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Scalable Perovskite Solar Cells: Challenges Toward Commercial Deployment

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ABSTRACT

Perovskite solar cells (PSCs) have made a lot of progress in a short amount of time, showing that they have a lot of promise for low-cost, high-efficiency photovoltaics. These improvements have gone from a proof-of-concept (about 3.8% in 2009) to single-junction lab cells that go above 26% and tandem devices that go above 34% (certified records). But we still have to fix some big problems before we can use commercial technology on a large scale. One of the biggest problems is moving deposition processes from small lab equipment to large-area modules while making sure that the films stay the same and the devices work properly. It is also important to make sure that the system works well for long periods of time in a variety of difficult environmental conditions. People are worried about lead's toxicity, the possibility of lead leaking, and the best ways to handle lead when it is no longer needed. It is important to combine and protect modules in a way that makes them strong enough to handle real-world mechanical and thermal stresses. It is very important to find ways to make industrial goods that are cheap. This includes roll-to-roll, sheet-to-sheet, and vacuum-based processing, all of which must follow industrial standards and certification requirements.

1. Introduction

Since the first working perovskite-based solar cell was reported in 2009, the power conversion efficiency of perovskite solar cells (PSCs) has gone up more than ever before. Also, there has been a quick change in the types of devices and materials used [1,2]. Some of the properties of hybrid metal halide perovskites with a general ABX_2 structure are high absorption coefficients, long charge-carrier diffusion lengths, adjustable band gaps, and the ability to be processed in solution at low temperatures. These perovskites, such as $MAPbI_2$ (Methylammonium Lead Iodide) and $FAPbI_2$ (Formamidinium Lead Iodide), as well as mixed-cation perovskites, are very useful for next-generation photovoltaic applications [3–6].

Despite significant advancements in the lab, numerous engineering, environmental, and regulatory challenges persist, complicating the commercialization of PSCs [7–9]. Factors contributing to decreased efficiency in larger systems include non-uniform film, an increase in defects, edge losses, and challenges associated with module-level integration [10–14]. Nonetheless, significant challenges persist that complicate the certification process and long-term utilization [15].

Some of these problems are being sensitive to heat, moisture, oxygen, and UV radiation, as well as worries about lead poisoning. Other problems are worries about lead poisoning.

2. From Lab Cells to Module – Fabrication methods for scale

2.1 Small Area Fabrication vs Large Area Demands

Spin coating is the method used to make most high-efficiency photovoltaic solar cells (PSCs). It is done on substrates that are less than one square centimetre in size. This process takes place in a lab where all the conditions are carefully controlled. Even though it's easy to change the film's shape and thickness, this method isn't good for making things on a large scale. When a lot of things are being made or when they are being made all the time, some important parts of the process need to be watched. These include making crystals, getting rid of the solvent, making a smooth wet film, and stopping defects from spreading across large areas or moving substrates. Pinholes, changes in thickness, differences in grain size, and inconsistencies in series resistance are all common problems that happen during the scaling process. [21–23] The module isn't working right because so many things have happened.

2.2 Scalable Deposition Methods

To address the constraints of spin-coating, scalable deposition techniques including slot-die coating, blade coating, spray coating, inkjet printing, and roll-to-roll (R2R) processing have been extensively investigated [24–27]. These solution-based techniques provide high throughput and compatibility with flexible substrates; however, achieving uniform perovskite crystallization and film morphology across extensive areas continues to be difficult [28–30].

Vapor-based methods, like dual-source vacuum evaporation and all-vacuum processing, on the other hand, offer great film uniformity and compositional control, but they cost more to set up and run [31–33].

More and more, people think that hybrid manufacturing methods that combine solution processing with vacuum-deposited layers are good ways to make PSC on a large scale [34].

The choice between sheet-to-sheet and roll-to-roll manufacturing depends on the type of substrate, the amount of throughput needed, and how well the two methods work together. R2R processing is especially appealing for flexible modules because it could lower the cost of making each watt, as long as the devices last a long time and work reliably [35].

3. Key Technical Barrier in Scaling

3.1 Film Uniformity and Reproducibility

The application of a thick coating leads to uneven solvent evaporation, resulting in the formation of crystallization fronts. This may result in phase impurities and alterations in the grain size of the material [36–38]. Various approaches have been developed to enhance the size of processing windows and improve the reliability of results. These include solvent engineering, adding additives, processing without antisolvents, and controlled drying environments [39–41]. The strategies have been made to deal with the problems that have come up. Recently, using machine learning to improve processes has become a promising way to increase yield and consistency in making scalable perovskite solar cells [42].

3.2 Defects, Grain Boundaries, and Recombination at Scale

The role of defect density and grain-boundary chemistry is crucial in understanding non-radiative recombination losses, especially in large-area devices [43,44]. The introduction of mechanical strain and thermal gradients during the scale-up process can lead to the formation of trap states and hasten degradation. Strategies for passivation that utilize organic and inorganic salts, Lewis's acids and bases, grain-boundary modifiers, and interface engineering through self-assembled monolayers or two-dimensional perovskite layers are crucial for restoring open-circuit voltage and fill factor at the module level [45–48].

