



Synthesis of Novel Perovskite-organic Hybrid Materials for High-efficiency Photovoltaic Devices

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Herein, we reviewed the synthesis methods of perovskite organic hybrid materials for high-efficiency photovoltaic devices. Perovskite material has a chemical structure of ABX₃ that resembles that of CaTiO₃. In this type of material, A is an organic cation, B represents a metal

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cation species, and X represents a halide ion. The devices are widely applied due to a number of factors such as long charge carrier diffusion lifetimes and length, high absorption coefficients, and good optical absorption band edge. The power conversion efficiency of the perovskite organic-inorganic hybrid is about 25 %, which illustrates the rapid increase and the need for commercialization. To improve the performance of the perovskite materials, synthesis techniques such as solid phase synthesis, as well as gas phase synthesis, and liquid phase synthesis are applied. The X-ray diffraction technique is discussed as a tool for crystal structure determination of the materials, as well as scanning electron microscopy for morphology. This review summarizes the common synthesis techniques for perovskite solar cells and how the morphology and structural properties influence device performance.

Keywords: Perovskite; organic cation; inorganic metal cation; halide; X-ray diffraction.

1. INTRODUCTION

Solar power has seen considerable technological advancements in recent years, making it the number one source of naturally abundant energy. China has the greatest growth rates, while the United States and Japan follow in line. Following them are three European countries: the United Kingdom (4th), Germany (5th), and France (6th) [1].

In order to expand their market presence, alternative technologies must offer an appealing mix of superior power conversion efficiency, cost-effective production, and exceptional stability. Due to their remarkable efficiency and affordability in terms of production, hybrid organic-inorganic metal halide perovskite, or $\text{CH}_3\text{NH}_3\text{MX}_3$ or MAMX_3 , also known as perovskite solar cells (PSCs), have the potential to become a dominant technology in the photovoltaic (PV) industry. Here, MA stands for CH_3NH_3 , M for Pb or Sn, and X for Cl, Br, or I. PSCs have outperformed silicon-based solar cells thanks to substantial research undertaken worldwide during the past eight years, especially in laboratory settings [2,3,4]. The discovery of the calcium titanate, sometimes referred to as calcium titanium oxide (CaTiO_3), in 1839 by German mineralogist Gustav Rose led to a marked growth in the field. Perovskite, which is the name of the mineral, is in recognition of the Russian mineralogist Lev A. Perovskite (1792–1856) [5]. In the hybrid organic-inorganic metal halide perovskite ($\text{CH}_3\text{NH}_3\text{MX}_3$), a cationic organic compound, CH_3NH_3^+ , a cation of a divalent metal (Pb^{2+} or Sn^{2+}), and a monovalent halide anion (Cl^- , I^- or Br^-) are present. Due to their exceptional optoelectronic characteristics and the possibility of synthesizing them by solution-based methods [6,7,8], researchers have investigated these materials for the purpose of creating novel substances for organic diodes [9] and transistors [8].

Kojima and coworkers have used $\text{CH}_3\text{NH}_3\text{PbBr}_3$ and $\text{CH}_3\text{NH}_3\text{PbI}_3$ as sensitizers in solar cells since 2009. These kinds of solar cells have significantly advanced as a result of this. These cells have not only increased from 3.8 % to 20.8 % in power conversion efficiency (PCE), but they also have favourable characteristics like long charge carrier diffusion length, high absorption coefficients, narrow band gaps, good carrier mobility, low cost, and simple fabrication procedures [10,11]. The remarkable outcomes were mostly attributed to the organic-inorganic perovskite composite. Perovskite's chemical formula is generally written as ABX_3 , where A represents organic cation (like CH_3NH_3^+), B shows metal cation (like Pb^{2+}), and X for a halide anion as shown in Fig. 1.

