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Article

Evaluation of Perovskite Solar Cell Development

Anthony Chibuike Ohajianya

Department of Physics, Federal University of Technology, P.M.B 1526, Owerri, Nigeria
Email: anthony.ohajianya@futo.edu.ng

Abstract: Perovskite solar cells (PSCs) are solar cells with the light-absorbing layers made of perovskite materials. Perovskite materials are a class of materials that possess a distinct crystal structure that resembles that of mineral perovskite. PSCs have received significant attention in recent years due to their remarkable power conversion efficiency, uncomplicated manufacturing process, cost-effectiveness, and potential for large-scale production. However, PSCs face challenges, particularly in terms of stability and durability. Perovskite materials are known for their sensitivity to moisture and oxygen. This can lead to reduction in their performance over time. Researchers are actively engaged in enhancing the stability of perovskite solar cells via various approaches, including interface manipulation and the incorporation of stabilizing agents. Endeavors are underway to surmount obstacles such as trap-assisted nonradiative recombination and inadequate ambient stability. Through further progress in formulation, composition, and interfacial optimization, PSCs hold promise in nearing their theoretical efficiency threshold of 31% and emerging as a feasible candidate for commercial and industrial applications. The power conversion efficiency (PCE) of perovskite solar cells have been steadily increasing over the years while the stability has not advanced much. Currently, the PCE and stability of single-junction perovskite solar cells have reached 27.0% and 10,000 h, respectively. Perovskite Tandem and Hybrid Tandem solar cells have achieved higher efficiencies of 30.1% and 36.1%, respectively. Efforts are still ongoing to explore different approaches to further increase the efficiency, improve stability under real working conditions, and employ lead-free perovskite materials.

Keywords: perovskite solar cells, perovskite materials, interface engineering, efficiency, stability, durability

1. Introduction

A perovskite solar cell is a type of solar cell in which the light-absorbing layer is made of perovskite materials. Perovskite solar cells have received a lot of attention in recent years because of their high power conversion efficiency, simple manufacturing process, low cost, and large-scale production [1]. Because of their distinct advantages, they have emerged as a promising alternative to traditional solar cells, such as silicon-based photovoltaic solar cells [2]. Perovskite solar cells are made up of a perovskite material sandwiched between two charge transport layers, which is typically a hybrid organic-inorganic compound. The perovskite layer absorbs sunlight and generates electron-hole pairs, which the charge transport layers separate and collect to generate an electric current [3]. The composition and structure of the perovskite material, the quality of the charge transport layers, and the device architecture all influence the efficiency of perovskite solar cells [4]. The high power conversion efficiency of perovskite solar cells is one of their primary advantages. Because perovskite materials have high absorption coefficients, they can efficiently capture a wide range of the sunlight spectrum [5].

Furthermore, perovskite solar cells have shown high carrier mobility and long charge carrier diffusion lengths, allowing for efficient charge transport and collection [5]. These factors contribute to perovskite solar cells' high

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efficiency, which has been steadily increasing in recent years. Nevertheless, perovskite solar cells face challenges, particularly in terms of stability and durability. Perovskite materials are known to be moisture- and oxygen-sensitive, which can reduce their performance over time [6]. Researchers have been actively working to improve the stability of perovskite solar cells using a variety of methods, including interface engineering and the introduction of stabilizing molecules [5, 6]. These efforts aim to improve perovskite solar cells' long-term stability and operational repeatability, making them more suitable for practical applications.

The current research on perovskite solar cells also include the probe of novel materials and methods to improve their overall efficiency. In recent years, hybrid perovskites have emerged, combining organic and inorganic elements to create materials that show better thermal and photostability [7]. Such progress not only target stability but also aim to reduce the environmental impact associated with perovskite solar cells through the riddance of toxic materials like lead [8, 9]. Perovskite solar cells' lightweight and flexible nature makes them entrancing for a range of use, including building-integrated photovoltaics (BIPV) and portable solar devices, possibly enlarging their market reach beyond traditional applications [10, 11].

Moreover, the scalability of perovskite solar cell manufacturing processes, such as roll-to-roll printing, presents a pathway towards cost-effective production and distribution [12, 13]. These innovations could significantly bring down the cost per watt of solar energy produced, enhancing the economic viability of solar technologies in regions with constricted access to traditional energy sources. Recent advancements in encapsulation techniques are also encouraging, as they help mitigate the degradation of perovskite materials from environmental factors, thereby improving the longevity of solar cells in real-world conditions [14].

With these continual improvements and the synergy of interdisciplinary research, perovskite solar cells stand at the forefront of the renewable energy transition, promising cleaner and more sustainable energy solutions for the future. Understanding the material science behind these developments will play a crucial role in resolving the existing challenges while unlocking the full potential of PSC technology [15]. Further investigation into operational stability under various environmental conditions is essential for paving the way toward widespread implementation in different climates and installations.

