Research of technical approach for improving the stability of perovskite solar cells

Shiran Cheng [1, *], Huiming Mai [2] and Isaac He hao Lin [3]

[1] No.80 High school, Beijing, China

[2] School of Sing Chin Academy, Guangzhou, China

[3] Basis international school of Guangzhou, Guangzhou, China

* Corresponding Author Email: cshiran@sas.upenn.edu

Abstract. This paper examines the technical approach for enhancing the stability of pervoskite solar cells and suggests prospective solutions for efficiency increase. This is a working theory that is based on the structure of perovskite, experiments that can increase solar cell efficiency, such as accelerated aging tests, and methods to increase perovskite stability, such as encapsulation techniques to shield the layer from oxygen and moisture. This study dose not only focus on stability improvement, but also concentrate on offer the challenges and the recent developments of the commercial use of the perovskite cell in order to contribute the present understandings and the rational use of renewable resources.

Keywords: Perovskite solar cells; Stability; Encapsulation.

1. Introduction

A perovskite solar cell is a cell consisting of a perovskite-structured compound, most commonly the metal halide salts such as things like lead iodide or some organic salts as well. Not only the material, but also the efficiency of Perovskite is very high because it can use many different kinds of materials and obey a chemical formula that is ABX3. Since the materials of pervoskite are really convenient to produce, so they are prone to degradation by moisture, heat, and light. These kinds of problems will limit their long-term performance and reliability. The aim of this paper is that to introduce the process of perovskite more deeply and provides the ways to improve the stability of perovskite through its costs, material and the technology which can work more efficiently. In addition, perovskites have the potential to make solar panels that can be easily applied to a variety of surfaces, including flexible and textured solar panels. These materials also have lightweight, low cost and high efficiency comparable to the current dominant silicon photovoltaic materials. They are becoming the focus of increasing research and investment, however, there are a number of challenges that businesses wishing to harness their potential must overcome to make perovskite solar cells commercially competitive.

2. The structure and properties of perovskite solar cells

The perovskite crystal structure was first discovered as the naturally occurring mineral calcium titanium oxide, as shown in fig. 1, is referred to as a perovskite. Following this same arrangement those perovskitesmight have very useful properties. While single junction solar systems have a theoretical conversion efficiency of about 33%, the most efficient current silicon solar panels seen on homes only operate at about 20% efficiency. The potential for butpervoskite solar cells to achieve significantly greater efficiency limitations can push the limits of what is feasible for solar electricity. It therefore has a benefit over conventional silicon solar cells.

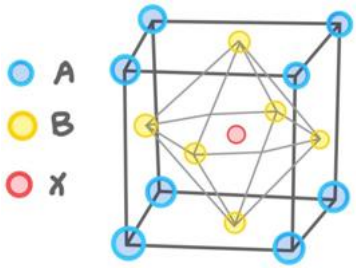


Fig. 1 Crystal structure of perovskite

3. Strategies for Improving Perovskite Solar Cell Stability

For the factors mentioned above that affects the instability of the perovskite solar cells, several methods with different mechanisms are developed [1].

3.1. Encapsulation Techniques

The first way is encapsulation techniques. First and foremost, encapsulating the solar cell with a barrier layer prevents it from degradation. There are 4 methods of encapsulation as shown in table 1. Fig.2 and fig.3 show the structure of glass-glass encapsulation and atomic layer deposit on perovskite solar cells.

Table 1. Methods of encapsulation

Encapsulation technique	Working mechnism	Advantages
Glass-glass encapsulation	Solar cells sandwiched between glass layers	Enhanced durability, protection against environmental factors
Thin-film Encapsulation	Barrier layer deposited on the perovskite solar cell	Compatibility with flexible substrates, scalability
Lamination	Solar cell sandwiched between encapsulant layers	Cost-effectiveness, scalability, ease of integration.
Atomic Layer Deposition	Precise deposition of uniform encapsulation layer	Highly uniform film deposition, precise thickness control [2]



Fig. 2 Structure of Glass-glass encapsulation on perovskite solar cells

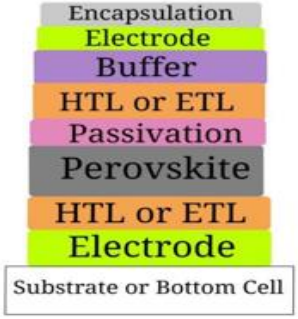


Fig. 3 Structure of ALD (Atomic layer deposit) on perovskite solar cells

3.2. Use of Additives to Improve Perovskite Film Formation and Stability

Solvent additives are often used to optimize the perovskite precursor solution and improve the film formation process. These additives, such as chlorobenzene or toluene, can influence the solubility and nucleation of the perovskite materials, leading to better film coverage, reduced grain boundaries, and improved crystallinity [3].