The hybrid organic-inorganic lead halide perovskite chemical was initially used in 2009 as a sensitizer for solar cells that are sensitive to visible light. The obtained efficiency was 3.8 % for X = Br and 3.1 % for X = I when exposed to one solar irradiation [10]. Using material made of perovskite as a sensitizer in quantum dot-sensitized solar cells (QDSS) in 2011 produced a 6.5 % efficiency [13]. Although the liquid electrolyte created instability, these two results showcased the potential of perovskite for usage in solar cells. The initially fabricated solid-state perovskite, which had an efficiency of 9.7 %, was found in 2012 [14]. Another work was published in the same year in the sphere of science, reporting a solid-state perovskite with an efficiency of 10.9 % [15]. Since then, solar cells using perovskite have rapidly improved, reaching a peak efficiency of 22.1 % in 2015. Within a short time, the outstanding development made in perovskite solar cells established them as the most significant scientific achievement in the photovoltaic sector [16,17,18]. The production of superior perovskite thin films largely entails two deposition techniques: solution-based deposition

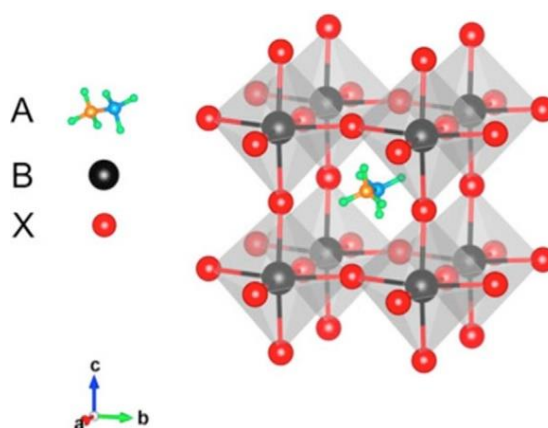


Fig. 1. The standard chemical formula for PSC hybrid organic-inorganic metal halide [12]

and vapor-based deposition. The solution-based deposition method is both economically efficient and friendly during operating conditions, particularly when working with flexible substrates [19,20,21].

Furthermore, the vapor-based deposition process is a technique that can be commercially used in the production of PSCs [22,23]. It has been observed that the deposition techniques are efficient and involve minimum material consumption. There are numerous reasons why scientists are drawn to the PSCs industry. The HOIP-based materials have a variety of exceptional optical and electrical characteristics, making them ideal for use in solar applications.

2. SYNTHESIS INORGANIC-ORGANIC PEROVSKITE DEVICES

Recent research has demonstrated that hybrid halide perovskite exhibits a photoelectric phenomenon. As a result, it is applied in energy capture and utilization for domestic purposes. In 2009, Miyasaka et al. introduced the hybrid perovskite solar cell, which attained a power conversion efficiency (PCE) of 3.8 %. PSCs have achieved a power conversion efficiency (PCE) of 25.7 % within a relatively short period [24]. The increased effectiveness of this competition is due to the excellent optoelectronic properties of the hybrid PSCs [25,26,27,28,29]. Minemoto et al. [30] discovered many important characteristics of the material, such as a direct energy band gap, a good absorption coefficient, and advantageous charge transport properties.

Nevertheless, the inability of perovskite absorbers to maintain stability in the presence of air limits the impressive increase in power conversion efficiency in hybrid halide perovskite.

Shorter diffusion lengths and higher trap state densities of polycrystalline thin-sheet perovskite solar cells have a significant impact on their efficiency [25,30]. Perovskite single crystals have a substantially reduced trap state density in comparison to polycrystalline thin films, which are about six times lower. Furthermore, their diffusion length is quite long, often measured in micrometres [30]. Utilizing large grain-sized or single-crystal perovskite material led to a boost in the efficiency of solar cells [28]. The notable improvement in perovskite efficiency may be ascribed to the heightened mobility and diffusion length of carriers, which arise from the decrease in charge trapping due to the lowering of the interfacial area associated with big grains. This reduction also reduces hysteresis.

