wjert, 2024, Vol. 10, Issue 12, 01-21. *Review Article* **ISSN 2454-695X**

World Journal of Engineering Research and Technology

WJERT

www.wjert.org **SJIF Impact Factor: 7.029**

TOWARDS ENHANCED PEROVSKITE SOLAR CELLS: A REVIEW OF MATERIALS, FABRICATION ENVIRONMENTS, AND TECHNIQUES

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Article Received on 27/09/2024 **Article Revised on 17/10/2024** **Article Accepted on 07/11/2024**

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ABSTRACT

One of the renewable energy sources, solar energy, is seen to be an effective substitute for fossil fuels, which have exacerbated climate change and had detrimental effects on the environment. The two methods for harvesting solar energy are solar photovoltaic (SPV) and concentrated solar power plants (CSP), with SPV being the most popular. Perovskite solar cells (PSCs) and silicon-based solar cells (SBCs) have demonstrated notable power conversion efficiency (PCE) within the SPV family. PSCs have been the subject of much research over the past 20 years, and because of their high absorption coefficient, effective carrier mobility, direct bandgap, long charge diffusion length, low cost, and flexible fabrication, they have shown great promise as a photovoltaic technology. These features make PSC a prospective candidate for replacing silicon in SPVs. By 2021, PSC achieved an encouraging PCE of over 25%. This review discusses PSCs commonly used and alternative materials, fabrication environments, and techniques. The influence of fabrication environments on the cell layers of thin films, and studies on the cell materials and fabrication techniques were also discussed.

KEYWORDS: Efficiency, Energy, Fabrication, Perovskites, Photovoltaic, Renewable, Solar.

1.0 INTRODUCTION

Like all solar cells, perovskite solar cells (PSCs) function by producing electron-hole pairs when photons, or light particles, from the sun strike the solar cell. This process is known as the photovoltaic effect. To assist the transit of these electron-hole pairs and produce an electric current, solar cells employ semiconductor materials, most commonly silicon (Green & Ho-Baillie, 2014). A p-n junction, which unites n-type (electron-rich) and p-type (hole-rich) semiconductors, is a feature of solar cells, and to separate and route charge carriers to produce an electrical current, this junction is essential. Nelson (2003) states that voltage is produced by the separated charges moving in opposite directions due to the electric field created by the p-n junction. The wavelength of light that a semiconductor material can absorb and transform into electricity is determined by its energy band gap. For solar cell applications, materials with band gaps that match sun spectra are chosen (Luque and Hegedus, 2011).

According to Williams and Farawar (2016), photovoltaic technologies can be broadly classified into two groups: thin-film solar cells, which are based on thin-film technology, and wafer-based, or first-generation PVs. Thin film solar cells, or perovskite solar cells, belong to the third generation of photovoltaic systems. PSCs use films that are only a few microns thick, which makes them, like other second- and third-generation solar cell manufactures, roughly 10 to 100 times more efficient than silicon solar cells. Both organic and inorganic components make up their active layers. This active layer's most prevalent structure is an organic-inorganic substance based on lead or tin halide (Williams and Faraway, 2016).

PSCs, or perovskite-based solar cells, can be inorganic or organic. The light-absorbing layer of organic PSCs, also known as organometallic halide PSCs, is made of hybrid perovskite materials that combine organic and inorganic elements. They belong to a class of crystalline materials having the formula ABX3, where X can be either chlorine, Cl, or bromine, Br, or iodine, I, and A can be either cesium (Cs), methylammonium (MA), or formamidine (FA); B can be lead, Pb or tin, Sn (Xiao et al., et al., 2017 in Cheng, So and Tsang, 2019). Methylammonium lead iodide ($CH_3NH_3PbI_3$) is the most used organic-inorganic perovskite compound. These substances are a mixture of inorganic metal halides like tin iodide and lead iodide with organic cations like formamidine or methylammonium (Aslam, Mahmoud and Naem, 2021).

Organometallic halide perovskites, or OHPs, have become a highly effective class of semiconducting materials that can be applied to a broad range of optoelectronic devices, such as photodetectors (Shen et al., 2017 in Cheng, So and Tsang, 2019), solar cells (Kojima et al., 2009; Cheng et al., 2015 in Cheng, So and Tsang, 2019), light-emitting diodes (Cho et al., 2015; Yu et al., 2018 in Cheng, So and Tsang, 2019), transistors (Yu et al., 2018, in Cheng, So and Tsang, 2019), and X-ray images (Wei et al., 2017 in Cheng, So and Tsang, 2019). Because of their promise for PV applications, OHP-based solar cells are the most researched devices among such applications (Kojima et al., 2009 in Cheng, So and Tsang, 2019). Conversely, all inorganic perovskite materials are used in inorganic PSCs as light-absorbing layers. Common examples include $CsPbI_3$, $CsPbBr_3$, or $CsPbCl_3$ (Sahu and Palei, 2023).

