Analysis of Future Prospects of Perovskite-Based Solar Cells

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ABTRACT

A revolutionary all-solid-state, hybrid solar cell based on organic-inorganic metal halide perovskite ($CH_3NH_3PbX_3$) materials has piqued the interest of scientists all around the world, and is regarded as one of the top ten scientific accomplishments of 2013. Due to the advantages of its high extinction coefficient, high charge mobility, long carrier lifespan, and long carrier diffusion distance, perovskite materials can be employed not only as a light-absorbing layer, but also as an electron/hole transport layer. Perovskite solar cells' photoelectric power conversion efficiency has grown from 3.8 percent in 2009 to 22.1 percent in 2016, making them the greatest choice for a new generation of solar cells to replace existing silicon solar cells in the future. In this study, we outline the formation and process of perovskite solar cells, describe the distinct role of each layer, and concentrate on the enhancement of such layers' function and its impact on cell performance. The perovskite light-absorbing layer's synthesis methods and performance properties are then reviewed. Finally, the obstacles and potential for perovskite solar cell development are briefly discussed.

Keywords-- Solar Cells, Perovskite, Future Prospects, Structures and Functioning

I. INTRODUCTION

Traditional fossil energy sources cannot satisfy the sustainable growth of human society due to rising global energy consumption and pollution. The use of clean, renewable energy sources has become a requirement for human society's progress. Solar power, among a number of new energy sources, is unquestionably one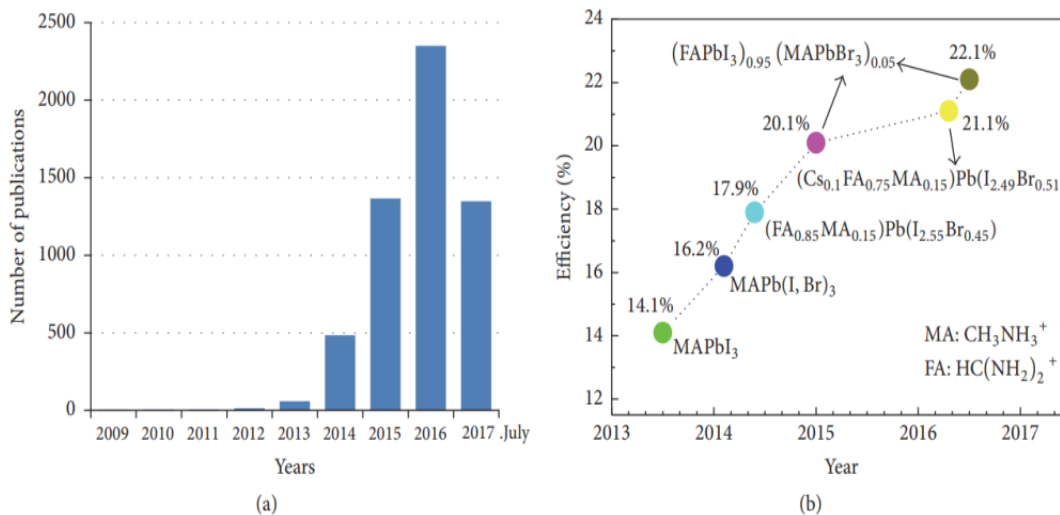 of the most promising. A solar cell is a device that uses photovoltaic or photochemical reactions to transform light energy directly into electrical energy. The photovoltaic effect was first identified in 1839 by the French physicist Becquerel. Adams et al., British scientists, discovered in 1876 that a selenium semiconductor could generate electricity when exposed to sunshine. In 1883, Frits created the first semiconductor/metal junction solar cell using a piece of germanium coated with a thin layer of gold, despite the efficiency being 1%. In 1954, Pearson et al. of US Bell Labs produced the first crystalline silicon solar cell with a conversion efficiency of 4.5 percent, ushering in a new era for solar energy usage. The photovoltaic conversion efficiency of monocrystalline silicon and polycrystalline silicon solar cells currently used in industrial applications is greater than 20%. However, silicon-based solar cells are expensive, require difficult preparation, and pollute the environment. In the laboratory, cadmium telluride and copper indium gallium selenium thin-film solar cells exhibit excellent photovoltaic conversion efficiency, but industrial applications are limited by high production costs, pollution, and other issues. As a representative of the third-generation solar cells, they have recently achieved a photoelectric conversion efficiency of more than 13% in the laboratory and have developed rapidly due to their significant advantages, which include low cost, simple process, and high efficiency. However, there are two drawbacks to dye-sensitized cells. To begin with, the absorbing layer is thick (> 10 m) to assure total absorption of sunlight's energy because complete light absorption in solid-state cells is difficult with a thinner absorbing layer. Second, light bleaching is a problem that organic dyes can't prevent. These Researchers have developed outstanding all-solid dye compounds in response to two issues. Kojima et al.