Moreover, the decrease in the size of major imperfections in the extensive grains also enhances the enhancement [29]. Consequently, it is imperative to select a perovskite material with a high level of crystallinity to improve the efficiency of solar cells. Despite significant progress in the efficiency of PSCs, the issue of environmental sustainability and stability remains unresolved. Recent research has demonstrated that the organic components present in the PSCs exhibit inadequate thermal and light stability [30,31]. Bello et al. [32] investigated the benefits of single-crystal synthesis in comparison to polycrystalline synthesis. The investigation uncovered the absence of grain boundaries in the structure of a single crystal, which enhances its resilience under severe weather conditions. Significant research efforts have been focused on this goal in recent years [33,34].

The structural stability of a material refers to its ability to retain a certain crystalline phase despite changes in temperature and pressure without

exhibiting polymorphism [34]. The insufficient stability of perovskites may be attributed to two primary categories: external and internal factors. Extrinsic variables refer to factors in the external environment, such as oxygen and moisture. On the other hand, internal factors include thermal instability, hygroscopicity, and ion migration [35]. The inherent instability of HOIP solar cells under the influence of water, air, heat, and Ultraviolet radiation results in the degradation of the perovskite absorption layer. According to research by Frost et al. [36], MAPbI₃ can bond with a water molecule and take up a hydrogen ion from the methylamine ion. This eventually leads MAPbI₃ to degrade into a hydrate of hydrogen iodide (HI) and methylamine. It was found that substituting organic ions with ion groups that do not include protons, such as (CH₃)₄N⁺, would boost perovskite stability. Moreover, the presence of toxic heavy metal in the most widely used cluster (MAPbI₃) has made it more difficult to commercialize and increased the likelihood that it would degrade in humid environments. Thus, this study examines the assertion made by Frost and his team members to produce a unique type of lead-free organo-inorganic halide perovskite and evaluates its environmental friendliness, moisture stability, and appropriateness for use in solar cells.

2.1 Solution Processing-Based Method

Solution processing techniques commonly achieve the deposition of perovskite. Many

techniques for processing solutions include drop-casting, doctor blade, spin-coating, screen printing, dip-coating, spray-coating, inkjet printing, and slot die coating [37].

2.2 Vapor-Based Deposition (VBD)

Compared to solution-processing methods, the VBD provides a solution for creating photovoltaics (PVs) and shows the fabrication of uniform films. Large-scale applications of this method are mostly found in the thin-film solar industry, liquid crystal displays, and glazing. The perovskite layer's thickness affects the solar cells' absorption efficiency. Since it takes longer for electrons and holes to reach their contacts in thick films, they operate for longer periods of time than thin layers, which absorb less sunlight. Suppose the film is not homogenous across its region. In that case, it will come into contact with both the hole transport material (HTM) and the electron transport material (ETM), causing the fill factor (FF) and open-circuit voltage (Voc) to decrease. Vapour-based deposition outperforms other technologies due to its ability to manufacture large-scale multi-stacked thin films with consistent thickness. However, vacuums are required throughout the vapour-based deposition process to increase the average particle travel distance between hits, which leads to the production of very clean and uniform thin films. There are two main classifications for the vapor-based approach: physical and chemical [37].