Conventional architecture and inverted architecture are the two types of PSC architecture that are commonly used. In a conventional architecture, the perovskite/HTL/top electrode, FTO/ETL/mesoporous metal oxide scaffold layer, and the n-i-p junction (Figure 1a) are assembled. Pinholes can be minimized, and the thickness of the perovskite layer increased by using the mesoporous metal oxide (mp - TiO2 or mp - Al2O3) as a scaffold layer (Lee et al., 2012). The common HTLs are PTAA and Spiro-OmeTAD, while the common ETLs are SnO2 and TiO2. According to Saliba et al. (2016), the conventional construction achieved the highest device efficiency to date. In this design, the perovskite absorber is positioned above the electron transport layer (ETL).

Inverted structure, p-i-n junction (Figure 1b) is made up of ITO/HTL/perovskite/ETL/top electrode. The common ETL is PCBM, and the common HTLs are PEDOT: PSS, PTAA, and NiO. Low-temperature procedures can be used to construct this structure. The perovskite absorber in this structure is topped by the electron transport layer, ETL (Lin, n.d).

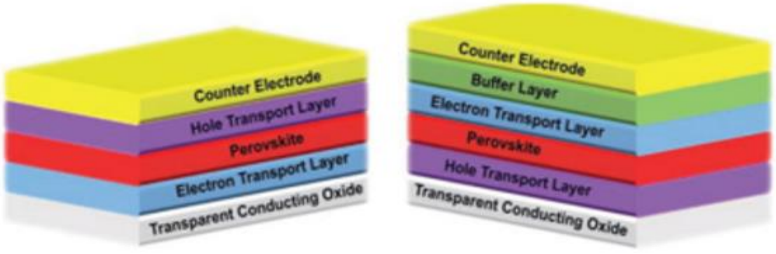

Figure 1: (a) Conventional n – i – p structure (b) Inverted p – i – n structure
Source: Zhang et al., 2021

Initially, dye-sensitized solar cells were used to create perovskite solar cells. The initial PSC device topologies were based on the standard DSSC structure, where the perovskite material served as the dye sensitizer. Following the substitution of the solid hole-transporting layer for the liquid electrolyte, device designs progressed to mesoscopic topologies. Later, device topologies changed to planar structures where the perovskite material alternated between layers that transported holes and those that transported electrons (Song et al., 2016).

There are two primary architectures that can be used to produce single-junction organic PSCs: the standard (n – i – p) architecture and the inverted (p – i – n) architecture. Although PSCs with n – i – p have the highest known PCE, PSCs with p – i – n are gaining popularity because of their high operating stability and current efficiency levels of above 22% (Zhimin et al., 2019; Zheng et al., 2020 in Zhang et al., 2021).

2.0 MATERIALS

2.1 Commonly Used and Alternatives

The three main layers that make up the structure of perovskite solar cells (PSCs) are the hole transport layer (HTL), the electron transport layer (ETL), and the perovskite absorber layer. While there are standard materials for each layer, research is continually looking for alternatives to enhance stability, performance, and environmental impact.

Lead-based perovskite known as methylammonium lead iodide, or $MAPbI_3$, is currently employed as the material for the absorber layer. It is well recognized that this material's lead content is hazardous to both people and ecosystems (Ren et al., 2022). Exposure to lead can cause a few health problems, with the neurological system, development, and cognitive function being notably affected. Furthermore, lead has the potential to be environmentally hazardous, particularly if it seeps into water or soil systems (Sanders et al., 2009). The extensive use of perovskite solar cells is in fact hampered by the possible toxicity of lead-based perovskite materials (O'Connor & Hou, 2021). Lead-based perovskites are being replaced with non-toxic tin (Sn)-based perovskites, such as $MASnI_3$. These materials present an eco-friendlier choice, although their efficiency and stability are currently being challenged. Perovskites based on bismuth (Bi) have also been studied because of their promise of good stability and non-toxicity. To improve their photovoltaic qualities, research is still being done (Suresh and Chandra, 2021).