Figure 1: (a) The number of publications retrieved from the Web of Science (Tomson Reuters) by the subject search "perovskite solar cells" as a function of the year (b) The National Renewable Energy Laboratory (NREL) has certified the highest efficiencies of perovskite solar cells.

Japan discovered in 2009 that the organic metal halide perovskite is similar to dyes and can absorb sunlight. To reach power conversion efficiency (PCE) of 3.8 percent, perovskite can be used in desensitized solar cells with a liquid electrolyte as a sensitizer. Kim et al. reported for the first time in 2012 all-solid-state perovskite solar cells with a PCE of 9.7%. Perovskite solar cells have gotten a lot of interest recently because of their high efficiency and affordable cost. The National Renewable Energy Laboratory confirmed the highest conversion efficiency of 22.1 percent in 2016. (NREL). More advancements in perovskite solar cell performance are projected to break the conversion efficiency and production cost bottlenecks. Perovskite solar cells are of considerable scientific and practical significance as one of the most promising new photovoltaic cells. Figure 1 depicts the significant rise in the number of publications on perovskite solar cells, as well as the highest efficiency

certified by the National Renewable Energy Laboratory (NREL).

This study reviews recent achievements in perovskite solar cells and delves into the architecture and operating principles of perovskite solar cells, as well as the specific functions and characteristics of each layer and the methods used to create perovskite light-absorbing layers. Finally, based on the findings, we propose future study directions.

II.   PEROVSKITE SOLAR CELLS: STRUCTURES AND FUNCTIONING

2.1 Solar Cell Materials Made of Perovskite

The calcium titanate (CaTiO3) chemical, which has a molecular structure of type ABX3, is used to create the perovskite material. The cubic lattice-nested octahedral layered structures and unusual optical, thermal, and electromagnetic properties of perovskite materials have drawn a lot of attention.
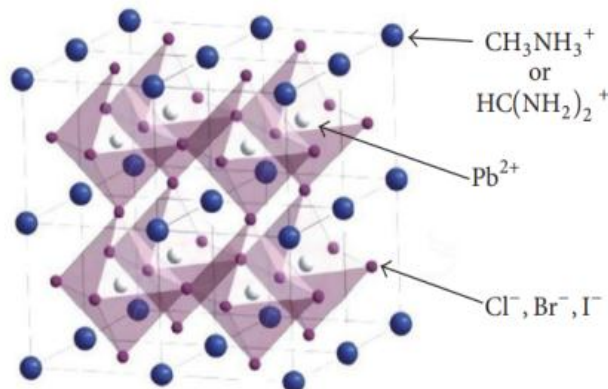
Figure 2: The cubic lattice structure of perovskites reprinted with permission

Perovskite materials are a type of organic inorganic metal halide compound with the perovskite structure, in which Group A (methyl ammonium, $CH_3NH_3^+$, MA^+, or formamidinium, $CH(NH_2)_2^+$, FA^+) is located in the vertex of the face-centered cubic lattice, and metal cation B (Pb_2^+, Sn_2^+, and so on) and halogen X anion(Cl^-, Br^-, or I^-, or a coexistence of several halogens)The metal-halogen octahedra are connected to produce a three-dimensional network structure that is stable. Figure 2 depicts the structure of the.