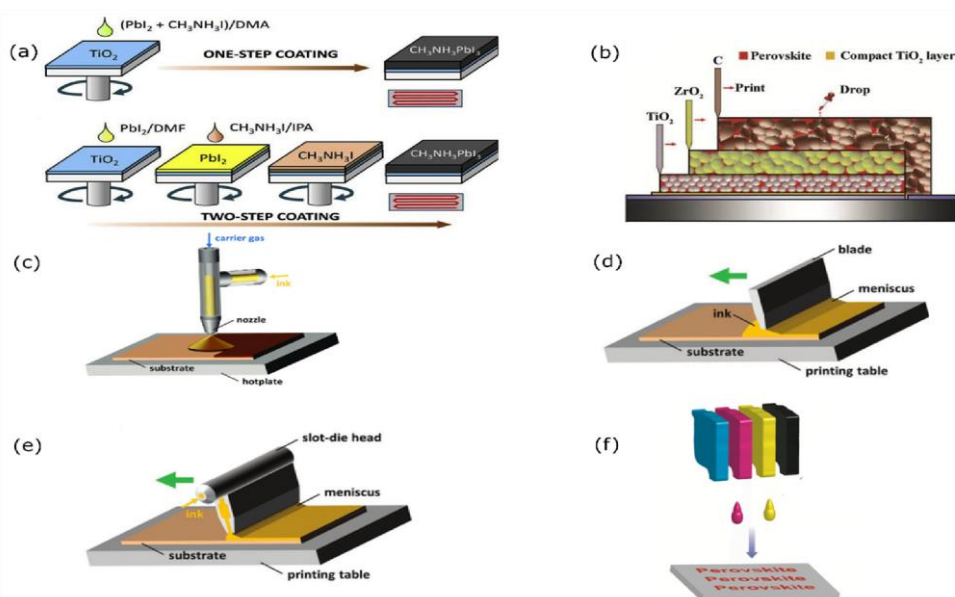


Fig. 2. Different PV fabrication techniques: (a) spin coating [38], (b) drop-casting [38], (c) Spray-coating, (d) doctor blade, and (e) slot-die coating [39], (f) Inkjet printing [40]

2.3 Chemical Vapor Deposition (CVD)

PVs, which have good scalability and no pinholes, are deposited on a massive scale using chemical vapour deposition (CVD) technology. By using two different precursors in a co-evaporation technique, the layers of the perovskite are deposited. A carrier gas (argon) is mixed with the precursor, heated, and then deposited at a lower temperature on a substrate. The films produced by this technology have larger sizes, longer carrier lifetimes, are perfectly uniform, and are free of pinholes. Perovskite layers have mostly been made by chemical vapour deposition (CVD), which has been employed to reduce the drawbacks of using small amounts of materials and the difficulties involved in controlling flux deposition [41,22]. Chemical vapour deposition (CVD) can also be easily scaled up for perovskite layer depositions and produces a significant material yield ratio [42]. Still, a vacuum and constant co-evaporation of the sample material are requirements, which are challenging to apply in an industrial setting.

3. PEROVSKITE TANDEM PHOTOVOLTAICS

It has been proposed that perovskite tandem photovoltaics (PVs) can enhance the overall resilience, longevity, and performance of perovskites. In a tandem photovoltaic (PV) system, a perovskite layer covers a cell, which might be copper indium gallium selenide (CIGS) or silicon [43]. This configuration allows for increased efficiencies beyond the limit of a single

junction [44] without significantly increasing manufacturing costs [45,31]. Sixty-seven per cent of the solar energy that PV cells receive is wasted because of the semiconductors' poor absorption capacity. Semiconductors absorb photons with energy higher than their bandgap energy (E_g), converting the received energy into an amount equal to E_g . This would have a significant impact on a photovoltaic (PV) system's power conversion efficiency (PCE), which is directly correlated with the open-circuit voltage (V_{oc}) and short-circuit current of the PV cells (J_{sc}). Tandem photovoltaics are a practical solution for this problem [46].

Tandem photovoltaics (PVs) use stratified structures made of different bandgap materials. Higher bandgap materials are found toward the top of the cell, whereas smaller bandgap materials are found near the bottom. The materials at the bottom of the stack efficiently use the bulk of the incoming energy by absorbing low-energy photons and absorbing high-energy photons. One of the most well-known tandem cell structures is the double-junction tandem device. Depending on the stacking method used, the system configurations may be divided into two categories: two-terminal (2-T) and four-terminal (4-T) tandem [46].

A front cell, an opaque rear electrode, and a transparent front electrode are arranged to form the 2-T tandem cells. As shown in Fig. 3, the rear cell is a substrate that is divided from the front cell by an interconnection layer (ICL) [47].