The substance currently utilized for the electron transport layer (ETL) is titanium dioxide (TiO_2). However, the comparatively high conduction band location of this material may cause an imbalance with the energy levels of the perovskite layer. Charge recombination and a decrease in the device's overall performance may arise from this mismatch. There is a limited absorption of visible light by TiO2. Consequently, a considerable amount of incident sunlight might not be absorbed by the TiO2 layer, resulting in a decrease in the overall effectiveness of light harvesting (Murakami & Koumura, 2019). Because it can be processed at low temperatures and has a high electron mobility, zinc oxide (ZnO) is a possible substitute. Researchers are attempting to address the worry regarding its instability when exposed to UV light. Phenyl-C61-butyric acid methyl ester (PCBM), an organic molecule, has superior electron-accepting qualities and can be processed at low temperatures, which makes it a good substitute for inorganic ETLs (Mahmood, Sarwar & Mehran, 2017). Another alternate ETL material is nickel oxide (NiO), an inorganic HTL material with excellent hole mobility and good stability. When compared to organic HTLs, it is comparatively less expensive (Suresh and Chandra, 2021).

The PSC's hole transport layer is now made of Spiro-OMeTAD, yet using it comes with a number of difficulties. According to Huang et al. (2021), Spiro-OMeTAD is characterized by a poor electron affinity, oxidation susceptibility, high cost, intricate production methods, and the presence of heavy metals like cobalt and lithium. Low overall device efficiency may arise from inadequate electron extraction from the perovskite absorber layer due to the Spiro-OMeTAD's low electron affinity. Because of the material's susceptibility to oxidation, cell performance and efficiency may gradually deteriorate. Spiro-OMeTAD's intricate fabrication methods can cause performance variances and impede large-scale production. Concerns about sustainability and the environment are brought up by Spiro-OMeTAD's significant metal content. One organic semiconductor that has been utilized as a less expensive substitute for Spiro-OMeTAD is Poly(3-hexylthiophene) (P3HT). Although it provides good hole mobility and stability, more doping could be necessary to get the best results (Suresh and Chandra, 2021). Because of its stable and effective hole transport characteristics, nickel oxide (NiO), which is also utilized as an ETL, can function as an HTL. For inorganic HTLs, its affordability makes it a desirable choice. CuSCN, or copper thiocyanate, is an additional inorganic HTL material that shows promise. It is inexpensive, has high hole mobility, and provides exceptional stability. It is suitable with a variety of perovskite materials due to its transparency and wide bandgap (Suresh and Chandra, 2021).

2.2 Study on PSCs Materials

Many review studies have focused on solar cell materials and applications, as in Jung and Park (2015), Mahmood, Sarwar and Mehran (2017), Mesquita, Andrade and Mendes (2018), Ali et al. (2021), Suresh and Chandra (2021), and Bora et al. (2022).

The development of perovskite solar cells (PSCs) is the main topic of Jung & Park (2015), which also covers material science, fabrication methods, and improving device performance. The production of different perovskite materials and their deposition techniques, including vapor deposition and solution processing, are reviewed in this article. Device architectures such as planar, tandem, and mesoporous structures are analyzed. Efficiency, stability, and scalability are evaluated by characterization methods such as scanning electron microscopy, X-ray diffraction, and photovoltaic performance studies. The article shows that PSCs have significantly increased their efficiency, with gains of over 20%. It offers solutions for problems like scalability and stability, including compositional engineering and encapsulation. Because of PSCs' great efficiency, low production costs, and adaptability in device integration, the authors highlight their potential for use in commercial applications.

Mahmood, Sarwar and Mehran (2017) review materials and properties of electron transport layers (ETLs) in perovskite solar cells (PSCs) and their impact on efficiency. The authors analyze various inorganic and organic electron transport materials (ETMs) used in PSCs. They compare deposition techniques, such as spin coating and vapor deposition, and evaluate ETL properties like energy levels, charge mobility, and film morphology. The study includes a comprehensive review of performance metrics, stability tests, and the role of interfacial engineering in enhancing device efficiency and longevity. The review identifies TiO_2, ZnO, and fullerene derivatives as effective ETLs, enhancing PSC efficiency up to 20.1%. Key challenges include improving stability and reducing hysteresis. Strategies such as interface modification and new material exploration are suggested to address these issues, aiming for long-term stability and commercialization of PSCs.

Mesquita, Andrade, and Mendes (2018) discuss the materials, configurations, and stability features of perovskite solar cells (PSCs). The study employed a comprehensive review and analysis approach to evaluate various materials used in PSCs, their structural configurations, and the stability challenges associated with these solar cells. The findings highlighted key insights into enhancing PSCs' efficiency through material innovation, optimal configuration design, and strategies to improve stability for prolonged operational lifetimes.

