sufficient nozzle open durations, posing a difficulty for film crystallization. Spray coating may quickly coat a large area of perovskite film. However, the ink droplets sprayed from the nozzle can overlap and impact the final film thickness and crystal quality. To conclusion, the slot die coating process will be the ideal contender for future scalable production of PSMs.

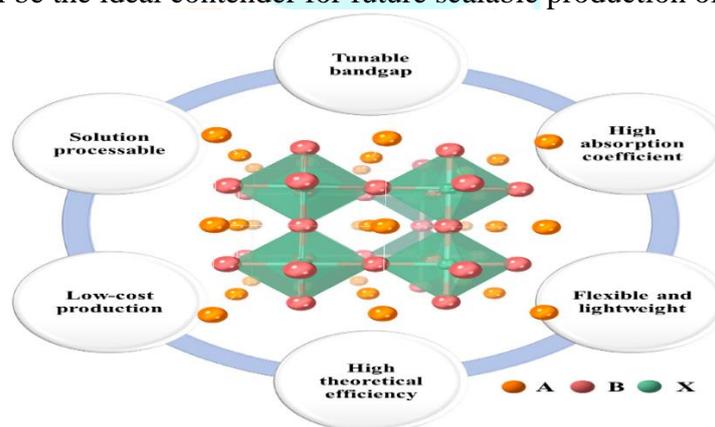


Fig:3 Stability Of PCS

(3) The Toxicity of Lead in PSCs

Lead toxicity in perovskite solar cells (PSCs) is a significant concern that poses challenges to their commercialization and widespread adoption. The water-soluble nature of lead-based perovskites increases the risk of lead leakage, which can have severe environmental and health consequences. Lead exposure can cause a range of adverse health effects, including blood lead poisoning, organ failure, nephrotoxicity, hepatotoxicity, neurotoxicity, and reproductive toxicity in humans and animals. Historical evidence shows that lead's toxic properties have been well-known for centuries, with symptoms such as abdominal colic, nausea, vomiting, constipation, and anaemia being documented in occupational settings. To address the toxicity issue in PSCs, researchers have developed various strategies. These include lead sequestration materials for encapsulation and functional layers, lead isolation-capture techniques, and the exploration of lead-free double perovskites (LFDPs) as alternative photoactive materials. Additionally, efforts are being made to establish recycling solutions and closed-loop lead management systems to promote sustainability and reduce environmental risks. While these approaches show promise in mitigating lead toxicity, continued research and development are crucial to ensure the safe and widespread deployment of perovskite photovoltaic technologies.