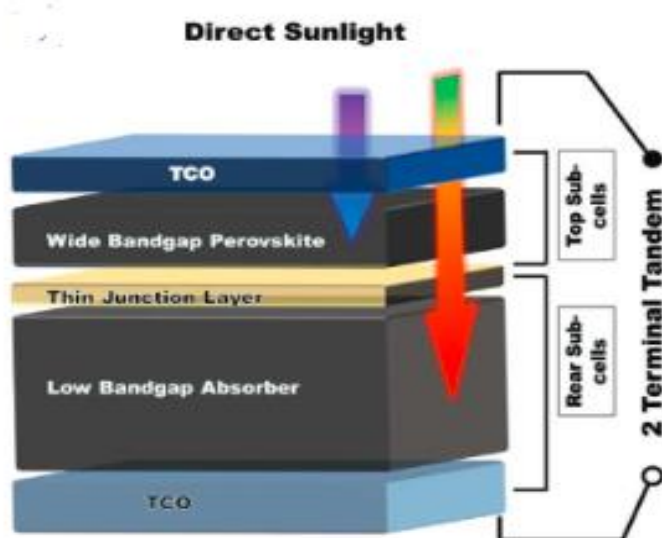


Fig. 3. A schematic representation of 2T tandem solar cell [47]

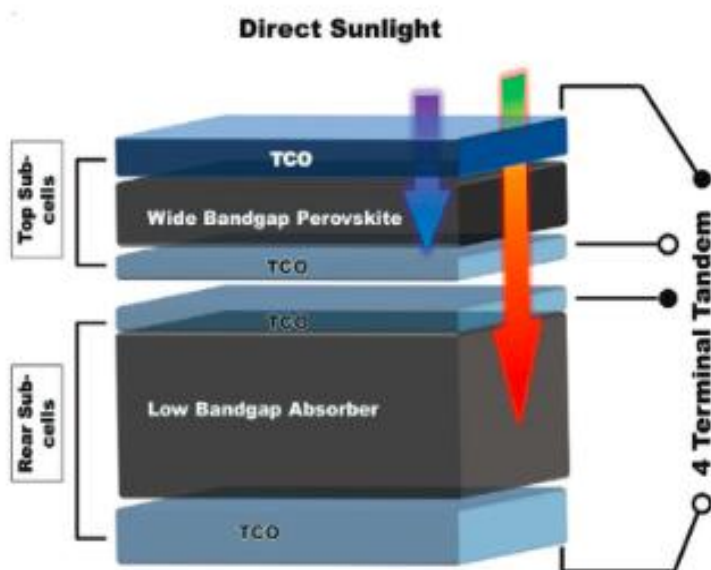


Fig. 4. A schematic representation of a 4T tandem solar cell [47]

At the interconnecting layer (ICL), the carriers that are photogenerated from either one of the sub-cells recombine. On the other hand, as Fig. 4 illustrates, 4-T tandem cells are made up of two separate components with independent electrodes that are joined by a dichromatic mirror [47].

However, as compared to 2-T tandem PVs, using more electrodes in the design would result in more optical loss and a higher total cost. Furthermore, 2-T tandem PVs are less expensive to construct than 4-T tandem PVs. However, producing 2-T or monolithic tandem PVs is more challenging [46].

4. INKJET PRINTING

Photovoltaic cells, field-effect transistors, and optoelectronic devices are all manufactured utilizing inkjet printing technology. It's a technique that employs pattern addition without the requirement for physical touch. The approach is based on the deliberate discharge of ink onto a surface via a small opening from a reservoir. A liquid droplet is expelled due to an external bias. The contraction of the chambers caused by this bias generates a shock wave inside the liquid, resulting in ejection. The technology is well-known for its large-scale manufacturing versatility, speed, and little material usage. However, the biggest disadvantage is the likelihood of a clogged nozzle due to the poor solvent qualities of the materials utilized [48,49].

5. SYNTHESIS OF HYBRID PEROVSKITE CRYSTALS

Researchers have made significant efforts to improve organometal halide perovskite films for photovoltaic (PV) applications. However, in order to advance fundamental research on the physical characteristics of these materials and acquire a better knowledge of the crystal formation process, superior big perovskite single crystals and diversified nanostructures are still required [50].