The development, difficulties, and developments of large-area perovskite solar cells (PSCs) for scalable applications are the main topics of Ali et al.'s (2021) study. The review analyzes recent literature on PSCs, emphasizing material properties, fabrication techniques, and scalability issues. It examines various perovskite materials, including organic-inorganic hybrids, and assesses their performance metrics. The study evaluates different device architectures and their impact on efficiency and stability. It also highlights the challenges of scaling up from laboratory to industrial-scale production, including uniformity and defect management. The review identifies significant advancements in efficiency, with some PSCs achieving over 25% efficiency. Key challenges include enhancing long-term stability and scalability. Strategies such as compositional engineering and advanced fabrication methods are essential for improving performance and achieving commercial viability.

The main topics covered by Suresh and Chandra (2021) are the advancements, components, and uses of perovskite solar cells (PSCs). It offers a thorough evaluation of the various materials used in PSCs, their effectiveness, and their long-term stability. The purpose of the paper is to discuss the several issues that PSCs must deal with, such as manufacturing procedures, mechanisms of deterioration, and the possibility of large-scale commercial applications. The authors gathered and examined data from multiple PSC investigations using a thorough literature review methodology. They explored the effects of various perovskite materials on solar cell performance, such as all-inorganic and organic-inorganic hybrid perovskites. The review encompassed an assessment of diverse fabrication procedures, including vapor deposition and solution processing, to comprehend their impact on the performance and durability of PSCs. Additionally, the authors explored the role of different transport layers and electrode materials in enhancing the overall performance of solar cells. The power conversion efficiencies (PCE) of perovskite solar cells have significantly improved, according to the authors, often surpassing 25%. The study made clear that a key factor in determining the effectiveness and durability of PSCs is the selection of materials and construction techniques. All-inorganic perovskites showed superior stability in environmental circumstances, but hybrid organic-inorganic perovskites were recognized for their great efficiency. The assessment also noted important issues that must be resolved for PSCs to be commercially viable, including moisture sensitivity and thermal instability. The authors proposed that additional investigation into encapsulation methods and the creation of novel materials might aid in resolving these problems and open the door for the widespread use of PSCs.

The study conducted by Boro et al. (2022) focuses on a thorough evaluation of perovskite solar cells (PSCs). It mostly goes over the many materials that are used to make PSCs, assesses how effective PSCs are, and talks about stability concerns with PSCs. The authors thoroughly reviewed the body of research on PSC materials, fabrication techniques, and performance measures using a systematic review methodology. After that, efficiency and stability data from different research are compiled and analyzed to detect trends and important conclusions. Lastly, the authors examine how various perovskite compositions affect the overall efficiency and robustness of the solar cells. According to the study, because of their superior photovoltaic qualities, hybrid organic-inorganic perovskites—methylammonium lead iodide, or MAPbI3—are widely used materials. To address concerns about toxicity, recent research is also looking for lead-free substitutes. PSCs have seen impressive increases in efficiency; many lab-scale devices have reached over 25% efficiency. Device architecture, fabrication methods, and material composition are some of the elements that affect efficiency. For PSCs, stability is still a significant concern. The page lists several degradation processes, including UV-induced deterioration, heat, and moisture. To increase stability, it also covers several encapsulation methods and material modifications.

3.0 FABRICATION

3.1 Fabrication environments

Perovskite solar cells (PSCs) are extremely susceptible to the surrounding environmental variables throughout their manufacturing process. The fabrication environment has a vital role in influencing the quality and performance of PSCs (Fahsyar et al., 2021). Elevated humidity levels during the manufacturing process can have negative effects on the perovskite film, including the formation of small holes, an increase in surface roughness, and an unfavorable structure. These factors can ultimately result in the deterioration of the film's quality (Zhang et al., 2021). The primary environments examined in this review are inert and ambient.

An inert manufacturing environment refers to a controlled setting where reactive gases, like as oxygen and moisture, are absent. This is usually accomplished by utilizing a glovebox filled with inert gases like nitrogen or argon. The presence of this environment greatly improves the durability and longevity of perovskite solar cells (PSCs) by reducing the deterioration caused by moisture and oxygen. The presence of an inert atmosphere facilitates the creation of perovskite films of superior quality, characterized by a reduced number of imperfections, hence leading to enhanced solar efficiency. Conversely, an ambient fabrication environment denotes the typical climatic circumstances where the existence of air, which includes oxygen and moisture, is inevitable. The fabrication of PSCs under normal atmospheric conditions has shown a power conversion efficiency (PCE) that is comparable to those produced in controlled situations. The study conducted by Zhang et al. (2021) shown that the materials exhibited excellent long-term stability, with no deterioration observed upon exposure to air.