The materials with this structure have the four characteristics listed below. To begin with, the materials have outstanding photoelectric characteristics, low exaction binding energies, and high optical absorption coefficients (up to 10^4 cm^{-1}). Second, perovskite, as a light-absorbing layer, can efficiently collect solar energy. Finally, the materials have a high dielectric constant, which allows electrons and holes to be efficiently transferred and collected. Finally, electrons and holes can be sent at the same time, with transmission distances of up to 100 nm or even more than 1 m. If the materials are used in solar cell devices, these characteristics result in a high open-circuit voltage (V_{oc}) and a high short-circuit current density (J_{sc}). When you're out in the sun, you'll notice a difference in your skin.
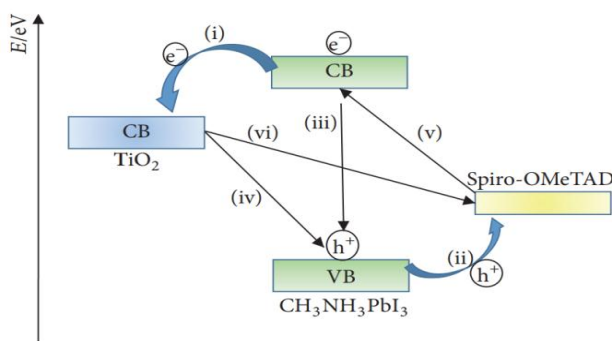

Figure 3: Energy levels and electron and hole transport processes in an HTM/perovskite/TiO_2 cell are depicted schematically to generate exactions, the perovskite layer absorbs light first (electron-hole pairs). These exactions can produce free carriers (free electrons and holes) to generate a current or can recombine into exactions due to differences in the exaction binding energy of the perovskite materials. The diffusion distance and lifetime of the carrier are lengthy because of the low carrier recombination probabilities of $CH_3NH_3PbI_3$ ($MAPbI_3$) and other perovskite materials, as well as the increased carrier mobility. The carrier diffusion distance for $MAPbI_3$ is at least 100 nm and for $MAPbI_{3-x}$ Cl_x is greater than 1 m. The increased performance of perovskite solar cells is due to the longer difusion distance and lifetime of carriers. An electron transport material (ETM) and a hole transport material (HTM) each collect ten of these free electrons and holes (HTM). Electrons are transmitted from the perovskite material to TiO_2, which is then employed for the ETM layers before being collected by FTO. The holes are tr ansmitted to the HTM layer at the same time and collected by the metal electrode. Finally,

the photocurrent is generated in the outside circuit by connecting the FTO and the metal electrode.

To achieve charge transfer, Marchioro et al. believed that electron-hole pairs separated at the two heterojunction interfaces of TiO_2/perovskite and Spiro-OMeTAD/perovskite, followed by electrons injecting into TiO_2 (process I in Figure 3) and holes injecting into HTM (process (ii)). At the same time, a number of undesirable behaviours, such as exaction annihilation (process (iii) , photoluminescence, or nonradioactive recombination, as well as reverse transmission of electrons and holes (processes (iv) and (v) and recombination at the TiO_2/HTM interface (process (vi), will occur. Figure 3 depicts the electron and hole transportation mechanisms in an HTM/perovskite/TiO_2 cell.

The mesoporous structure and the planar heterostructure are two types of perovskite solar cell structures that have been created in recent years. The microscopic architecture and the planar heterojunction structure of two typical perovskite solar cells are depicted in Figure 4. These two types of cell architecture are discussed below, along with their properties and research progress.