5.1 Crystal Growth

The procedure of producing bulk crystals of organic-metal halide (OMH) perovskite is similar to classic solution-based crystal growth. To make single crystals of hybrid perovskite, a highly concentrated solution of perovskite precursor—which comprises both inorganic lead halide and organic salts—is typically cooled gradually to remove the solvents. Several studies have proven the effective production of gigantic hybrid perovskite single crystals up to a centimetre in size [28, 25, 51, 52, 53]. Bakr et al. used a technique known as antisolvent vapor-assisted crystallization (AVC) to cultivate sizable, superior single crystals of MAPbBr₃ and MAPbI₃. The crystals exhibited low trap densities, ranging from 10⁹ to 10¹⁰ cm⁻³, and extended charge carrier diffusion lengths exceeding 10 μm. This process involves progressively dispersing the antisolvent dichloromethane (DCM) into the perovskite

solution. This promotes the production of high-quality perovskite crystals and allows for precise adjustment of their dimensions. The antisolvent approach has found wide application due to the production of high-quality perovskite thin films using a rapid crystallization procedure. Bakr and colleagues devised an inverse temperature crystallization (ITC) strategy to generate MAPbBr₃ and MAPbI₃ crystals more rapidly than earlier procedures [51]. This approach relies on the fact that the solubility of MAPbBr₃ or MAPbI₃ in DMF decreases significantly when the solution temperature rises from room to 80 °C. The phenomenon of inverse solubility was employed to speed the formation of MAPbX₃ crystals from heated precursor solutions by carefully controlling solution temperature and concentration. Huang and his colleagues successfully cultivated large-sized MAPbI₃ single crystals with a maximum size of around 10 mm utilizing a highly efficient top-seeded solution-growth (TSSG) approach. When exposed to sunlight, these crystals exhibited electron-hole diffusion lengths exceeding 175 μm [25].

During this procedure, microscopic MAPbI₃ crystals were placed at the base of a receptacle to ensure a thoroughly saturated solution, while the upper half of the solution was purposefully chilled to make it supersaturated. As a result, introducing a crystal seed in the upper portion of the solution allows it to increase in size by absorbing smaller crystals in the lower zone. Liu et al. [52] recently described a simple technique for producing huge MAPbX₃ (X = Cl, Br, I) perovskite crystals, with the biggest crystal measuring 71 mm * 54 mm * 39 mm. This approach is based on the phenomenon of heterogeneous nucleation caused by a seed.

5.2 Synthesis of Nanocrystals

Initially, researchers commonly employed mesoporous TiO₂ or Al₂O₃ sheets to regulate the development of perovskite nanocrystals in the early stages of their production [13,54].

The team created solar cells using the standard perovskite precursor solution, with no surfactant ligands added. As a result, the mesoporous scaffold's pore size determined the size of the crystals. Various solution techniques were utilized to create hybrid perovskite nanostructures of various sizes and morphologies without the usage of templates. Jin et al. effectively created single crystalline

nanowires, nanorods, nanobelts, and nanoplates of MAPbI₃ and MAPbBr₃ perovskites by dissolving and recrystallizing lead halide films deposited on substrates [55]. Perovskite nanocrystals have higher photoluminescence at ambient temperature and longer carrier lifetimes than bulk crystals or thin films.

The production of monodispersed hybrid MAPbBr₃ perovskite nanoparticles, measuring 6 nm, was initially reported by Galian et al. via a non-template technique [5]. In the presence of oleic acid and octadecene, a reaction between PbBr₂ and the medium-sized alkyl ammonium bromide was used. It is possible to keep the nanoparticles uniformly dispersed and preserved in a number of solvents for more than three months. Application of reasonably priced commercial raw materials, all-inorganic lead halide nanocrystals (such CsPbX₃) may be produced by using the previously mentioned processes [56]. Through the use of compositional modulations, it is feasible to finely tune the emission spectra throughout a wide spectrum, ranging from 410 nm to 700 nm. This property makes them ideal for a variety of optoelectronic applications. In addition to three-dimensional organic-inorganic hybrid perovskites, two-dimensional equivalents are particularly intriguing due to their unique new features and wide range of applications. Bao and his colleagues successfully manufactured two-dimensional MAPbX₃ (X = Cl, Br, or I) perovskite nanosheets with a thickness equivalent to that of one unit cell. This was done through the use of a hybrid technique that included both solution and vapor-phase operations [57]. The two-dimensional nanocrystals are of excellent quality and have a significant degree of photoluminescence that can be tuned throughout a wide wavelength range. Yang's team reported the direct synthesis of ultra-thin, single-crystalline, two-dimensional hybrid (C₄H₉NH₃)₂PbBr₄ perovskites via solution-phase growth [58]. This type of stacked two-dimensional perovskite requires much bigger organic cations.

