Research Question: How Have the Recent Advancements in Perovskite Materials, Device Architectures, Stability, And Scalability Improved Efficiency?

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Abstract: ***This paper provides a comprehensive review of the recent advancements in Perovskite solar cells, focusing on the improvements in perovskite materials, device architectures, stability, and scalability. The paper begins with an overview of renewable energy sources and the role of Perovskite solar cells in this context. It then delves into the structure and operation of a typical Perovskite solar cell, highlighting its advantages such as high efficiency, low-cost manufacturing, and versatility. The paper also discusses the recent breakthroughs in Perovskite materials, including the development of tandem and multijunction cells, enhanced stability through additives and encapsulation techniques, and the exploration of lead-free perovskites. Despite the challenges related to scalability and long-term stability, the paper concludes that Perovskite solar cells have shown significant potential for future energy applications.***

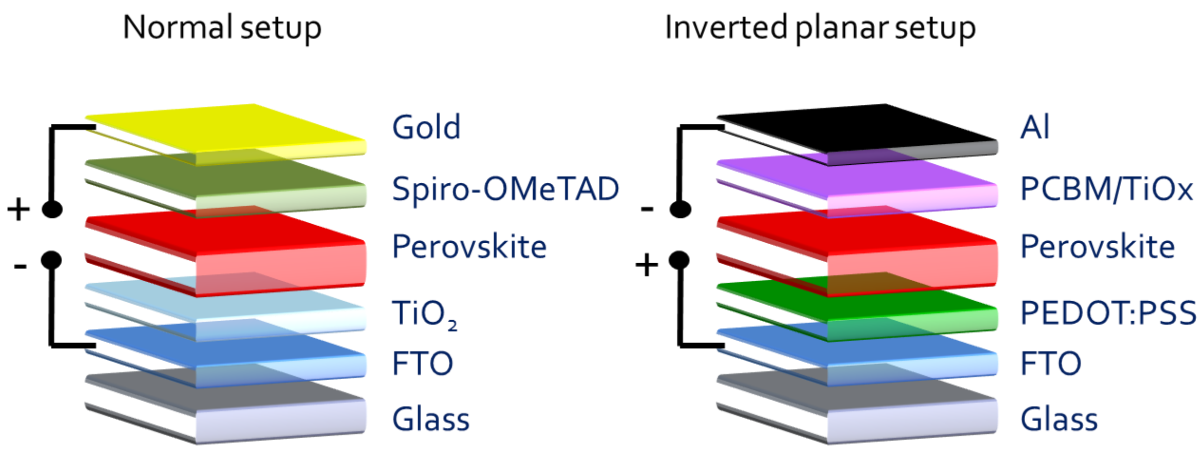
Keywords: Renewable Energy, Perovskite Solar Cells, Device Architectures, Silicon-based solar cell, multijunction solar cells, Stability, and Scalability

1. Introduction

Advancements in technology, the industrial revolution, and the growth of the world's population push for energy demand. In order to overcome energy demand, reduce import costs, and environmental protection, developed countries, and developing countries are concentrating on renewable sources of energy. Renewable energy refers to energy derived from sources that are naturally replenished and can be used without depleting their resources. Unlike fossil fuels, which are finite and non-renewable, renewable energy sources are continuously available and can be harnessed without causing significant harm to the environment. These energy sources are considered sustainable and have a lower impact on climate change and air pollution. This paper will focus to evaluate the recent advancements in Perovskite solar cells. Further, it will investigate the benefits of recent advancements in perovskite materials, device architectures, stability, or scalability.

Perovskite solar cells are a type of photovoltaic device (a nonmechanical device that converts sunlight directly into electricity) that utilizes a unique class of materials called perovskites. They are mainly known for high efficiency, low-cost manufacturing, and versatility. The main advantage of perovskite solar cells is their ability to absorb a broad range of light wavelengths, including both visible and near-infrared. This large absorption spectrum allows them to capture a greater portion of the solar spectrum, leading to higher power conversion efficiencies.

Structure of a perovskite solar cell:
A typical perovskite solar cell consists of several distinct layers that work together to convert sunlight into electrical energy. The structure begins with a transparent conductive substrate, often made of materials like indium tin oxide (ITO) or fluorine-doped tin oxide (FTO). This substrate allows light to pass through and serves as the bottom electrode.