In addition to stability and material composition, further research is being directed toward optimizing the device architecture of perovskite solar cells. The integration of advanced techniques, such as tandem solar cell structures, where perovskite cells are layered with other photovoltaic materials, has demonstrated the potential to exceed the Shockley-Queisser limit, thereby achieving even higher efficiencies [16]. These tandem configurations allow for better utilization of the solar spectrum, making it possible to harness more energy from sunlight compared to traditional single-junction designs [17].

Another area of ongoing investigation is the interface between the perovskite layers and charge transport materials, where reducing energy loss through nonradiative recombination is critical [18]. Researchers are exploring new materials and fabrication methods to engineer these interfaces with atomic precision, which could pave the way for improved charge extraction and overall device performance [19].

Moreover, the recycling and end-of-life management of perovskite solar cells are increasingly gaining attention as environmental considerations become more pivotal in technology adoption. Strategies to recover valuable materials from decommissioned solar cells will not only reduce waste but also contribute to a circular economy within the solar energy sector [20].

The development of regulatory frameworks and efficiency standards specifically tailored for perovskite solar cells will be essential to ensure their safe and effective integration into existing energy infrastructures. Collaboration between researchers, manufacturers, and policymakers is necessary to address these aspects and cultivate a thriving ecosystem that promotes the adoption and commercialization of perovskite solar technology.

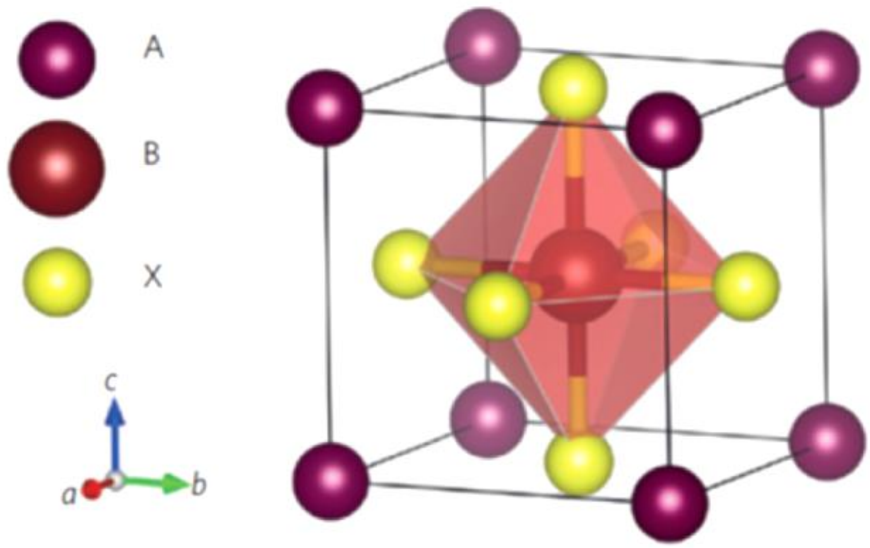
Ultimately, the convergence of material innovation, improved manufacturing techniques, and sustainable practices will critically determine the trajectory of perovskite solar cells, positioning them as a cornerstone technology in the renewable energy landscape. Further insights into long-term performance and application-specific adaptations will facilitate their transition from laboratory-scale breakthroughs to practical energy solutions globally [19].

The aim of this study is to review the progress in Perovskite solar cell development in terms of technology, materials, efficiency, stability, applications, and remediation of environmental concerns.

2. Perovskite Materials

Perovskite materials are a class of materials that have a unique crystal structure similar to that of the mineral perovskite. The mineral calcium titanium oxide ($CaTiO_3$)was the first perovskite crystal to be discovered. The generalchemical formula for perovskite compounds is ABX_3, where 'A' is a monovalent cation usually themethylammoniumion(CH_3NH_3), 'B'is a metallic cation usually Pb, and 'X' is an anion that bonds to both of them, which is a halogen ion (usually I but Cl and Br can also be used). The perovskite structure is made up of a three-dimensional network of corner-sharing BX_6 octahedra, with the A cations located in the voids between theoctahedra[21]. Perovskite structures canbe created by combining a variety of components. Its compositional versatility allows researchers to create perovskite crystals with a wide range of physical, optical, a nd electrical properties. Examples of perovskite materials include methylammonium lead iodide ($MAPbI_3$), formamidinium lead iodide ($FAPbI_3$), and cesium lead bromide ($CsPbBr_3$). The structure of perovskite materials is shown in Figure 1.

Figure 1. Perovskite materials' crystal structure: "A" site is typically CH_3NH_3I (MAI), $NH_2CH_3NH_2I$ (FAI), Cs; "B" site is commonly Pb, Sn; "X" site could be Cl, Br or I (Source: [22])



Perovskite materials have gained a lot of attention in recent years because of their unique properties and potential applications in a variety of fields. Photovoltaics is one area of interest where perovskite materials have shown great promise as light-harvesting materials in solar cells. The thermal behavior and crystal phase structure of organic-inorganic hybrid perovskites such as $CH_3NH_3PbX_3$ (X = I or Cl) have been extensively studied [21]. These materials have also been used in transistors, light-emitting diodes, and quantum dots, according to Fu et al.[23].