2.2 A Mesoporous Structure is a Term used to Describe a Porous Structure

Because of their high porosity and enormous specific surface area (up to 1000 m^2/g), mesoporous materials have been extensively explored and widely utilized. The use of mesoporous materials in perovskite solar cells allows the photosensitive material to stick to the mesoporous metal oxide framework, increasing the photosensitive material's light-receiving area and increasing the device's efficiency. A typical mesoporous solar cell has an FTO electrode, a dense electron transport layer, a mesoporous oxide layer, a perovskite layer, a whole transport layer, and an electrode layer, as illustrated in Figure 4 (a). The most common mesoporous framework material is TiO_2, which allows perovskite Nano crystals to infiltrate into the pores of mesoporous TiO_2 and form an interconnected absorbent layer by solution spin-coating. All of these help to improve the device's photoelectric conversion efficiency. TiO_2 plays a significant functional role in this structure, conveying electrons, preventing holes, and slowing the recombination of electron-hole pairs in the FTO conductive substrate. In addition to TiO_2, mesoscopic metal oxides such as ZnO, Al_2O_3, and ZrO_2 are often utilised as frame materials. The Te hole transport layer collects holes created in the perovskite absorbing layer and transports them to the metal electrode's surface. The most commonly used hole transport substance is spiro-OMeTAD (2,2´,7,7´-Tetrakis [N,N-di(4-methoxyphenyl) amino]-9,9´-spirobifuorene).Noble metals such as Au, Ag, and Pt are commonly used as counter electrode materials. This type of arrangement can effectively reduce electron and hole recombination while simultaneously providing the requisite diffusion length for effective electron and hole collection.

All-solid-state MAPbI3 solar cells based on the microscopic structure of porous nano-TiO_2 were reported by Kim et al. and Burschka et al. The FF were 0.62 and 0.73, respectively, while the PCEs were 9.7% and 15.0 percent. The high-quality perovskite films generated by the two-step solution deposition process are largely responsible for the remarkable improvement. Burschka et al. theorized that the conversion takes place within the nonporous host as soon as the two components (MAI and PbI_2) come into contact, allowing for far more control over the perovskite shape. At the end of 2014, Yang et al. announced a PCE of more than 20% using a microscopic TiO_2/$FAPbI_3$ perovskite solar cell architecture. Quiet et al. used a one-dimensional TiO_2 Nano array microscopic structure with MAPbI2Br as the light-absorbing layer to create all-solid-state perovskite solar cells with an V_{oc} of 0.82 V and a PCE of 4.87 percent. In their study, Quiet et al. found that when the length of the one-dimensional TiO_2 nanowire increased, the PCEs climbed and eventually declined, indicating a balance between electron transport and perovskite loading. Many scientists have explored the architecture of perovskite cells using Al_2O_3 as the microscopic material, since perovskite solar cells based on microscopic TiO2 require high-temperature sintering.
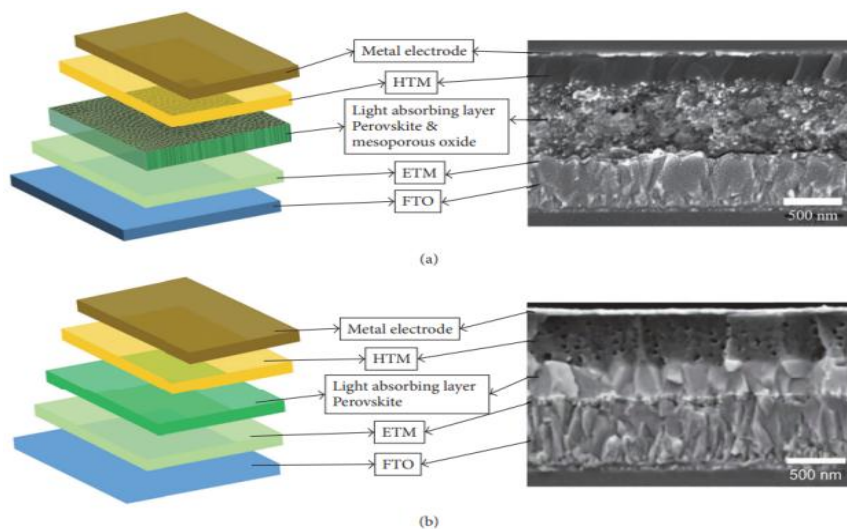
Figure 4: Schematic diagram and SEM section image of mesoscopic architectural PSCs and planar heterojunction structure PSCs, respectively