5.3 Two-step Solution Process

PbI₂ is typically dissolved in DMF and spin-coated onto the substrate to form a layer of PbI₂ in the early stages of the two-step solution technique [19]. After that, the film is processed at a low temperature for a specific period of time (e.g., 70 °C). After the film has dried, it is immersed for the appropriate amount of time in an MAI solution (for example, 10 mg/ml) in 2-

propanol. It is then cleaned in pure 2-propanol to get rid of any last bits of MAI. To get crystallization, more heat annealing usually has to be done. When this two-step solution technique was first used, Gratzel et al. demonstrated a certified efficiency of 14.1% [19]. Afterwards, Huang's research team developed a method known as thermal annealing-induced inter-diffusion to produce perovskite films that are free from any pinholes [59]. Thermal annealing induces a transformation of the stacked PbI_2/MAI bilayer structure into perovskites. Several organizations later used this method to manufacture PSCs with relatively high efficiency [2,11,60,25]

6. WORKING PRINCIPLE AND DEVICE ARCHITECTURES

A solar cell operates through four major processes: light absorption and exciton formation, charge carrier separation, transport of charge, and collection. Light sensitizers with diverse optoelectronic properties are created using a variety of devices. For example, an n-i-p (or p-i-n) configuration is required when the light-absorbing material is an intrinsic semiconductor, but a p-n configuration is adequate when the active material is p-type (or n-type). As a result, HOIP materials are extremely appropriate for both p-i-n and p-n materials because of their ability to efficiently transfer charges over long distances in a balanced fashion [26]. The original perovskite solar cells featured a mesoporous structure with a large mesoporous layer (mp- Al_2O_3 or mp- TiO_2) serving as a framework. This design was based on standard DSSCs. The mesoporous scaffold in this design is injected with perovskites and sandwiched between layers of electron transport (mostly titanium dioxide) and hole transport layers. The mesoporous structure has been proven to increase the efficiency of charge collection by reducing the distance over which charge is transported. In the first step, the mesoporous layer frequently had a thickness of more than 500 nm (or maybe several micrometres) to properly gather a significant quantity of sunlight [10,14,13,15,19].

Nonetheless, a portion of the material may stay in amorphous phases with low crystallinity due to pore size constraints that prevent perovskite crystals from forming [61]. This will undoubtedly degrade the device's performance. Surprisingly,

a compact perovskite capping layer with big grains forms on the surface of the porous layer when the thickness of the mesoporous layer is reduced to less than 300 nm [62,63,19,64], resulting in a bilayer structure.

7. CHARACTERIZATION

The material specifications for perovskite photovoltaics (PVs), including both structural and morphological criteria, are described in this section. One method that may be used to determine the crystal structure of a layer formation is X-ray diffraction (XRD) examination [65]. The conditions of synthesis dictate the three different types of MAPbI_3 structure. The material is in an orthorhombic phase at temperatures lower than 163 K. There is a transition into a tetragonal phase between 163 K and 327.3 K. After 327.3 K, it changes and takes on the characteristics of a cubic phase [66]. At 60 °C, the material undergoes significant modifications as it moves from the tetragonal to cubic phase. Improved particle sizes result from this transition, as several studies using X-ray diffraction (XRD) analysis have shown. In contrast to the tetragonal phase, the XRD pattern shows the emergence of several new peaks, which denotes the cubic phase [67,68,69]. Using a polymer electrolyte, Rahul et al. [70] created a perovskite solar cell and identified the material's x-ray diffraction pattern, which is seen in Fig. 5.