Fabricating PSCs in ambient circumstances eliminates the need for expensive equipment like gloveboxes and inert gas supply, making it a more cost-effective option. Nevertheless, when perovskite materials are exposed to moisture and oxygen, they undergo faster degradation, leading to reduced efficiency and shorter lifespans of the devices. To tackle these difficulties in natural surroundings, scientists must devise methods of encapsulation and create perovskite compositions that are more resilient to changes in the environment.

The selection between inert and ambient fabrication environments is contingent upon the objectives and limitations of the manufacturing procedure. Although it is generally preferred to create the most efficient PSCs in an atmosphere without any reactive elements, recent advancements have demonstrated great improvement in fabricating PSCs in a regular environment (ambient), resulting in power conversion efficiencies (PCEs) above 20%. In order to enhance the quality of perovskite films and maximize the efficiency of perovskite solar cells (PSCs) in a normal environment, it is necessary to employ several techniques such as additive engineering, solvent engineering, composition engineering, interface engineering, preheating procedures, and other related approaches (Zhang et al., 2021).

3.2 Influence of an Inert Fabrication Environment on PSCs Layers Thin Films

Perovskite materials exhibit sensitivity to moisture and oxygen, leading to the degradation of their structure and performance. By carrying out the fabrication process in an atmosphere devoid of reactive substances, the perovskite layers are shielded from the detrimental effects of the surrounding environment. This safeguarding measure significantly improves the long-term durability of the solar cells (Zhang et al., 2021). Decreasing the number of flaws and impurities in the materials results in enhanced charge transport and decreased recombination losses. This, in turn, can greatly enhance the power conversion efficiency of PSCs (Cheng, So and Tsang, 2019). Utilizing an inert atmosphere during the deposition process reduces flaws and impurities, leading to the production of superior perovskite/absorber layer films with fewer pinholes and improved crystallinity (Chadaram, 2021). Employing a regulated inert atmosphere during fabrication guarantees uniform and repeatable characteristics of the film, a critical factor for the widespread production and commercial utilization of PSCs (Fahsyar et al., 2021).

Titanium dioxide (TiO_2) and zinc oxide (ZnO), which are frequently utilized in ETLs, can experience surface oxidation upon exposure to air. Constructing the electron transport layer (ETL) under controlled conditions can greatly enhance the efficiency and durability of perovskite solar cells (PSCs). Creating inert conditions, which are often devoid of oxygen and moisture, is beneficial for minimizing the volume and interface flaws in ETL. These flaws can hinder charge transmission and decrease the overall performance of the device (Hossain et al., 2020).

Manufacturing hole transport layer materials for perovskite solar cells (PSCs) in an oxygen-free environment greatly enhances their structure, crystal quality, durability, and overall efficiency. The regulated atmosphere keeps the layers from being exposed to oxygen and moisture, both of which can negatively affect their quality. As a result, the improved film quality and durability of the PSCs contribute to increased efficiency and greater long-term stability. It is imperative to maintain an inert atmosphere during the fabrication process to achieve uniform and reproducible film characteristics. This is particularly important for large-scale manufacturing and commercial deployment (Shen et al., 2024).

The production of hole transport layers (HTLs) in an atmosphere devoid of reactive substances is essential for attaining optimal efficiency and durability in solar cells. The regulated environment facilitates the production of consistent and flawless thin films, which are crucial for effective charge extraction and reducing device malfunctions (Xu et al., 2020).

According to Parashar et al. (2021), it is conceivable to produce perovskite solar cells (PSCs) under normal atmospheric circumstances, and this can result in efficient devices. The study emphasizes that PSCs can retain their efficacy and stability even when manufactured in uncontrolled settings, hence rendering the manufacturing process more feasible and economical for mass production. Manufacturing in a non-reactive environment.

3.3 Influence of an Ambient Fabrication Environment on PSCs Layers Thin Films

Manufacturing perovskite solar cells (PSCs) in a normal atmosphere presents many difficulties because of the existence of moisture and oxygen. Environmental conditions have a notable impact on the shape and formation of perovskite thin films, as stated by Zhang et al. (2021).