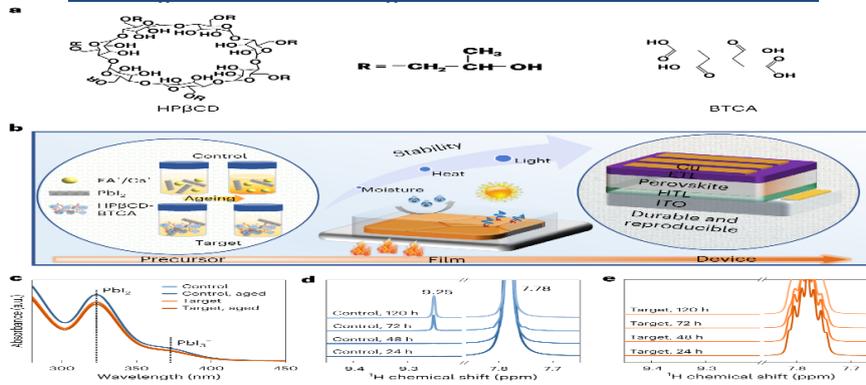


Fig:4 Supramolecular Shielding in PSCs

(4) Encapsulation of PSMs

Encapsulation of plant secondary metabolites (PSMs) is an important technique in the food and pharmaceutical industries. This process involves coating PSMs within inert materials to protect them from environmental factors and control their release. The encapsulation of PSMs can enhance their stability, specificity, and bioavailability, while also improving product quality and reducing production costs. Interestingly, the choice of encapsulation technique depends on the state of the core material (solid, liquid, or gaseous) and the desired properties of the final product. For instance, spray drying is the most commonly used encapsulation technique for food products, particularly for volatile compounds and oils. However, the encapsulation efficiency can be affected by various factors, including the properties of wall and core materials, emulsion preparation, and drying process conditions. In conclusion, encapsulation of PSMs offers numerous benefits, such as masking undesirable flavors, preserving unstable constituents, and enabling controlled release of ingredients. As research in this field continues to advance, future applications may include encapsulation of enzymes, microencapsulation of biosensors, and the development of novel technologies like self-assembly. The growing importance of encapsulation technology in the food industry suggests that it will remain a major focus of research and innovation in the coming years.

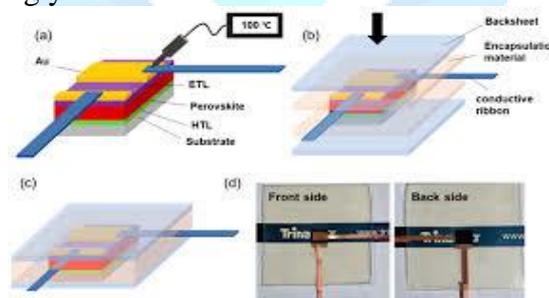


Fig:5 Encapsulation of Perovskite Solar cell

(5) Flexible Perovskite Solar Cells and Modules

Flexible perovskite solar cells (F-PSCs) have emerged as a promising alternative to conventional silicon solar cells, offering unique advantages such as lightweight design, bendability, and compatibility with roll-to-roll fabrication processes. These characteristics make F-PSCs particularly suitable for portable and wearable electronics, as well as integration with architectures and wearable electricity-generating devices. The efficiency of F-PSCs has seen remarkable progress, with power conversion efficiencies (PCEs) reaching up to 25.09% on flexible substrates and 26.1% on rigid substrates. Moreover, flexible perovskite solar modules have achieved impressive results, with a world record PCE of 16.43% for a device with a surface area of ~900 cm². This progress can be attributed to process optimization, the use of new transport materials, interface and compositional engineering, and passivation techniques. Interestingly, there are some contradictions in the reported efficiencies across different papers. For instance, Yang et al. (2023) reports PCEs of 23.73% for rigid substrates and 22.24% for flexible substrates, which are slightly lower than the values mentioned. Additionally, Meng et al. (2020) reports PCEs of 19.87% and 17.55% for effective areas of 1.01 cm² and 31.20 cm², respectively, highlighting the challenges in scaling up F-PSCs while maintaining high efficiency. In conclusion, F-PSCs and modules have shown tremendous potential for various applications, including wearable electronics, space energy systems, and multifunctional integrated buildings (Xu et al., 2023). However, challenges remain in terms of mechanical stability, scalability, and long-term performance. Ongoing research focuses on improving the flexibility and durability of these devices, with innovative approaches such as the use of dynamic

"ligaments" for self-healing properties (Yang et al., 2023) and the development of asymmetric π -extended self-assembled monolayers for enhanced interface quality (Tong et al., 2024). As the technology continues to advance, F-PSCs are poised to play a significant role in the commercialization of perovskite solar cells and the broader renewable energy landscape.