Other types of perovskite materials exist in addition to organic-inorganic hybrid perovskites, such as layered double perovskites and nitride perovskites. Layered double perovskites have the potential to broaden the diversity of two-dimensional perovskites while also improving their properties and applications. On the other hand, nitride perovskites have been synthesized and discovered to possess piezoelectric properties, making them suitable for a myriad of applications [24].

The optoelectronic properties of perovskite materials have also been investigated. They have been used in a variety of devices, such as solar cells, light-emitting diodes, photodetectors, and lasers [25, 26]. Perovskite semiconductors are appealing for these applications due to their unique combination of properties such as tunable bandgap, ambipolar charge transport, and solution processability [25].

There has also been research on chiral perovskite materials, which have intrinsic inversion-symmetric structures and unique physicochemical properties. Chiral perovskites combine the benefits of chiral materials and halide perovskites, allowing for the development of next-generation optoelectronic and spintronic devices [27, 28].

Perovskite materials have been studied for their potential as low-toxicity and high-performance thermoelectric materials in the field of thermoelectric applications. Thermoelectric properties of oxide perovskites have been studied, and hybrid perovskites have shown promise for wearable energy generators and cooling devices [29, 30].

Due to their unique properties and crystal structure, perovskite materials have shown great potential in a variety of fields. They are still the subject of extensive research and development, with efforts aimed at improving their stability, performance, and comprehension of their fundamental properties [23, 31].

3. Structure and Operation of Perovskite Solar Cells

The structure of perovskite solar cells typically consists of a layered architecture. The active layer is made up of perovskite material, which absorbs sunlight and converts it into electrical energy. This layer is sandwiched between two charge transport layers - the electron transport layer (ETL) and the hole transport layer (HTL). The ETL helps to collect and transport the generated electrons, while the HTL aids in collecting and transporting the positive charges or holes. This layered structure allows for efficient charge transport and separation, leading to high power conversion efficiencies in perovskite solar cells. The substrate is the base layer upon which the entire perovskite solar cell is built. It provides structural support and acts as a foundation for the other layers. Typically made of glass or a flexible material like plastic, the substrate is coated with a transparent conductive oxide (TCO) layer, such as indium tin oxide (ITO) or fluorinated tin oxide (FTO) [32, 33]. The TCO layer allows for the passage of light through the cell and also serves as an electrical contact to extract the generated electricity. In addition to the TCO layer, the substrate also plays a crucial role in preventing moisture and oxygen from entering the perovskite solar cell [34]. This is particularly important as perovskite materials are known to be sensitive to moisture and oxygen, which can degrade their performance and stability over time. To address this issue, researchers have been exploring various strategies to improve the moisture and oxygen barrier properties of the substrate. One approach involves using advanced encapsulation techniques, such as atomic layer deposition (ALD) or plasma-enhanced chemical vapor deposition (PECVD), to deposit thin layers of barrier materials onto the substrate. These barrier materials, such as aluminum oxide or silicon nitride, can effectively protect the perovskite material from moisture and oxygen, extending its lifespan and enhancing its performance [35]. Additionally, researchers are also investigating the use of polymer coatings with excellent moisture and oxygen barrier properties, which can be applied in a cost-effective and scalable manner [36, 37]. By implementing these improved encapsulation methods, the long-term stability and reliability of perovskite materials can be significantly enhanced, bringing us closer to their widespread commercialization in various applications, such as solar cells and light-emitting diodes.

The electron transport layer (ETL) is located above the TCO layer and facilitates electron transport from the perovskite layer to the bottom electrode. Metal oxides such as titanium dioxide (TiO_2) or zinc oxide (ZnO) are commonly used ETL materials [38, 39]. Other materials that can be used for the ETL include CdS, $Zn(O_{0.3},S_{0.7})$, ZnS and ZnSe [40].

The most important component of a solar cell is the perovskite layer. It is responsible for the absorption of light and the generation of electron-hole pairs. Typically, the perovskite layer is made up of a hybrid organic-inorganic material such as methylammonium lead iodide ($CH_3NH_3PbI_3$). The composition and morphology of the perovskite layer are important in determining device performance [4, 41].

The hole transport layer (HTL) sits on top of the perovskite layer, facilitating the transport of holes from the perovskite layer to the top electrode. Organic small molecules or polymers, such as poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS), are the commonly used HTL materials. Other potential materials for the HTL include Cu_2O, CuSCN, NiO, and $CsSnI_3$ [40].

Lastly, there is the top electrode, which receives the holes generated in the perovskite layer and completes the circuit. The top electrode is usually made of a metallic material, such as gold (Au) or silver (Ag) [3]. The structure of $CH_3NH_3Sn_xPb_{(1-x)}I_3$ perovskite solar cell is shown in Figure 2, while the energy band diagram is shown in Figure 3.