Unlike TiO_2, Al_2O_3 merely serves as a support layer in the device and does not have the same functional responsibilities in photo anode electron transport as TiO_2. As a result, the Al_2O_3 particle interaction becomes less critical, preventing high-temperature sintering. The electrons created by light irradiation in perovskite light-absorbing materials are not injected into Al_2O_3's conduction band, but are instead transferred directly from the perovskite to the FTO conductive layer. In 2012, Lee et al. developed $MAPbI_3$ perovskite solar cells with Al_2O_3 as the support material, achieving an V_{oc} of 980 mV, FF of 0.63, and PCE of 10.9 percent. The device's conversion efficiency climbed to 12.3 percent once the process conditions were optimized. To improve the PCE of Al_2O_3-based devices even further, $Au@SiO_2$ nanoparticles with a core shell structure were doped into the Al_2O_3 layer, resulting in a 11.4 percent photoelectric conversion efficiency. Insulating support layers such as Al_2O_3, ZrO_2, and SiO_2 can also be employed. The solar cells with ZrO_2 nanoparticles and $MAPbI_3$ have an V_{Oc} of 1070 mV and a PCE of 10.8%. Hwang et al. compared a series of perovskite solar cells with different sized SiO_2 nanoparticles (15–100 nm) as the support layer and found that the PCE was 11.45 percent when the size of the SiO_2 nanoparticles was 50 nm, which was slightly higher than the PCE (10.29 percent) of the devices with the same-sized TiO_2 nanoparticles.

2.3 Heterostructures on a Plane

Figure 4 depicts the typical planar heterojunction configuration of perovskite solar cells (b). The planar structure differs from the microscopic structure in that it eliminates the porous metal oxide framework. Between the perovskite materials and the two layers, two interfaces (the electron transport layer and the hole transport layer) are produced. As a result, the electron transport layer and the hole transport layer separate the electron hole pairs quickly and effectively. Research on perovskite solar cells with a planar heterojunction structure contributes to better knowledge of light absorption and electron-hole separation mechanisms, as well as device optimization flexibility for the development of highly efficient lamination perovskite solar cells. The $FTO/TiO_2/MAPbI_2Cl/spiro-OMeTAD/Ag$ planar heterojunction structure of perovskite solar cells published by Snaith's group had a PCE of 1.8 percent. Under ideal manufacturing conditions, Tereafer created a set of planar solar cells with a maximum PCE of 15.7 percent, an V_{oc} of 1.03 V, and an FF of 0.749.

By employing yttrium-doped TiO_2 as the electron transport material and modifying the ITO to lower the working function, Zhou et al. were able to achieve greater electron mobility. The device's open-circuit voltage and short-circuit current were considerably improved, with a PCE of 19.3 percent. Malinkiewicz et al. developed $MAPbI_3$ perovskite solar cells with a PCE of 12% by replacing the dense TiO_2 film with poly(3, ethylenedioxythiophene): polystyrene sulfate (PEDOT: PSS).

An inverted planar heterostructure is a type of structure that can be used to make flexible perovskite solar cells.

III. PEROVSKITE LIGHT-ABSORBING LAYER PREPARATION TECHNIQUES

The solution technique, the vapour-deposition method, and the vapour-assisted solution method are the

three types of synthesis methods for the light-absorbing layer of perovskite solar cells. The solution process is easy and cost-effective. However, in synthetic crystals, more internal flaws will be formed, and the whole transport layer will be in direct contact with the electron transport layer, lowering the device's filling factor and open-circuit voltage. The vapour-deposition process produces perovskite flakes with a high surface density and minimal defects, which improves the fling factor and open-circuit voltage. This approach, on the other hand, necessitates a high-vacuum environment and consumes a lot of energy. The benefits of both the solution and evaporation methods are combined in the vapour-assisted solution approach. At a lower vacuum, perovskites with fewer internal flaws can be produced. The various deposition processes for the perovskite layer are depicted in Figure 5. In Table 2, the fabrication procedures for perovskite layers are compared.