3.3 Module Interconnection and Laser Scribing

To connect sub-cells in series for monolithic module integration, precision laser scribing (P1–P2–P3) [49] is needed. There are a lot of big problems that need to be fixed, like cutting down on inactive zones, cutting down on resistance caused by scribing, and protecting nearby functioning layers from damage from heat or mechanical stress. To get reliable connections, you need to change the laser's wavelength, pulse duration, and energy density. This is especially true when you use new device stacks and flexible substrates [48,51].

3.4 Environment Stability during Manufacturing

The processing of ambient air has the potential to greatly enhance manufacturing throughput; however, it also subjects perovskite films to humidity and oxygen during the stages of deposition and crystallization [52]. Recent studies indicate that strong ink formulations and additive engineering facilitate ambient fabrication with satisfactory efficiencies; however, it remains essential to establish long-term stability under damp-heat and ultraviolet exposure to comply with industrial standards [53,54].

4. Operational Stability and Degradation Mechanisms

One of the biggest problems with PSC commercialization is that it is not stable enough to work. (Fig. 1.)Some ways that things break down are: moisture getting in, photo-oxidation caused by oxygen, thermal decomposition, ion migration, phase segregation, ultraviolet-induced interfacial reactions, and corrosion of metal electrodes [55–58]. The design of a device is very important because it controls the ways that things break down. The arrangement of functional layers has a direct impact on ion transport and interfacial stability. Also, mechanical and thermal stresses that happen during module manufacturing and long-term outdoor use often make these effects worse, which speeds up the decline in performance [59].

4.1 Encapsulation Strategies

Encapsulation is vital because it keeps heat and moisture out of perovskite solar cells (PSCs) modules, which can cause devices to break down faster. Changes in humidity and oxygen levels can have a big effect on the perovskite materials. Water can begin to tear down the perovskite layer. Photo-oxidation might get worse when there is light and oxygen. This highlights how crucial it is to employ strong encapsulation to protect bad things from getting to the device's active layers. Scientists have tried fitting things together in many ways to solve this challenge. Many people believe that glass-glass lamination is one of the greatest ways to do this because it keeps oxygen and moisture out quite well. Polymer edge seals with the glass encapsulation are typically employed to keep water out of the margin of the module, which gets the most sunlight. Resins that can be cured with UV light are easy to work with and cling to other objects well, which makes them useful for manufacturing a lot of things. Flexible perovskite modules function well with multilayer barrier films that comprise layers of both organic and inorganic materials [60-62].

Encapsulation is a very important way to deal with lead-based perovskites when it comes to safety and the environment. Encapsulation keeps things from getting inside the device and fixes problems at the same time. When there is simulated mechanical damage, like cracking, abrasion, or impact, and when the environment is bad, epoxy-based encapsulating materials have done a great job of keeping lead from leaking.

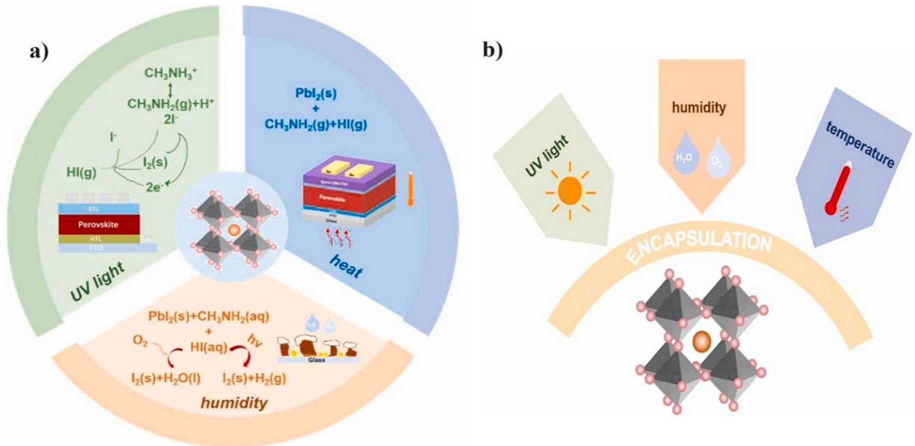

Fig. 1. a) Schematic illustration of the various instability factors in PSCs and their degradation pathways. b) Schematic illustrating the blocking of all degradation factors that contribute to the device stability.

Even with these changes, there are still a lot of things that need to be fixed. It's still hard to make a hermetic seal that lasts for decades, especially when the device goes through thermal cycling like it does in real life. The layers in perovskite devices and the materials around them have different thermal expansion coefficients, which could cause a lot of stress on the devices. This stress could break the barrier, make it weaker, or cause it to come off. We need to do more research to find materials and designs that are very strong, can handle heat, and don't let air or water in. This will make sure that PSC modules can be used safely for a long time [63,64].