Figure 2. Structure of CH3NH3SnxPb(1−x)I3 perovskite solar cells (Source: [42]).

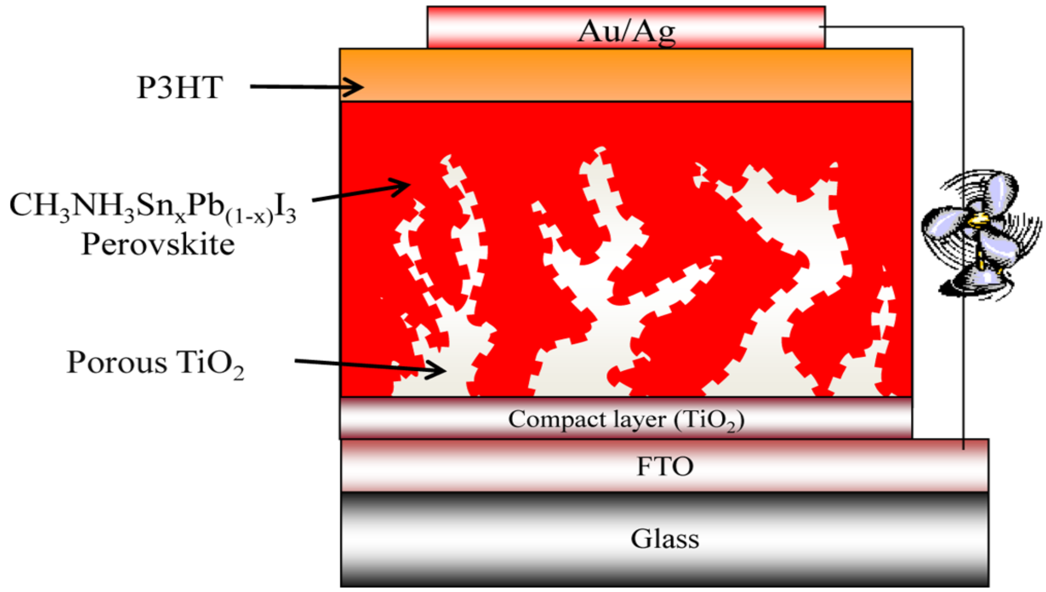
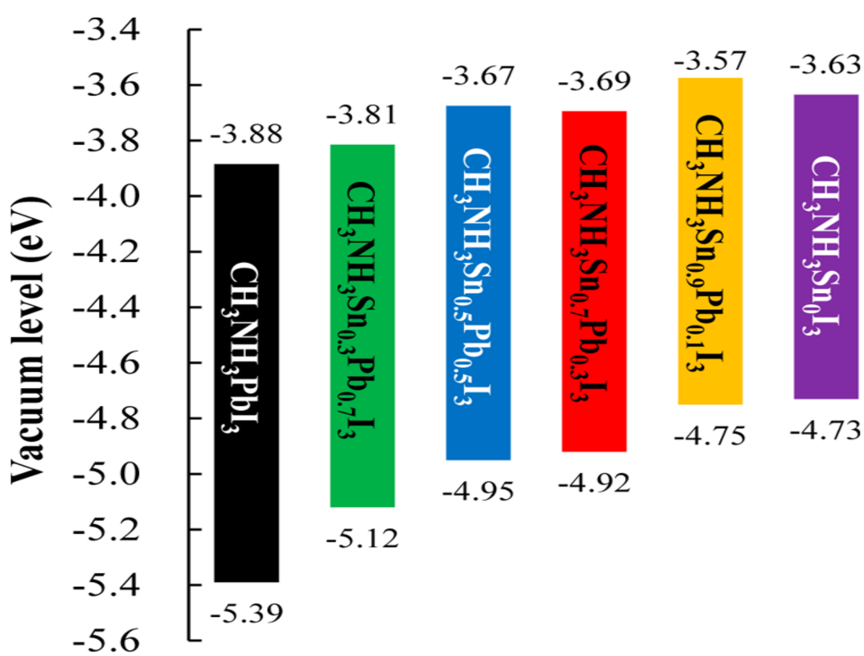
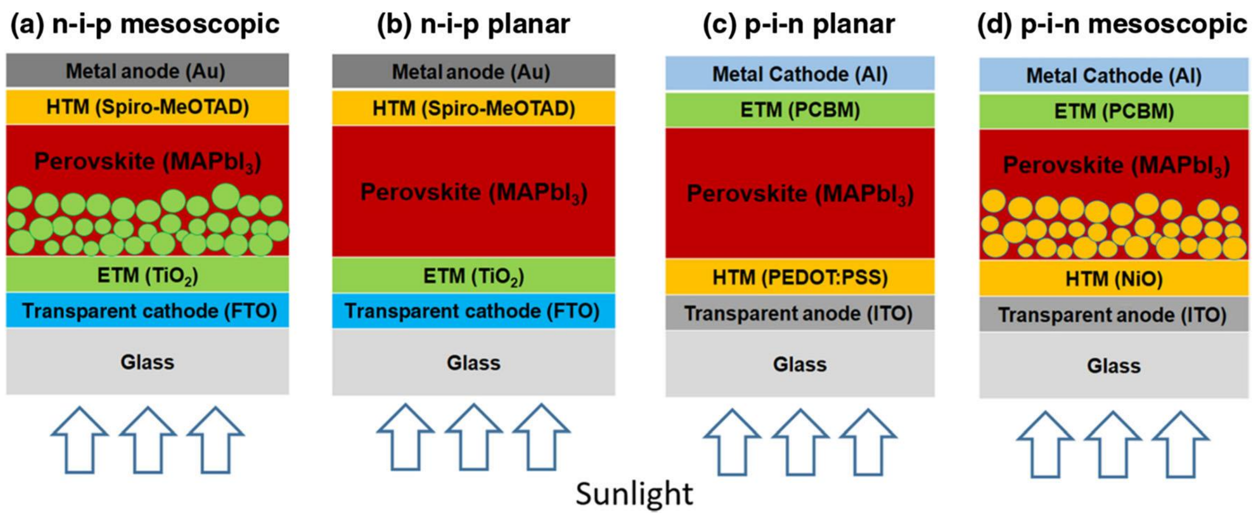