3.1 Method of Solution

According to the number of deposition processes, solution synthesis methods for perovskite materials can be divided into one-step and two-step methods. The manufacture of the perovskite light-absorbing layer in a single step is briefly detailed below. To make the light-absorbing perovskite layer, PbX_2 and MAX are dissolved in solvents at a specific stoichiometric ratio, which is then immediately spin-coated on a TiO_2 substrate and dried at an appropriate temperature and environment. The solvent utilized, the annealing temperature, and the annealing time all have an impact on the crystal quality and characteristics of the perovskite layer. Although the one-step deposition procedure is simple, controlling the form and size of synthetic crystals is difficult. Liang et al. were the first to suggest a two-step sequential deposition approach. The precursor solution for the spin-coating on the TiO_2 substrate in this approach is a saturated methanol solution of PbI_2. The PbI_2-coated substrate is then submerged in a 2-propanol solution containing MAI for an appropriate amount of time before being washed with 2-propanol. The PbI_2 interacts with MAI and forms the perovskite layer after drying at a sufficient temperature.

TABLE 2: A comparison of the common fabrication techniques.

Method	Description	Advantages	Disadvantages
One-step solution deposition	A solution containing the organic and inorganic components is spin-coated on a substrate followed by annealing to form perovskite	Cost-effective, straightforward to implement	Poor film quality leads to limited efficiency, choice of a solvent that can simultaneously dissolve both components is limited
Two-step solution-based processing	A solution of the inorganic component is spin-coated on a substrate, subsequent spin-coating (or immersing) of a solution containing the organic component followed by annealing	Better photovoltaic performance compared to one-step methods	Less control over film thickness as compared to vacuum processes
Dual-source vapour deposition	The organic and inorganic components are coevaporated and then annealed to give perovskite	Better film uniformity, as compared to solution processes leading to better efficiencies	Vacuum process leads to high energy requirements, and it is difficult in simultaneously controlling the deposition rates of both components
Sequential vapour deposition	A bilayer film of the inorganic and organic components is prepared by sequential deposition, followed by thermal annealing to give perovskite	Eliminates problems of one-step codeposition	Vacuum process, which leads to high energy requirements, higher costs, limiting mass production
Vapour assisted solution process	First, an inorganic component is deposited by spin-coating and then is exposed to the vapour of the organic component at an elevated temperature	Combination of vapour and solution-based processes gives better film quality	Vacuum process leads to high energy requirements

The morphology and optoelectronic properties of functional $MAPbI_3$ films are influenced by dipping time and MAI solution concentration. Burschka et al. used a slightly modified two-step process to make perovskite solar cells with a high PCE of 15% instead of dipping the PbI_2 film. The two-step approach is superior to the one-step solution method for fabricating perovskite films under high humidity, while relative humidity of less than 60% has a negative impact on overall performance.

3.2 Method of Vapor Deposition

The synthesis of the perovskite absorbing layer via vapour-deposition is usually done in a high-vacuum environment. Thermal evaporation from dual sources of PbX_2 and MAX deposits PbX_2 and MAX on the percolated TiO_2 substrate simultaneously or alternately. At the proper temperature and environment, $MAPbX_3$ is produced and then crystallized into a perovskite film. Snaith et al. were the first to describe evaporation-deposited $MAPbI_3$ film and use it in planar heterojunction perovskite solar cells, reaching a PCE of 15.7 percent and a J_{sc} of 21.5 $mAcm^{-2}$. The process, however, necessitates a high temperature to convert solid PbI_2 to vapour. The procedure necessitates a lot of equipment and can emit harmful fumes. If a new metal halide with a low evaporation temperature and low toxicity could be created and chosen to replace PbI_2, the

problems of perovskite layer production could be eliminated.