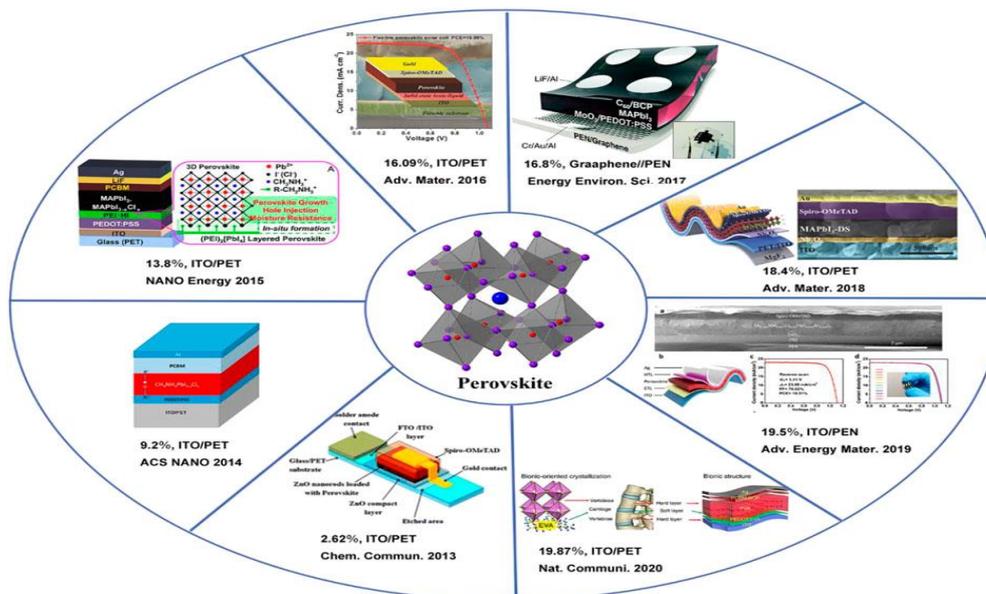


Fig:6 Flexible perovskite solar cells and modules

III. FUTURE PERSPECTIVES

In this system, we have systematically analyzed the current status, remaining challenges and promising directions towards commercialization for perovskite solar cells. PSCs have made remarkable achievements during the past few years begetting from the deeper understanding of the information process and increasingly mature fabrication techniques. Researcher have been focused on the transition from lab to fab for both academia and industry. Currently, perovskite solar cells are in the early stages of industrialization, with a growing number of start-ups and new-energy enterprises starting to deploy production lines. With capital continuously pouring it, the industry community and academia need to hold a rational attitude at this moment and speed up the fundamental research to sweep away the hurdles in the way of commercialization.

The ongoing development of upscaling performance is one of the most important elements influencing the commercialization of perovskite solar cells. As of right now, small-area PSCs with a PCE of over 26% are significantly more efficient than the majority of reported PSMs. PSMs that are more than 20% efficient typically have an area of less than 100 cm². Large-scale perovskite solar modules set a record of 19.9% with an active area of 810 cm², which is lower than the 24.4% of crystalline silicon modules at 13177 cm². The upscaling of PSCs is still a long way off. It is still difficult to produce repeatable and uniform large-area perovskite films, despite extensive research into perovskite inks with compositions suitable for large-scale manufacturing processes. Additionally, obtaining all device layers through fully scaled fabrication procedures is a major problem, and further research is still needed to determine the best processing methods for large-scale production.

For PSMs, operational stability is another unsolvable issue. Halide ions (such I⁻) from the perovskite layer can quickly degrade metal electrodes by direct contact in the P2scribe channels, aside from the susceptibility of perovskite materials to outside environments (including humidity, temperature, and light). Therefore, it is necessary to build suitable top electrodes. Effective internal and external encapsulation techniques must also be investigated in order to prevent lead leakage and degradation. It is also necessary to address migration or diffusion. Establishing a consistent characterization process is also important for appropriately evaluating the findings produced by various research groups from around the globe.

In addition to studies focusing on perovskite solar cells and modules, encapsulation is an important industrialization stage that shouldn't be overlooked because of its potent capacity to improve stability and prevent lead leakage. In general, perovskite device encapsulation technology has advanced quickly in recent years. An important milestone has been reached since it has made it possible for increasingly stable perovskite devices to go close to market standards. The encapsulation technology of perovskite devices still faces certain immature technological issues, nonetheless, such as large-scale, cost, and mechanism issues. Using advanced CVD, ALD, and other technologies are ways to address these issues. Additionally, encapsulation technology

can concentrate on additional perovskite device characteristics including flexibility, stretchability, heat dissipation, self-cleaning, and aesthetics, among others.

Even while crystalline Si solar cells continue to dominate the photovoltaic market today, there is increasing room for Si solar cells to become more affordable and more efficient. As a result, PSCs emerge as viable alternatives with significant upside potential. Despite its difficulties, we think PSCs have the potential to completely transform the solar energy sector and provide a viable route to a low-carbon, sustainable future with continued study and investment.

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