Table 2. Additives used in perovskite precursor

Name of additives	Mechanisms for improvement
Solvent Additives	Influence on the solubility and nucleation of the perovskite materials
Anti-Solvent Additives	Promoting controlled solvent evaporation, resulting in larger and more uniform perovskite crystal grains
Lewis Base Additives	Interaction with the perovskite precursor solution modifying its properties
Surfactant Additives	Improving the perovskite film morphology and reduce surface defects
Additives for Moisture and Stability	Enhancing the moisture resistance and stability of perovskite films

3.3. Incorporation of Alternative Materials to Increase the Stability of the Cell's Electron Transport Layer

3.3.1. Metal Oxides

Metal oxides like titanium dioxide and zinc oxide have been extensively utilized as electron transport layer (ETL) materials. These metal oxides exhibit excellent electron transport properties, high chemical stability, and appropriate energy level alignment with perovskite layers. Surface modifications, such as the addition of dense or mesoporous layers, can further enhance the performance and stability of metal oxide ETLs.

3.3.2. Organic Semiconductor Materials

Organic semiconductors have been explored as alternative ETL materials. Organic ETLs can offer advantages such as improved flexibility, solution processability, and compatibility with other layers in the device. However, achieving long-term stability remains a challenge due to their susceptibility to moisture and degradation under prolonged exposure to environmental conditions.

3.3.3. Perovskite Derivatives

Certain perovskite derivatives, such as mixed-cation perovskites or all-inorganic perovskites, have shown promise as stable ETL materials. These derivatives can exhibit improved stability compared to traditional methylammonium lead iodide ($MAPbI_3$) perovskites. For example, cesium-based perovskites (e.g., $CsPbI_3$ or $CsPbBr_3$) have demonstrated enhanced stability and suitable electron transport properties, making them potential candidates for ETL applications.

3.3.4. 2D Materials

Two-dimensional (2D) materials have attracted attention for ETL applications. These materials offer excellent charge transport properties, high stability, and tunable energy levels. They can be used as standalone ETLs or incorporated as interlayers within the device structure, improving charge extraction and reducing interfacial recombination.

3.3.5. Conductive Polymers

Conductive polymers have been investigated as alternative ETL materials. These materials offer good charge transport properties, solution processability, and the ability to form conformal coatings. However, their long-term stability and compatibility with other device components remain important considerations.

3.4. Exploration of New Device Architectures to Mitigate Degradation Pathways

3.4.1. 2D/3D Perovskite Heterostructures

One approach involves incorporating a thin layer of two-dimensional (2D) perovskite on top of the traditional three-dimensional (3D) perovskite layer. The 2D/3D perovskite heterostructure can help passivate defects and reduce ion migration within the perovskite material, leading to improved stability. The 2D layer acts as a protective barrier, shielding the 3D perovskite layer from external factors and reducing degradation.

3.4.2. Triple Cation or Mixed Cation Perovskites

Traditional perovskite materials, such as methylammonium lead iodide ($MAPbI_3$), can be prone to degradation due to the volatility of the organic cations. By incorporating additional cations, such as formamidinium (FA) and cesium (Cs), into the perovskite structure, stability can be enhanced. These mixed cation perovskites exhibit improved phase stability, reduced ion migration, and enhanced environmental resistance.

3.4.3. Passivation Layers and Interfacial Engineering

Introducing passivation layers at the interfaces of the perovskite solar cell can help mitigate degradation pathways. These layers, such as self-assembled monolayers (SAMs), metal oxides, or polymers, can effectively reduce surface defects, trap states, and charge recombination. Interfacial engineering techniques aim to optimize the energy level alignment and charge extraction efficiency, leading to improved stability and device performance.