On top of the substrate, a compact layer is deposited to enhance the cell's electrical contact and improve charge extraction. This layer is commonly made of materials like titanium dioxide (TiO2) or zinc oxide (ZnO). It helps facilitate the efficient transfer of electrons from the active layer to the substrate.

Next comes the main component of the perovskite solar cell: the active layer. This layer contains the perovskite material, which is responsible for absorbing sunlight and generating electrical charge carriers (electrons and holes). The perovskite layer is typically composed of a metal halide perovskite, such as methylammonium lead iodide (CH3NH3PbI3) or the MAHL perovskite. The choice of perovskite material can vary depending on research or development preferences.

Above the perovskite layer, another charge transport layer is added to facilitate the extraction of holes generated in the perovskite material. This layer, known as the hole transport layer (HTL), is often made of organic materials like poly(3,4-ethylenedioxythiophene) (PEDOT) or poly(styrenesulfonate) (PSS).

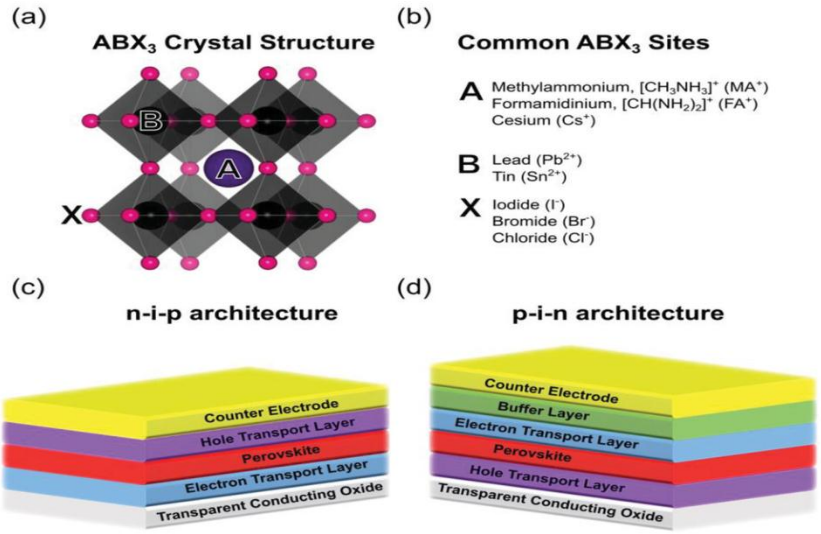
Finally, the top electrode, known as the cathode, is deposited on the hole transport layer. Common materials used for the top electrode include metals like gold (Au) or silver (Ag) or conductive polymers. The top electrode completes the circuit and collects the electrons generated by the perovskite layer.

In addition to this, in recent years hybrid organic-inorganic perovskites (HOIP) have been introduced. While both hybrid organic-inorganic perovskites (HOIPs) and typical perovskite solar cells share a similar structure, they do have a few key differences.

Hybrid organic-inorganic perovskites (HOIPs) have a unique structure that combines both organic and inorganic components. The crystal structure of HOIPs is based on the perovskite arrangement, where the organic cations are located in the interstitial spaces between the inorganic metal-halide framework. This structure gives HOIPs their distinctive properties, including their excellent light absorption capabilities and charges transport properties.

The inorganic metal-halide framework consists of metal cations, such as lead (Pb), tin (Sn), or a combination of different metals, and halide anions, such as iodide (I), bromide (Br), or chloride (Cl). The metal-halide framework forms a three-dimensional lattice structure, providing stability and structural integrity to the material.

Within the interstitial spaces of the metal-halide framework, organic cations are situated. The most commonly used organic cation in HOIPs is methylammonium (MA). These organic cations contribute to the unique optical and electronic properties of HOIPs, as they influence the bandgap and charge transport properties of the material.



So, in conclusion, the main difference lies in the composition of the organic cations incorporated within the perovskite structure. In typical perovskite solar cells, the most commonly used organic cation is methylammonium (MA). On the other hand, HOIPs refer specifically to perovskite materials that incorporate hybrid organic cations, such as a combination of MA and FA or other organic cations.