Uncontrolled ambient conditions can cause fast and uneven crystal development, leading to irregular shape and unequal distribution of crystals in the perovskite layer. The variation in crystal development can have a negative impact on the efficiency and stability of the PSCs (Younas et al., 2021). To address these problems, scientists have devised techniques to regulate the manufacturing process, even under normal environmental conditions. The utilization of additives and the refinement of precursor compositions have demonstrated potential in enhancing the quality of films and the performance of devices (Fahsyar et al., 2021)

Recent progress has also concentrated on developing manufacturing methods on a wide scale that can uphold the production of high-quality films in normal atmospheric conditions. These encompass novel techniques for depositing and annealing materials that are more adept at managing the existence of moisture and oxygen during the manufacturing procedure (Krishna, Sunder and Tiwari, 2021).

Although there have been significant breakthroughs, perovskite materials are still highly sensitive to ambient conditions. This sensitivity requires meticulous monitoring and often the implementation of additional protective measures to maintain long-term stability and achieve high efficiency (Zhang et al., 2021).

Based on the information provided, it can be inferred that ambient fabrication offers practical and cost-effective advantages. Continued research is essential to overcome the difficulties related to ambient fabrication and fully use the capabilities of PSCs in practical applications.

3.4 Fabrication techniques

There are several ways to create perovskite thin films, including spin-coating, doctor-blading, filtering techniques, and more (Baker et al., 2017; Deng et al., 2015; Jeon et al., 2014). Thermal evaporation, chemical vapor deposition, inject-printing, spar coating, and slot-die coating are additional fabrication methods. While doctor blading and filtering are preferred for large-scale applications, spin-the coating is frequently utilized in lab-scale research due to its ability to generate high-quality thin films (Lin, 2020). To attain homogeneous morphology for the spin-coating approach, an antisolvent technique is frequently used (Jeon et al., 2014). Both the shape and the defect density of perovskite films can be affected by optimizing the mixed solvent mixture and selecting the appropriate antisolvent (Ahn et al., 2015; Paek et al., 2017).

Most high-efficiency organic PSCs are fabricated in a glovebox under inert conditions using a tiny device area, < 0.1 cm^2 (Lee et al., 2017; Cheng, So and Tsang, 2019). Even though large-area PSC fabrication has advanced significantly (Li et al., 2016). Due to the several elements that influence PSC deterioration, such as moisture, oxygen, UV radiation, and temperature, long-term stability under ambient working settings continues to be one of the major problems in PSCs (Yuan et al., 2016).

To create organic PSCs without the need for an inert environment, perovskite film growth needs to be carefully regulated in an ambient atmosphere to achieve good crystallinity and a clearly defined morphology. Additionally, roll-to-roll processing could be combined with cutting-edge industrially printed processes to enable the large-scale scaling up of PSCs (Zhang et al., 2021). Similar ideas that facilitate scale-up and stability have been proven (Zimmermann et al., 2019). Still, most large printed and stable PSCs have efficiency levels of no more than 20%.

Perovskite films manufactured in ambient atmospheres have made tremendous progress, but they typically have lower efficiency than PSCs fabricated in inert environments. Notably, research has also covered the advantages of an ambient environment (Zhang et al., 2020).

Achieving a power conversion efficiency (PCE) of over 25% in laboratory-scale perovskite solar cells (PSCs) has been made possible by enhancing the formulations of perovskite materials, improving the fabrication processes of the devices, and employing high-quality film formation methods. These advancements are based on a thorough understanding of the charge dynamics at the interfacial layers, as explained by Jeong et al. in 2020. High-performance perovskite solar cells (PSCs) typically consist of a sandwich structure, with a perovskite absorber positioned between a metal oxide-based electron-transporting material (ETM) and an organic hole-transporting material, HTM (Jeon et al., 2015; Heo et al., 2013; Snaith, 2013; and Stranks et al., 2013 in Jeong et al., 2020). HTMs have a crucial role in enhancing the performance of PSCs due to the ability to create high-quality perovskite and ETMs through different processing methods (Jeong et al., 2020). The exceptional optoelectronic characteristic of perovskite enables an increase in efficiency (Yin et al., 2016a; Wu et al., 2019a; and Jena et al., 2019 in Mazumdar et al., 2021). Jeon et al., 2014 utilized CH3NH3 Pb (I1 − xBrx)3 (x = 0.1–0.15), titanium dioxide, and poly(triarylamine) as absorbing, electron–transporting, and hole–transporting layers respectively, in order to construct an inorganic-organic hybrid PSC. This resulted in the formation of highly uniform and compact layers, achieving a certified power conversion efficiency of 16.2% without any hysteresis.