A modified vapour-deposition method known as "sequential vapour deposition" was proposed, in which PbX_2 was deposited first by thermal evaporation, followed by MAX vapour deposition. Because it's difficult to keep track of the MAI deposition rate during the code position process, this sequential deposition was created. The photovoltaic performance of sequentially deposited devices was shown to be highly dependent on the substrate temperature. According to Chen et al., the devices based on $MAPbI_3$ perovskite thin films made by the sequential vapour-deposition process had a PCE of 15.4 percent, according to Chen et al. Forges et al. announced a perovskite/perovskite tandem solar cell with a maximum PCE of 18% manufactured via sequential vapour deposition, demonstrating the potential of sequentially formed multilayer structures to improve the efficiency of single-junction perovskite devices.

3.3 Method of Solution with Vapour Assist

The vapour-assisted solution approach is a cost-effective way to make high-quality light-absorbing perovskite layers. It was created to overcome the shortcomings of both the solution and vapour-deposition methods. The following is a diagram of the vapour-assisted solution procedure. $MAPbX_3$ grains form by in situ reaction in MAX vapour at $120–165^0$ C in a nitrogen environment for 2–4 hours after PbX_2 is placed on FTO glass covered with TiO_2. Using the vapour-assisted solution approach, Chen et al. developed perovskite films with microscale grain sizes, minimal surface roughness, and total surface coverage for the first time. The films were used in planar heterojunction perovskite solar cells, and the average PCE was 12.1% with high repeatability. The $PbX_{2\ films}$ at the bottom of the perovskite cells cannot completely react with the MAX vapour in the vapour-assisted solution approach, raising the internal resistance and lowering the output power of the perovskite cells.

The development of preparation methods seeks to obtain compact perovskite flakes with high purity, few flaws, and high coverage among the above-mentioned preparation methods. The primary goals of this research are to increase the electrical contact between different layers, reduce defect density and carrier loss during transmission, and achieve high power conversion efficiency.

IV. CONCLUSION

This study reviews the principles and basic architecture of perovskite solar cells and discusses recent advancements in these materials. The adaptability of the perovskite light-absorbing layer manufacturing techniques, which include solution-deposition, vapour-deposition, and vapour-assisted solution procedures, is appealing, and these approaches are also described.

Perovskite solar cells have progressed quickly, however some crucial variables may limit their advancement. First, external environmental conditions (such as humidity, temperature, and UV light) have a significant impact on the stability of organic lead halide perovskite, resulting in low device stability and significant difficulties enclosing cells later on. As a result, developing a high-stability device composition, including the light-absorbing layer, electron/hole transport layer, and electrode materials, as well as developing a simple and effective device-packaging process, will be critical in promoting the viability of such devices. Second, the hole transportation substance Spiro OMeTAD, which is utilized in perovskite solar cells, is costly (10 times the market price of gold) and the synthesis procedure is difficult. To advance commercial uses of perovskite solar cells, it is therefore required to design and synthesize novel whole transport materials. Finally, because it is difficult to deposit a wide area of continuous perovskite film using the standard methods mentioned above, other methods should be improved in the future to manufacture high-quality, big-area perovskite solar cells for commercial manufacturing. Fourth, the Pb element used in perovskite solar cells is exceedingly poisonous, which will stymie perovskite solar cell industrialization. As a result, a low-toxicity or nontoxic component must be found in the future to replace Pb. Finally, the microscopic physics mechanism of perovskite solar cells remains poorly understood. As a result, a comprehensive theoretical model is required to explain why conversion efficiency is increasing. Theoretical research will not only aid in improving the performance of perovskite solar cells, but will also provide ideas for developing new materials and structures that are simpler and/or more efficient. In a nutshell, all of the aforementioned difficulties must be resolved before perovskite solar cells may be fully utilized.

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