Figure 3. Energy diagram for CH3NH3SnxPb(1−x)I3 perovskite (Source: [42]).



The perovskite solar cell device configuration is one of the main vital factors that determine the overall performance of the cells. Perovskite solar cells can be categorized as normal (n-i-p) and inverted (p-i-n) structures. This classification depends on which transport material (ETL/HTL) is situated on the exterior portion of the cell to first encounter the incident light. These two structures (n-i-p and p-i-n) can be further divided into mesoscopic and planar structures. The mesoscopic structure incorporates a mesoporous layer while the planar structure comprises all planar layers [43]. Researchers have also worked on perovskite solar cells without either ETL or HTL. Therefore, in term of device structure, there are six categories of perovskite solar cells which include: the mesoscopic n-i-p configuration, the planar n-i-p configuration, the planar p-i-n configuration, the mesoscopic p-i-n configuration, the ETL-free configuration, and the HTL-free configuration [43]. Figure 4 shows the four typical layered structures of perovskite solar cell.

Figure 4. The four typical layered structures of perovskite solar cell (source [43])



The overall operation of a perovskite solar cell begins with the absorption of photons by the perovskite layer, which produces electron-hole pairs. The electrons are extracted via the ETL and flow to the bottom electrode, while the holes are extracted via the HTL and flow to the top electrode. The flow of electrons and holes produces a current, which can be harvested as electrical power. The electrons flow through the bottom electrode, usually made of a conductive material such as gold (Au) or silver (Ag), towards the external circuit. This movement of electrons creates an electric current that can be utilized to power electronic devices or stored in a battery for later use. Similarly, the holes flow through the top electrode, completing the circuit. This process allows the perovskite solar cell to efficiently convert solar energy into usable electrical power.

4. Perovskite Solar Cell Fabrication Technologies

The fabrication of perovskite solar cells involves the deposition of perovskite films onto a substrate, which is a critical step in determining the performance and stability of the resulting devices. One common method for depositing perovskite films is the sequential deposition technique, as described by Burschka et al. [44]. In this method, theperovskite colored solution is deposited in a two-step process onto a mesoporous metal oxide film. First, PbI2 is introduced into a nanoporous titanium dioxide film, and then it is transformed into perovskite by exposing it to a solution of CH3NH3I. This sequential deposition method allows for better control over the perovskite morphology, resulting in improved performance and reproducibility of the solar cells [44].

Another approach for depositing high-quality perovskite films is through the direct intramolecular exchange of dimethylsulfoxide (DMSO) in the presence of formamidinium lead iodide (FAPbI3), as reported by Yang et al. [45]. This method results in FAPbI3 films with preferred crystallographic orientation, large-grained dense microstructures, and flat surfaces without residual PbI2. The use of films prepared by this technique has led to the fabrication of perovskite solar cells with maximum power conversion efficiencies greater than 20% [45].

In addition to these deposition techniques, there have been advancements in scalable fabrication technologies for perovskite solar cells. Blade coating and slot-die coating assisted with air quenching have shown high industrial compatibility and have been used to fabricate perovskite mini-modules with high power conversion efficiencies [46]. These techniques offer the potential for large-scale production of perovskite solar cells with high efficiency and stability.

To further improve the efficiency and stability of perovskite solar cells, researchers have explored various strategies, such as compositional engineering and intense pulsed light (IPL) annealing. Martin et al. [47] demonstrated the use of IPL annealing to achieve high-performance mixed-cation perovskite solar cells with a power conversion efficiency of 16.7%. This method allows for faster processing of the perovskite layer and represents an advancement toward scaled production of perovskite solar cells on flexible substrates.