Uses of Perovskite solar cells:

There are several uses for perovskite solar cells such as:

1) The main use of perovskite solar cells is Photovoltaic Power Generation. Photovoltaic Power Generation: Perovskite solar cells have the primary application of generating electricity from sunlight. They can be used to produce clean and renewable energy, either in standalone systems or as part of larger solar power installations. In the future, as they get more efficient they show large promise in developing large-scale electricity generation.
2) Building-Integrated Photovoltaics (BIPV): Perovskite solar cells can be included in construction elements like windows, facades, or roof tiles to produce solar power in an appealing and seamless way. Buildings with perovskite solar cell BIPV systems have the potential to be energy-efficient and can lessen their dependency on conventional energy sources.
3) In the future, perovskite solar cells can be used in Portable and Wearable Electronics. The lightweight and flexible nature of perovskite solar cells makes them suitable for applications in portable and wearable electronics. They can be integrated into devices like smartphones, smartwatches, fitness trackers, or electronic textiles to provide a self-sustaining power source. Perovskite solar cells offer the advantage of high power density and the ability to operate under varying lighting conditions. Further, they can be integrated into various consumer electronic devices, such as calculators, wireless chargers, or portable speakers. These devices can benefit

from the ability to harvest solar energy, reducing the need for conventional battery charging and enhancing their overall sustainability.

4) Off-Grid and Remote Area Applications: Perovskite solar cells have the ability to provide electricity to off-grid and distant locations that are cut off from conventional power infrastructure. Their low-cost manufacturing and high power conversion efficiencies make them an attractive option for powering remote sensors, weather stations, agricultural equipment, and other small-scale applications in areas with limited electricity access. Further, Perovskite solar cells have shown great promise for space applications, where high efficiency, lightweight, and reliable power sources are crucial. Their potential use in satellites, space probes, and other space missions could enable more efficient power generation and reduce the weight and cost of space systems.

Perovskite Solar Cells VS Silicon-based Solar Cells:

Silicon-based solar cells, also known as crystalline silicon solar cells, are the most commonly used and well-established type of solar cells in the industry. There are 2 types of Silicon-based solar cells:

1) Monocrystalline Silicon Solar Cells: These solar cells are made from a single crystal structure of silicon. They have a high purity level and are known for their high efficiency. Monocrystalline silicon solar cells have a uniform and even appearance due to their crystal structure, which results in high power output per unit area.
2) Polycrystalline Silicon Solar Cells: Polycrystalline silicon solar cells are made from multiple small silicon crystals. They are less expensive to produce compared to monocrystalline silicon solar cells since the manufacturing process is simpler and requires less silicon material. However, their efficiency is slightly lower compared to monocrystalline silicon solar cells due to the presence of crystal boundaries that can impede the flow of electrons.

Both types of silicon-based solar cells operate on the principle of the photovoltaic effect. When sunlight hits the surface of the silicon material, it generates an electric current by separating electron-hole pairs. The cost of manufacturing Monocrystalline Silicon Solar Cells is still significantly high as the process to obtain high-purity silicon is a complex and expensive process.

Hence why in recent years, perovskite solar cells have gained significant popularity due to their greater efficiency, lower manufacturing cost, and greater flexibility.

Monocrystalline silicon solar cells typically exhibit a range of efficiencies between 15% and 24%, while polycrystalline silicon solar cells have slightly lower efficiencies, typically falling within the range of 13% to 16%. In contrast, perovskite solar cells have shown a theoretically achievable efficiency exceeding 33%.