4.2 Interface and Transport Layer Stability

The charge transport layers are very important for how well and how long perovskite solar cells last. Electron transport materials like TiO_2 and SnO_2, as well as hole transport layers like Spiro-OMeTAD (2,2',7,7'- tetrakis (N, N-di-p-methoxyphenylamine)-9,9' -spirobifluorene) and PTAA (Poly(triarylamine)), have a big effect on how well charge is extracted, how well it recombines at the interface, and how long the device lasts [65]. It is possible to speed up the degradation process through the use of photocatalytic activity, hygroscopic dopants, and interfacial reactions. In the course of accelerated aging tests, the development of dopant-free hole transport layers, low-temperature processed metal oxides, and interfacial passivation strategies has led to an increase in the operational lifetimes of products [66–68].

5. Lead Toxicity and Environmental Concerns

5.1 The Lead Problem

The use of lead-based perovskite absorbers raises environmental and regulatory concerns, particularly during large-scale manufacturing, module breakage, and end-of-life disposal [69]. These particular concerns are especially prevalent during the manufacturing process. Through proper encapsulation, lead leakage can be significantly reduced, as demonstrated by experimental studies that simulate the impact of hail and mechanical damage [70,71]. However, it is still difficult to completely eliminate the safety risk.

5.2 Strategies to mitigate Lead Risk

Advanced encapsulation, the incorporation of lead-sequestering layers, the chemical immobilization of released zinc ions, recycling protocols, and the development of lead-free perovskite alternatives such as tin-based and double perovskites are some of the mitigation strategies that have been implemented [72–75]. The continued progress of lead-free systems suggests that they have the potential for niche applications and future commercialization [76], despite the fact that they continue to be less efficient and stable.

6. Encapsulation, Module Design, and Reliability

Glass-glass rigid modules, flexible polymer-based modules, and semi-transparent architectures all have different design and reliability problems [77]. Flexible modules need very low water-vapor transmission rates to stay stable. Rigid modules, on the other hand, have better barrier properties. Standardized and perovskite-specific testing protocols [78–80] must be used to show how strong the material is mechanically. This strength must be shown when the temperature changes, the humidity freezes, and the ultraviolet light hits it.

7. Manufacturing: Roll-to-Roll, Sheet-to-Sheet, and Vacuum Lines

Using roll-to-roll manufacturing, it is possible to make flexible PSC modules at a low cost and with a high output. Slot-die coating with in-line drying, annealing, and encapsulation has worked well on a small scale. However, it is still hard to get both high efficiency and long-term stability at the same time [81,82]. Two methods that show how to make things more uniform and improve the efficiency of current infrastructure are sheet-to-sheet processing and vacuum-based deposition [31–33].

8. Techno-Economic and Life-Cycle Assessment Considerations

Techno-economic studies show that PSC modules could have a competitive levelized cost of electricity (LCOE) compared to crystalline silicon photovoltaics, as long as they have a long enough operational life and a high enough manufacturing yield [83,84]. Life-cycle assessments stress the importance of good lead management, recycling, and getting materials from sources that are good for the environment in order to follow the rules and have less of an impact on the environment [85].

9. Standard, Certification, and Market Acceptance

For commercial use, perovskite solar cell (PSC) modules must meet safety and performance standards that are widely accepted [86]. IEC 61215 and IEC 61730 are two of these standards. These standards make sure that the equipment is safe to use electrically and mechanically, and they also make sure that it will work for a long time, even when exposed to harsh conditions. To fix the problems with stability, ion migration, and environmental safety that are specific to perovskite technologies, these technologies need to be adapted to work with them. These technologies were first made for regular silicon solar panels. It is therefore necessary to comply with these standards in order to get PSC modules certified, accepted by the market, and sold on a large scale. Because perovskites degrade in different ways, new testing protocols are being developed to better measure ion migration, photo-induced phase segregation, and moisture sensitivity [87]. Clear reporting, third-party certification, and field testing that works will all be important for the market to accept [88].

10. Recent Industry Developments and Demonstrations

A lot of companies have shared pilot-scale production lines and proven efficiency records for perovskite and perovskite-silicon tandem devices [89–91]. Module-level efficiencies exceeding 20% and tandem efficiencies surpassing 30% demonstrate scalability potential; however, extended outdoor testing is essential to validate long-term reliability [92,93].

11. Roadmap toward Commercial Deployment

To improve commercialization, it is important to focus on strong encapsulation and lead-management strategies, the development of scalable and eco-friendly inks, advanced interface engineering for large-area devices, demonstrating durable roll-to-roll manufacturing lines, standardized accelerated aging protocols, and circular-economy methods for recycling and managing products at the end of their life.

12. Conclusions

Perovskite solar cells have rapidly transitioned from experimental stages to practical, scalable photovoltaic solutions. Recent advances in scalable deposition, encapsulation, and interface engineering have made it much easier for laboratory-scale devices to work with industrial modules. However, the long-lasting stability, safety for the environment, standardized certification, and low-cost production still present major problems. Ongoing collaborative research and strategic partnerships among academic institutions, industry stakeholders, and regulatory agencies are essential for realizing the commercial potential of scalable perovskite solar cells [3,7,35,85].

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