Despite the progress made in perovskite solar cell fabrication technologies, there are still challenges that need to be addressed. Stability and durability are important factors that need to be improved to ensure the long-term performance of perovskite solar cells [47]. The development of stable perovskite precursor inks and coating methods for large-area perovskite PV device production is also crucial to improving the power conversion efficiency of perovskite solar [46]. Additionally, the scalability of manufacturing processes and the production capacity of roll-to-roll lines need to be optimized to meet the demand for large-scale production of perovskite solar [47].

In recent times, roll-to-roll attuned processes such as slot die coating, spray coating, doctor-blade, etc. have also been explored as a fabrication technique for perovskite thin-film solar cells in the field of large-area mass production manufacturing [48].

5. Progress in Efficiency and Stability of Perovskite Solar Cells

Perovskite solar cells have shown significant progress in terms of efficiency and stability in recent years. The efficiency limit of perovskite cells, particularly methylammonium lead iodide (CH3NH3PbI3) perovskite solar cells, has been investigated [49]. The efficiency limit of perovskite cells without angular restriction is about 31%, which comes close to the Shockley-Queisser limit of 33% achievable by gallium arsenide (GaAs) cells [49]. It has been established that the Shockley-Queisser limit can be reached with a 200 nm-thick perovskite solar cell by integrating a wavelength-dependent angular-restriction design with a textured light-trapping structure [49]. The influence of trap-assisted nonradiative recombination on the device efficiency has also been investigated [49].The efficiency limit of CH3NH3PbI3 perovskite solar cells has been predicted using a detailed balance model that considers the photon recycling effect [49]. The model employs the AM 1.5 spectrum of the Sun and the experimentally measured complex refractive index of perovskite material to obtain convincing predictions. The roles of light trapping and angular restriction in improving the maximal output power of thin-film perovskite solar cells have also been clarified [49].

The power conversion efficiency (PCE) of perovskite solar cells has rapidly increased from 3.8% to more than 22% in recent years, rivaling the efficiency of market-reference silicon solar cells [50]. However, increasing the stability of perovskite solar cells is becoming more important to meet industry standards [50]. The stability of perovskite solar cells under real-world working conditions is a major challenge for their commercialization [50]. The poor ambient stability of perovskite solar cells has limited their industrialization and application in real environmental conditions [6]. Therefore, research efforts have been focused on improving the stability of perovskite solar cells. It has been identified that the factors responsible for the low stability of perovskite solar cells are more of intrinsic than extrinsic in nature. While the extrinsic factors which include the effect of moisture and oxygen in ambient air have been dealt with to a large extent via encapsulation, the intrinsic factors which bother on the device internal compositions and operations are more difficult to handle [51, 52, 53].

Lead-based perovskite solar cells have shown high efficiency, with certified efficiency reaching over 21% as at 2018 [54]. However, the toxicity of lead makes it a nonideal candidate for use in solar cells. As a result, lead-free perovskite materials, such as mixed tin and germanium perovskites, have been proposed as alternatives [54]. These lead-free perovskite materials have shown band gaps ideal for solar cells and have the potential to enhance the performance of perovskite solar cells [54].

In addition to improving efficiency and stability, research has focused on the fabrication and preparation methods of perovskite solar cells. Two-dimensional perovskite solar cells have emerged as a promising new type of solar cell due to their unique advantages, such as strong spectral absorption, low cost, adjustable composition, excellent structure, and excellent photoelectric characteristics [3]. To overcome the challenges associated with the stability of perovskite solar cells, researchers have been exploring various strategies. One approach is the use of hexamine molecules to enhance the stability of the perovskite phase, enabling high-performance and air-processable perovskite solar cells [6]. Other strategies include surface modification, electrolyte solutions, and working temperature optimization. These efforts aim to improve the stability and long-term performance of perovskite solar cells, making them more suitable for practical applications. Also, research has focused on improving the preparation method of metal top electrode materials, introducing buffer layers, and modifying the interface of two-dimensional perovskite solar cells [3]. As can be seen in Figures 5 and 6, the highest efficiency and stability of perovskite solar cells achieved so far are 27.0% and 10,000 h, respectively [53, 55, 56, 57, 58]. Table 1 shows the details of the chronological development of perovskite solar cell in terms of perovskite composition, device structure, and efficiency [56, 58].