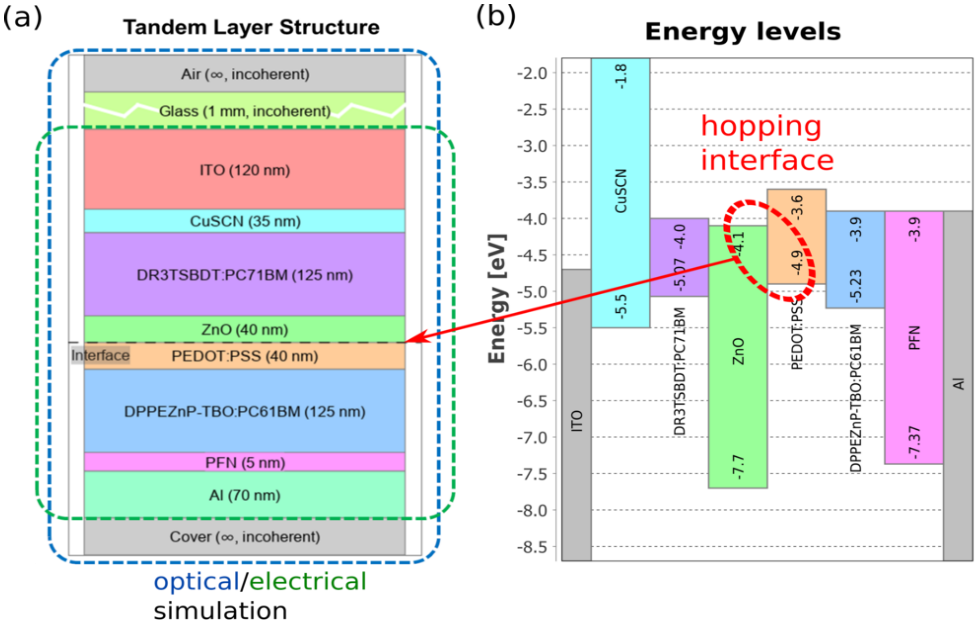
But, it's important to note that perovskite solar cells are still in the early stages of development and face challenges related to long-term stability, durability, and scalability. The materials used in perovskite solar cells can degrade in the presence of moisture and heat, which limits their outdoor durability. Hence, there are major research efforts focused on addressing these challenges to ensure the commercial viability of perovskite solar cells in the foreseeable future.

Multi-Junctional Cells

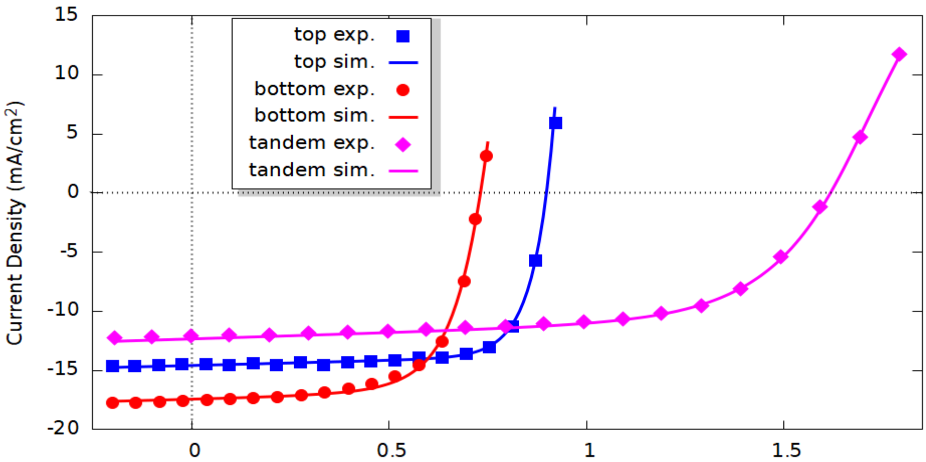
Designing multijunction solar cells requires optimization of a large number of structural and compositional parameters, such as band gaps and layer thicknesses of the component materials, but also the interlayer design for the series connection in the case of the industrially more relevant tandem devices.

While full optoelectronic device simulation including the recombination junction generated by the interlayer area is rare, optical simulation of the thin-film layer stacks in organic tandems is frequently used. The widespread use of silicon hetero-junction technologies, which combine large-scale textures with thin-film contact layers, as well as the peculiarities of the perovskite materials in terms of the effects of ion-migration, present difficulties for both optical and electrical simulation of such multijunction devices in the case of the perovskite-silicon tandem.

For a simulation of **organic tandem solar cells**, we consider the high-efficiency device architecture described in Li et al. Thin layers of CuSCN and PFN are used as anode and cathode buffer layers, respectively. The electrodes are formed by ITO and Al. The layer structure and the energy level alignment of the experimental model system used for the simulation. Accordingly, HOMO-LUMO (Frontier molecular orbital theory) levels are taken as indicated in the experimental reference, and the electron and hole transport levels of the individual bulk heterojunctions of the subcells. The initial layer stack and energy level alignment - including the hetero-interface - are displayed in the figure below.