To enhance efficiency even more, researchers have investigated the use of tandem- and triple-junction solar cells. The integration of perovskite solar cells with other technologies such as silicon or CIGS (Copper Indium Gallium Selenide) shows significant potential for attaining improved efficiencies (Saliba and Beard, 2019).

3.5 Study on Fabrication Techniques of PSCs

For more than ten years, there has been extensive research conducted on the creation, analysis, and assessment of PSCs. This is evident in the studies conducted by Kojima et al. (2009), Jeon et al. (2014), Deng et al. (2015), Baker et al. (2017), Kim, Seo & Park (2021), Jeong et al. (2021), Parashar, Sigh and Shukla (2021), Zhang et al. (2021), and Lin et al. (2022). Although all eight research provide major contributions to the progress of perovskite solar cell technology, each study has a distinct focus on different issues.

Kojima et al. (2009) focused on developing perovskite material with the aim of determining if the material is an efficient visible–light sensitizer through testing. The study synthesized methylammonium lead halide perovskites and deposited them on mesoporous TiO2 layers (ETL) using spin-coating technique. Next, the researchers integrate the material into a cell structure with a hole transport material and a metal electrode. Subsequently, the cell was characterized using X-ray diffraction (XRD) and scanning electron microscopy (SEM) techniques. The last stage involves quantifying the current voltage, fill factor, and total power conversion efficiency of the solar cell. Subsequently, it was discovered that methylammonium lead halide perovskites demonstrated favorable photovoltaic characteristics, attaining a power conversion efficiency (PCE) of 3.8%. The discovery emphasized the capacity of perovskites for effective utilization in solar cell applications.

The study by Jeon et al (2014) centers on the enhancement and refinement of solvent engineering methods to enhance the efficiency and durability of inorganic-organic hybrid perovskite solar cells (PSCs). To regulate the perovskite layer's crystallization process, the researchers used a mixed solvent system. The study showed that solvent engineering greatly improves the perovskite films' shape and crystallinity achieving a power conversion efficiency of 16 %.

In 2015, Deng et al. successfully created highly efficient organolead trihalide (OTP) perovskite solar cells (PSC) using a straightforward, high-speed, and cost-effective blade coating method. Methylammonium lead iodide (CH3NH3PbI3) and Poly (3,4 - ethylene dioxythiophene): poly (styrene sulfonate) are commonly referred to as PEDOT: Perovskite solar cells (PSS) were utilized as absorbing and hole-transporting layers, respectively. The cell's efficiency was determined to be 12.8%.

Baker et al. (2017) sought to scale up and improve mesoporous carbon perovskite solar cell (PSC) production. Increased throughput is needed for efficient production methods that preserve PSC stability and performance. Their process involved layer deposition by screen printing, spin coating, and doctor blading, followed by thermal annealing. A high-throughput production approach using doctor blading, and mesoporous carbon layers produced photovoltaic solar cells (PSCs) with great efficiency and stability.

Kim, Seo and Park (2021) conducted research on enhancing the efficiency of perovskite solar cells (PSCs). Researchers created PSCs (perovskite solar cells) using methylammonium lead iodide (MAPbI3) perovskite via spin-coating. The work optimized device architecture and layer deposition processes and characterized photovoltaic capabilities using current-voltage measurements and stability testing under typical illumination conditions. Solution-processed PSCs achieved 9.7% power conversion efficiency (PCE), proving their feasibility. The study highlighted PSCs' promise for high-efficiency, low-cost solar applications with improved material and device architecture.

Jeong et al. (2021) conducted research specifically on the advancement and refinement of perovskite solar cells (PSCs). The researchers deployed compositional engineering approaches using mixed-cation and mixed-halide perovskites. They also used passivation techniques and advanced characterization tools such as photoluminescence and impedance spectroscopy. Assessed the performance of the device by conducting efficiency and stability tests, as well as analyzing degradation under real-world operating settings. The study successfully attained an efficiency increase of more than 25% by enhancing operational stability, which resulted in lower degradation rates. These findings suggest that technology has the potential to be commercially viable.

Parashar, Singh and Shukla (2021) study explore the fabrication of perovskite solar cells (PSCs) in ambient conditions, addressing the challenge of producing high-efficiency PSCs outside controlled environments. The researchers utilized a series of protective techniques to mitigate the effects of moisture and oxygen during the fabrication process. These include the use of specific precursor solutions and careful optimization of the fabrication steps. The study demonstrated that it is possible to achieve high-efficiency PSCs under ambient conditions with efficiency values comparable to those produced in inert atmospheres. This finding is significant for the scalability and practicality of PSC production through spin-coating fabrication technique.