Figure 5. Progress in the stability of perovskite solar cells

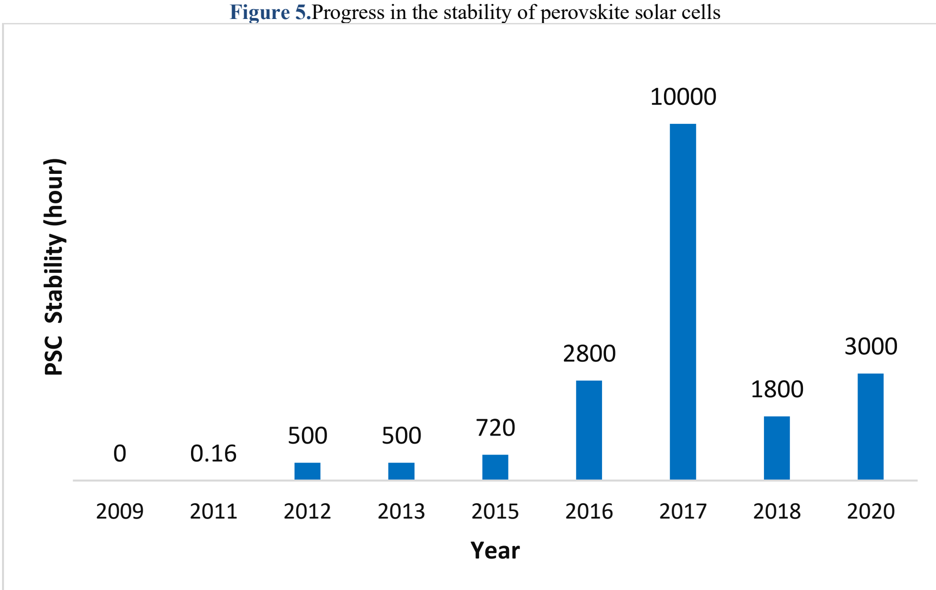


Figure 6. Progress in the efficiency of perovskite solar cells

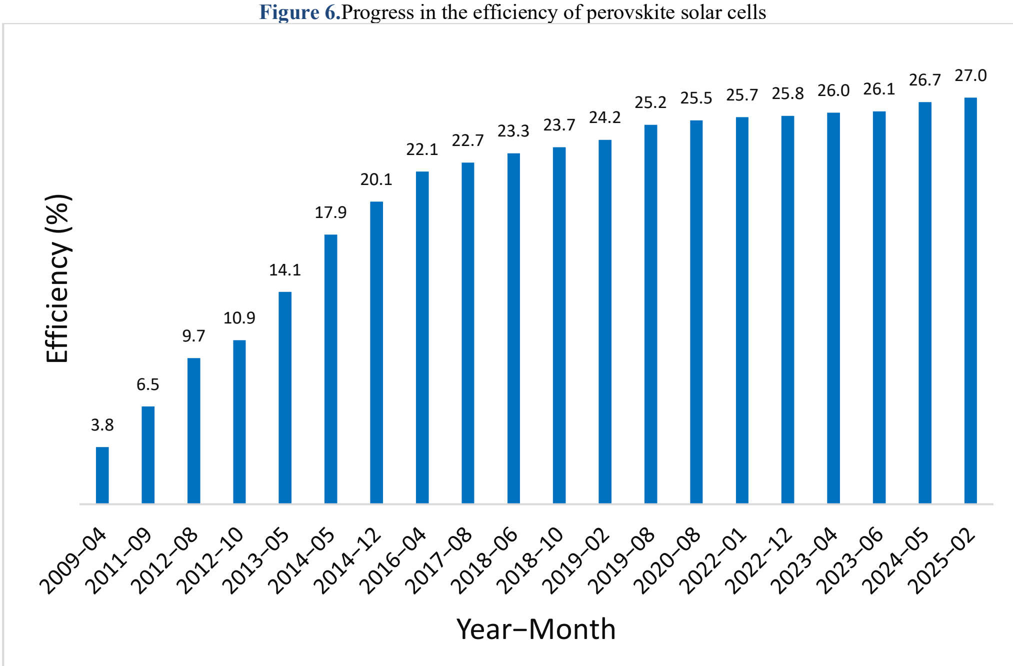


Table 1. Chronological Development of Perovskite Solar Cells

S/N	Perovskite Composition	Device Structure	Institute	Year−Month	PCE (%)
1	MAPbI3	liquid junction	Toin U.	2009−04	3.8
2	MAPbI3	liquid junction	SKKU	2011−09	6.5
3	MAPbI3	solid−state mesoscopic TiO2	SKKU	2012−08	9.7
4	MAPbI3	solid−state mesoscopic Al2O3	Oxford U.	2012−10	10.9
5	MAPbI3	mesoscopic TiO2	EPFL	2013−05	14.1
6	(FAPbI3)0.85(MAPbBr3)0.15	mesoscopic TiO2	KRICT	2014−05	17.9
7	(FAPbI3)0.95(MAPbBr3)0.05	mesoscopic TiO2	KRICT	2014−12	20.1
8	(FAPbI3)0.95(MAPbBr3)0.05	mesoscopic TiO2	KRICT/UNIST	2016−04	22.1
9	(FAPbI3)0.85(MAPbBr3)0.05	mesoscopic TiO2, fluorene−terminated HTM	KRICT	2017−08	22.7
10	FA0.92MA0.08PbI3	normal planar, SnO2 ETM	ISCAS, Beijing	2018−06	23.3
11	FA0.92MA0.08PbI3	normal planar, SnO2 ETM	ISCAS, Beijing	2018−10	23.7
12	not accessible	not accessible	KRICT/MIT	2019−02	24.2
13	not accessible	not accessible	KRICT/MIT	2019−08	25.2
14	not accessible	not accessible	UNIST	2020−08	25.5
15	not accessible	not accessible	UNIST	2022−01	25.7
16	not accessible	not accessible	UNIST	2022−12	25.8
17	not accessible	not accessible	ISCAS	2023−04	26.0
18	not accessible	not accessible	UST of China	2023−06	26.1
19	not accessible	not accessible	UST of China	2024−05	26.7
20	not accessible	not accessible	Soochow U.	2025−02	27.0

The cell that achieved the highest efficiency of 27.0% was produced in February 2025 at Soochow University, China. This highest efficiency was for single-junctionperovskite solar cells. Perovskite Tandem and Hybrid Tandem solar cells have achieved higher efficiencies of 30.1% and 36.1%, respectively [58].