Starting values for the optical and electrical parameters were taken from the literature. As in the experimental work, the single-junction solar cells were implemented with both absorber materials sandwiched between PEDOT: PSS as HTL and a PFN/Al contact. For the tandem simulation, the single junction material parameter values were taken as starting values and were kept at the same order of magnitude in the optimization of the new parameters for the CuSCN HTL, the ZnO ETL/interlayer, and the attempt-frequency for LUMO-HOMO (Frontier molecular orbital theory) transfer at the hopping interface. In this way, a good fit of all the JV curves could be achieved with a consistent parameter set, as displayed in the graph below.



Scalability

Scalability refers to the ability of a technology to be produced in large quantities and at a low cost, which is crucial for commercial viability and widespread adoption. While perovskite solar cells have shown remarkable progress in terms of efficiency and performance, scaling up the manufacturing process while maintaining their desirable properties has been a challenge.

An advantage of perovskite solar cells is their potential for low-cost and solution-based fabrication processes. Unlike traditional silicon solar cells, which require high-temperature and energy-intensive manufacturing techniques, perovskite solar cells can be fabricated using solution-based methods such as spin-coating, inkjet printing, spray coating, or roll-to-roll processes.

a) **Spin-coating process:** It involves depositing a solution containing the perovskite precursor onto a substrate, which is then spun at high speeds to create a thin, uniform film. The centrifugal force spreads the solution over the substrate, allowing for controlled deposition of the perovskite layer. Spin-coating offers simplicity, high precision, and good control over film thickness and morphology. However, it may not be suitable for large-scale production due to limitations in achieving uniform coatings over large areas.
b) **Inkjet printing:** It involves depositing precise droplets of perovskite precursor inks onto a substrate using an inkjet printhead. This allows for precise control over the deposition pattern and thickness, making it suitable for patterning complex structures. Inkjet printing offers the advantages of scalability, cost-effectiveness, and the potential for large-area fabrication. It also enables the

customization of perovskite solar cells, allowing for the integration of various designs and functionalities.

c) **Spray coating:** This method allows for the deposition of perovskite layers over large areas in a relatively short time. Spray coating offers scalability and potential for high-throughput production. It can be performed using various spray techniques, such as airbrush spraying, ultrasonic spraying, or aerosol jet printing. Spray coating has the advantage of being compatible with flexible substrates, making it suitable for roll-to-roll manufacturing processes.
d) **Roll-to-Roll processes(R2R):** These processes are continuous manufacturing methods used for the large-scale fabrication of flexible electronic devices. In the context of perovskite solar cells, R2R processes involve the sequential deposition of layers on a flexible substrate, such as plastic or metal foil. Techniques such as slot-die coating, gravure printing, or screen printing can be used in R2R processes to deposit the perovskite layers. These techniques allow for fast and continuous production, enabling the fabrication of perovskite solar cells on a large scale.

These techniques offer the potential for high-throughput and cost-effective production, making perovskite solar cells more scalable.

To improve the scalability of perovskite solar cells, researchers have focused on developing stable and reproducible manufacturing processes. This involves optimizing the formulation of perovskite inks, developing efficient deposition techniques, and refining the device fabrication steps. Process control and reproducibility are essential to ensure consistent performance and reliable production of perovskite solar cells on a large scale. For example, a recent development in optimizing the formulation of perovskite inks is adding additives for enhanced film formation. These additives can help modify the crystallization kinetics, nucleation, and growth of the perovskite film, leading to improved morphology, coverage, and crystallinity. Additives such as small organic molecules, surfactants, and solvents have been explored to enhance the perovskite film quality and reduce defects, resulting in improved device performance.

While significant progress has been made in improving the scalability of perovskite solar cells, there are still some challenges to overcome. Issues such as large-area deposition uniformity, upscaling of manufacturing equipment, and maintaining performance consistency across batches remain areas of active research. Additionally, the development of scalable and cost-effective methods for recycling and disposal of perovskite materials is also important for the long-term sustainability of the technology.