The research conducted by Zhang et al. (2020) centers on the production of organic-inorganic hybrid perovskite solar cells (PSCs) under normal atmospheric conditions. This study investigates techniques for manufacturing perovskite solar cells (PSCs) in non-controlled conditions, such as gloveboxes, with the goal of enhancing the practicality and scalability of the fabrication process for industrial use. The authors devised a method for manufacturing PSCs in normal atmospheric circumstances. The procedure involves selecting materials with low sensitivity to moisture and oxygen, employing efficient techniques to deposit the perovskite layer and other components in the presence of atmospheric air using the spin-coating technique, designing the solar cell architecture to minimize the impact of ambient conditions on performance and stability, and utilizing various analytical techniques to assess the efficiency, stability, and other performance metrics of the fabricated PSCs. The study revealed that the PSCs produced in ambient conditions exhibited a power conversion efficiency (PCE) similar to those manufactured in controlled environments. Furthermore, these PSCs exhibited excellent long-term stability, with no deterioration upon exposure to air. The developed approaches have the capacity to increase the production of PSCs on a larger scale, hence decreasing the cost and intricacy of the manufacturing process.

The study conducted by Lin et al. (2022) examines the impact of a Cu2O buffer layer on the hole transport layers in perovskite solar cells based on MAPbI3. The objective is to enhance the efficiency and performance of these solar cells by improving the features of the interface.

The researchers utilize a Cu2O buffer layer in perovskite solar cells based on MAPbI3. The employed methodologies encompass layer deposition, interface characterization, and performance evaluation of solar cells.

4.0 CONCLUSION

This article summarizes issues with the commonly used materials for the three key layers (perovskite, electron transport, and hole transport) of PSCs and the alternative materials that can replace them. From the studies reviewed lead-based perovskite layer is being replaced with non-toxic tin (Sn)-based perovskites, such as $MASnI_3$. These materials present an eco-friendlier choice, although their efficiency and stability are currently being challenged. Perovskites based on bismuth (Bi) have also been studied because of their promise of good stability and non-toxicity. Zinc Oxide (ZnO) exhibits great potential as an electron transport layer substitute owing to its high electron mobility and appropriateness for processing at low temperatures. Researchers are attempting to address the worry regarding its instability when exposed to UV light. Organic compounds like phenyl-C61-butyric acid methyl ester (PCBM) is a good substitute for inorganic ETLs because they have superior electron-accepting capabilities and are compatible with low-temperature manufacturing. Another alternate ETL material is nickel oxide (NiO), an inorganic HTL material with excellent hole mobility and good stability. An organic semiconductor known as poly(3-hexylthiophene) (P3HT) has been employed as a less expensive substitute hole transport layer. Although it provides good hole mobility and stability, more doping could be necessary to get the best results. Nickel oxide (NiO), which is also utilized as an ETL, can function as an HTL because of its stable and effective hole transport characteristics. CuSCN, or copper thiocyanate, is an additional inorganic HTL material that shows promise. It is inexpensive, has high hole mobility, and provides exceptional stability. Wide bandgap and transparency allow it to work with different types of perovskite materials.

There was also discussion of the impact of an ambient and inert fabrication environment on perovskite film, as well as the numerous research conducted on the methods of fabrication. The quality and effectiveness of PSCs are significantly influenced by the fabrication environment. Inert atmospheres devoid of oxygen and moisture, also known as controlled environments, are essential for preventing perovskite layer breakdown and guaranteeing homogeneous thin film development. The objectives and limitations of the manufacturing process determine which inert or ambient fabrication environment is best. Even while the most efficient PSCs can be fabricated in an inert environment, new work has demonstrated that it is now possible to fabricate PSCs outside of a glovebox, or ambient environment, with PCEs above 20%. Fabricating perovskite solar cells (PSCs) in ambient conditions is feasible and can lead to effective devices.

There was discussion of the often-employed PSC manufacturing methods, including spin coating, vapor deposition, filtration, and solution processing. Although filtering and doctor blading are better suited for large-scale applications, spin-coating is frequently utilized in lab-scale research due to its ability to generate high-quality thin films. The doctor blading process is simple, inexpensive, and capable of achieving high PSC efficiency. Solvent engineering is a potent tool for PSC manufacturing optimization.

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