6. Potential Applications of Perovskite Solar Cells

Perovskite solar cells have shown high power conversion efficiencies, with some reaching over 20% [45]. This makes them a promising candidate for next-generation solar devices [59]. The high efficiency of perovskite solar cells is attributed to their ability to absorb a broad range of the solar spectrum, including both visible and near-infrared light [45]. This broad absorption range is due to the tunable bandgap of perovskite materials [45].

Another potential application of perovskite solar cells is in space exploration. Perovskite solar cells have been tested in extreme conditions such as thermal cycling, high vacuum, and solar flares, and have shown promising performance [1]. In fact, perovskite solar cells have been launched into the stratosphere at a high altitude of 32 km, demonstrating their potential for use in space missions [1, 60].

Perovskite solar cells also have the potential to be used in wearable devices. Their low cost, simple manufacturing process, and lightweight properties make them suitable for integration into wearable electronics [61]. Additionally, perovskite solar cells can be fabricated as flexible and transparent devices, allowing for their incorporation into various wearable applications [62].

Furthermore, perovskite solar cells have the potential to be used in tandem and hybrid solar cells, where they are combined with other solar cell technologies and materials to achieve even higher efficiencies. For example, perovskite-silicon tandem solar cells have been investigated, with the aim of breaking the theoretical efficiency limit of single-junction solar cells [63]. Tandem solar cells can combine the advantages of different solar cell technologies to achieve higher overall efficiencies. Perovskite Tandem and Hybrid Tandem solar cells have achieved record breaking efficiencies of 30.1% and 36.1%, respectively [58].

7. Environmental Impact of Manufacturing and Using Perovskite Solar Cells

The most commonly used perovskite material in solar cells is methylammonium lead iodide (CH3NH3PbI3) [64]. However, the use of lead in perovskite solar cells raises concerns about its environmental impact and human health risks [65]. Lead is a toxic heavy metal that can have detrimental effects on the environment and human health. The toxicity of lead has been a major barrier to the commercial application of lead-based perovskite solar cells [9, 66, 67]. Lead-based perovskite solar cells also face stability issues, as they can degrade under external environmental conditions such as humidity, UV light, temperature, and electric fields [68]. To address these concerns, researchers have been exploring lead-free alternatives for perovskite solar cells. Tin (Sn) has emerged as a promising replacement for lead in perovskite materials [69]. Tin-based perovskite solar cells have shown potential for high efficiency and stability, making them attractive alternatives to lead-based perovskite solar cells [70]. Lead-free perovskite materials can achieve high power conversion efficiency (PCE) and exhibit good solar cell performance [65].

The environmental impact of manufacturing perovskite solar cells has also been a topic of research. Life cycle assessment (LCA) studies have been conducted to evaluate the environmental profile of perovskite solar cell fabrication [71]. These studies have identified the material and energy flows that contribute to the environmental impact of perovskite solar cell manufacturing. The outcomes of these studies vary depending on the methodological choices and assumptions made by the authors [71]. However, the sustainability of perovskite solar cells is a subject of debate, and further research is needed to fully understand their environmental impact [71].

8. Conclusion

In terms of device structure, there are six categories of perovskite solar cells which include: the mesoscopic n-i-p configuration, the planar n-i-p configuration, the planar p-i-n configuration, the mesoscopic p-i-n configuration, the ETL-free configuration, and the HTL-free configuration

The power conversion efficiency (PCE) of perovskite solar cells have been steadily increasing over the years while the stability has not advanced much. Currently, the PCE and stability of single-junction perovskite solar cells have reached 27.0% and 10,000 h, respectively. Perovskite Tandem and Hybrid Tandem solar cells have achieved higher efficiencies of 30.1% and 36.1%, respectively Efforts are still ongoing to explore different approaches to further increase the efficiency, improve stability under real working conditions, and employ lead-free perovskite materials.

Researchers have been actively working to improve the stability of perovskite solar cells using a variety of methods, including interface engineering and the introduction of stabilizing molecules. Efforts are being made to overcome challenges such as trap-assisted nonradiative recombination and poor ambient stability. With further advancements in preparation, composition, and interfacial engineering, perovskite solar cells have the potential to approach their theoretical efficiency limit of 31% and become a viable option for commercialization and industrialization.

Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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