Recent Advancements in perovskite materials:

Recently, there have been multiple breakthroughs in the research of Perovskite materials :

1) Tandem and Multijunction Cells: Power conversion efficiency can be raised even more when the two technologies with complementary absorption spectra are linked in a tandem configuration. Recent advancements have focused on developing perovskite-based tandem cells by integrating perovskite layers with other high-performance photovoltaic materials, such as silicon or other thin-film technologies. These tandem structures have demonstrated remarkable efficiencies, surpassing the performance of individual solar cell technologies. The efficiency of the developed hybrid solar cell should surpass the sum of the single-cell efficiencies by a good margin. Calculations show that an efficiency between 25 and 30 percent would be possible.
2) Enhanced Stability: Stability and durability have been major problems for perovskite solar cells. The issues are mainly related to moisture, oxygen, and heat exposure. Researchers have tried multiple methods to solve these issues:
   a) One method is the incorporation of additives into the perovskite layer. They act as stabilizing agents, helping to passivate defects and prevent degradation mechanisms within the perovskite material. For example, molecules like small organic additives or inorganic salts have been used to enhance film quality, reduce non-radiative recombination, and inhibit moisture-induced degradation.
   b) Encapsulation technique. It plays a crucial role in protecting perovskite solar cells from environmental factors such as moisture and oxygen, which can degrade the perovskite material over time. Common ways to do the Encapsulation technique is the use of barrier layers, thin films, or encapsulation coatings to provide a protective barrier around the perovskite layer. These encapsulation techniques can significantly improve the device's stability by minimizing exposure to harmful elements and prolonging its operational lifetime.
   c) Engineering the composition and structure of perovskite layers is another avenue for achieving improved stability. By focusing on optimizing the chemical composition of the perovskite material by substituting specific ions or introducing mixed-cation and mixed-halide formulations, these changes can lead to more stable perovskite structures with reduced susceptibility to degradation under environmental stressors. Further, the use of 2D perovskites or Ruddlesden-Popper perovskite structures exhibits improved stability compared to their 3D counterparts. These alternative structures offer enhanced environmental resilience and better resistance to moisture and heat, resulting in more stable perovskite solar cells.

Overall, the imposition of the above-mentioned methods has led to significant progress in improving the stability of perovskite solar cells. These strategies have led to enhanced resistance to degradation mechanisms, extended operational lifetimes, and improved reliability, bringing perovskite solar cells closer to practical implementation and commercial viability.

3) Lead-Free Perovskites: In response to the environmental and health concerns associated with the presence of lead in perovskite materials, researchers have actively pursued the development of lead-free alternatives. The use of tin (Sn) as the main metal cation has been a major breakthrough recently. Tin-based perovskite materials

have shown promising results in terms of both efficiency and stability. For example, some tin-based perovskite compositions have achieved power conversion efficiencies (PCEs) exceeding 10%, which is a significant milestone in the development of lead-free alternatives. But there have a few hurdles to cross yet, stability, due to their tendency to undergo phase transitions and exhibit lower thermal and environmental stability compared to their lead-based counterparts.

Eliminating lead toxicity not only ensures the safety of manufacturing processes and end-of-life disposal but also facilitates the widespread adoption of perovskite solar cells. Lead-free perovskite materials have the potential to be used in various applications, including solar panels, as well as in other optoelectronic devices such as light-emitting diodes (LEDs) and photodetectors. Further, research on this topic will help pave the way for the commercialization of lead-free perovskite solar cells and their integration into sustainable energy technologies in the future.

Overall, 8 these recent advances in Tandem and Multijunction Cells; an experimental tandem cell with a power conversion efficiency of 33.2%, which surpasses the previous world record of 32.5%.

2. Conclusion

Perovskite solar cells have shown significant advancements in recent years, particularly in terms of efficiency, stability, and scalability. The development of tandem and multijunction cells, enhanced stability through additives and encapsulation techniques, and the exploration of lead-free perovskites are some of the notable advancements. While there are several major advantages of Perovskite solar cells such as their high power conversion efficiency, their potential for low-cost manufacturing, and the versatility of perovskite materials, scalability remains a challenge but can be addressed through solution-based fabrication methods like spin-coating, inkjet printing, spray coating, and roll-to-roll processes. Overcoming stability and reproducibility issues, optimizing the manufacturing cost, and establishing quality control measures are crucial for the widespread adoption and commercial viability of perovskite solar cells.

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