3.4.4. Tandem or Multi-Junction Architectures

Tandem or multi-junction device architectures involve stacking multiple subcells with complementary absorption properties. In these architectures, a stable and efficient top cell, such as a silicon-based solar cell, is combined with a perovskite solar cell as the bottom cell. The top cell acts as a protective layer, shielding the perovskite layer from degradation-inducing factors such as moisture and UV light. Tandem architectures provide enhanced stability and efficiency by utilizing the strengths of different materials.

3.4.5. Flexible and Encapsulated Designs

Flexible and encapsulated device designs aim to improve stability by providing physical protection from moisture, oxygen, and other environmental factors. Flexible substrates and encapsulation materials with high barrier properties can prevent the ingress of moisture and oxygen, reducing degradation pathways. Additionally, flexible designs can accommodate mechanical stress and strain, mitigating device failure due to bending or stretching.

4. Experimental methods for evaluating perovisike solar cell stability

4.1. Damp Heat Test (DHT)

The damp heat test is based on the Arrhenius equation, which relates the rate of a chemical reaction to temperature and activation energy. The high humidity and temperature conditions accelerate the degradation processes in the solar cell, allowing for a faster evaluation of its stability.

To conduct the damp heat test on perovskite solar cells, a controlled environmental chamber is typically used to maintain the desired humidity and temperature conditions. The test conditions commonly employed for evaluating perovskite solar cell stability are around 85-90% relative humidity and temperatures ranging from 80-85 °C [4].

The duration of the test depends on the specific requirements an intended application of the solar cells but typically lasts several hundred hours to several thousand hours. Longer test durations can provide more accurate predictions of the material's stability and durability.

During the damp heat test, several parameters and analyses are conducted to assess the stability and performance of perovskite solar cells as shown in table 3.

Table 3. DHT parameters

Parameters	Description
Visual Inspection	The cells are visually inspected at regular intervals to monitor any physical changes.
Performance Measurement	The current-voltage (IV) characteristics of the solar cells are measured periodically to evaluate any degradation in their power conversion efficiency.
Monitoring of Stability Indicators	Several stability indicators are monitored during the test, such as the remaining charge carrier lifetime, impedance.
Material Analysis	Post-test analysis techniques are utilized to examine changes in the crystal structure, morphology, and chemical composition of the perovskite.

4.2. Thermal Cycling Test (TCT)

The thermal cycling test is an experimental method for evaluating the stability and reliability under temperature variations. Perovskite solar cells exhibit exceptional power conversion efficiencies but are sensitive to temperature fluctuations, which can lead to performance degradation. Therefore, understanding their behavior under thermal cycling conditions is crucial for their practical application. The thermal cycling test involves subjecting the perovskite solar cells to a series of temperature cycles within a defined temperature range. The test typically employs a thermal chamber equipped with heating and cooling mechanisms to control the temperature variations. The temperature range and cycling duration depend on the desired testing conditions and the intended application of the solar cells. During the thermal cycling test, several parameters and analyses are conducted to evaluate the stability and performance of perovskite solar cells, as shown in table 4.

Table 4. TCT parameters

Parameters	Description
Visual Inspection	Visual inspection involves closely assessing the solar cells for any physical changes or damages after each thermal cycle.
Performance Measurement	Assessing the performance degradation of perovskite solar cells.
Stress-Induced Degradation Indicator	[1] Assessing the charge carrier lifetime, hysteresis analysis and impedance spectroscopy [5].
Material Analysis	Post-test analysis techniques are utilized to examine changes in the crystal structure, morphology, and chemical composition of the perovskite.

4.3. Light Soaking Test (LST)

Light soaking test is an experimental method used to evaluate the stability and performance under continuous illumination. One of the main challenges in the commercialization of perovskite solar cells is their stability under operational conditions, particularly under continuous light exposure.

The light soaking test is designed to simulate the real-world operating conditions of a solar cell by exposing the device to continuous light irradiation for an extended period. This test helps to provide understanding of the degradation mechanisms and identify potential strategies to improve the stability of perovskite solar cells. Experimental methods for LST are summarized in table 5.

Table 5. LST parameters

Methods	Description
Sample preparation	Fabricate the perovskite solar cell using a suitable architecture, such as planar or mesoporous, and optimize the fabrication process to achieve high power conversion efficiency.
Encapsulation	To minimize the influence of external factors such as moisture and oxygen, encapsulate the solar cell using a suitable encapsulation material like glass or a polymer film [6].
Light source	Use a solar simulator or a light-emitting diode (LED) array to provide continuous light irradiation [7].
Temperature control	Maintain the temperature of the solar cell during the light soaking test.
Monitoring	Continuously monitor the performance parameters of the solar cell.
Duration	The duration of the light soaking test can vary from a few hours to several thousand hours, depending on the research objectives and the stability of the solar cell.
Data analysis	Analyze the performance parameters and degradation behavior of the solar cell during the light soaking test.

4.4. Ultraviolet Exposure Test

Ultraviolet exposure tests are conducted to evaluate the stability under prolonged exposure to UV radiation. These tests help researchers understand the degradation mechanisms and potential durability issues of PSCs, which are crucial for their commercialization and long-term performance. Experimental methods for evaluating PSC stability under UV exposure typically involve subjecting the cells to different UV radiation sources, monitoring their electrical and optical parameters, and analyzing the degradation mechanisms. The following are some of the key steps and considerations in conducting UV exposure tests for PSCs, summarized in table 6.

Table 6. UV Parameters

Parameters	Description
Selection of UV radiation source	PSCs are exposed to UV radiation sources that mimic the solar spectrum.
Exposure chamber design	PSCs are placed in a controlled environment to ensure consistent UV exposure.
UV exposure conditions	The UV exposure conditions can be chosen based on the intended application of the PSCs.
Monitoring electrical and optical properties	The electrical parameters of PSCs are measured before, during, and after UV exposure [8].
Characterization techniques	Various characterization techniques are employed to understand the degradation mechanisms and material changes induced by UV exposure.
Accelerated aging models	These models help predict the long-term stability under different environmental conditions.

4.5. Mechanical Stress Test

Mechanical stress tests are conducted to evaluate the stability and durability under mechanical loading conditions. These tests help determine the mechanical robustness of PSCs, their resistance to physical deformation, and potential degradation mechanisms related to mechanical stress.

Experimental methods for evaluating PSC stability under mechanical stress typically involve subjecting the cells to various mechanical loading conditions, measuring their electrical and optical

parameters, and analyzing any changes or degradation that occur. The following are some key steps and considerations in conducting mechanical stress tests for PSCs, shown in table 7.

Table 7. Mechanical Test parameters

Parameters	Description
Selection of mechanical loading methods	Different methods including bending, stretching, compressing, or cyclic mechanical loading can be used to apply mechanical stress to PSCs.
Test setup	PSCs are mounted or adhered to a substrate or frame that allows controlled application of mechanical stress.
Mechanical stress levels	The magnitude and duration of the mechanical stress applied to PSCs should be carefully determined.
Monitoring electrical and optical properties	The electrical parameters of PSCs are measured before, during, and after UV exposure [8].
Visual and microscopic inspection	PSCs are visually inspected, and microscopy techniques such as scanning electron microscopy (SEM) or optical microscopy are employed to examine the surface and internal structures of cells [9].
Material characterization techniques	Various characterization techniques can be used to analyze the degradation mechanisms induced by mechanical stress.
Finite Element Analysis (FEA) modeling	FEA models provide insights into stress distribution, strain levels, and potential failure points, assisting in the optimization of PSC designs and material selection to enhance mechanical stability [10].

5. Conclusion

This study provides valuable insights and strategies for enhancing the stability of perovskite solar cells. The findings contribute to the application of perovskite materials in solar cells and other fields, offering guidance for further research and improvement. Perovskite solar cells exhibit low production costs, high scalability, and impressive efficiency levels surpassing 25%. This, combined with their flexibility and versatility, positions them as strong contenders in the solar energy industry. Perovskite solar cells can be integrated into various surfaces and products, enabling seamless solar power generation. In conclusion, perovskite solar cells have the potential to transform the renewable energy landscape by offering an efficient, cost-effective, and environmentally friendly alternative to traditional solar cells. The unique properties of perovskite materials make them ideal for high-performance solar cells. Nonetheless, challenges related to moisture sensitivity, thermal stability, and photo-induced phase segregation need to be addressed. The optimization of efficiency and stability, as well as the establishment of large-scale manufacturing processes, are key factors for the commercial success of perovskite solar cells. Collaboration between researchers, industry, and policymakers is essential to create a supportive environment for the advancement and adoption of this technology.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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