The properties of HOIPs are impacted by organic monocations. Moisture penetration may be efficiently limited by introducing a substantial hydrophobic organic cation into the perovskite structure [71]. Furthermore, because of this structural design, the energy bandgap is both tunable and large. In addition, prolonging the organic mono-cation chain length prevents Sn^{2+} from oxidizing to Sn^{4+} [37].

Perovskite PVs are produced using a variety of techniques, which will provide devices with different crystal structures in addition to XRD characterization [72]. Scanning electron microscopy is used to determine the perovskite's morphology, which is an important factor in improving perovskite photovoltaics' performance. A great deal of work has been done to improve the manufacturing processes [73] and add additional chemicals to improve morphology [74,75].

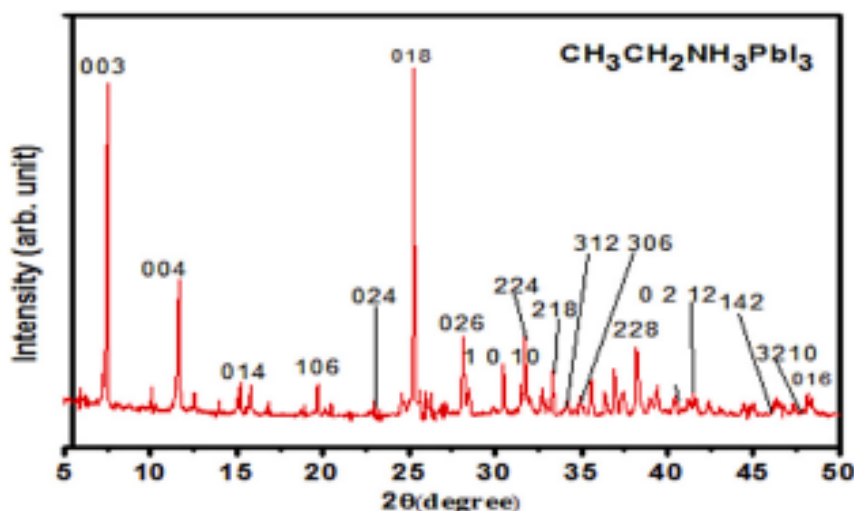


Fig. 5. X-ray diffraction pattern of $\text{CH}_3\text{CH}_2\text{NH}_3\text{PbI}_3$ [70]

8. SUMMARY AND PERSPECTIVES

It is worth noting that advancements in HIOP PSCs have been fast during the last decade, dramatically altering the possibilities for future solar technology. They made major contributions to solar cell research due to their high-power conversion efficiencies, simplified manufacturing techniques, and cost-effectiveness in terms of materials and structure. Perovskites with organic-inorganic hybrids have shown considerable promise for a wide range of optoelectronic applications other than solar cells. Over the last decade, tremendous resources have been directed into the development of enhanced perovskites and high-performance devices. Because of the rapid improvement in device performance, further basic research will assist in the progress of these solar cells. Understanding the fundamental characteristics of hybrid perovskite materials is crucial.

Although inorganic-organic hybrid perovskite solar cells have advanced significantly, they are still in the early phases of laboratory testing. To achieve future mass production goals, PSCs must exhibit significantly greater solar module efficiency while maintaining lower manufacturing costs than other solar technologies now available. As a result, there is still a lot of space to develop. Furthermore, before these technologies can be employed successfully, various complicated concerns must be extensively researched and solved, such as long-term stability, large surface area, module

creation, repeatability, I-V hysteresis mitigation, and lead toxicity assessment.

9. CONCLUSION

The synthesis procedures for perovskite materials are examined, as well as how thermal instability and structural distortions affect device performance. The chemical structure of the substance is depicted, with A representing the organic cation, B representing the metal cation, and X representing the halide ion. Common synthesis processes have been introduced, including chemical vapour deposition, doctor blade, spin coating, spray coating, and the sol-gel approach. Factors influencing device performance include large surface area modules, reproducibility, long-term stability, I-V hysteresis, and lead toxicity. Characterization techniques such as X-ray diffraction to determine crystalline structure and scanning electron microscopy to determine morphology are also discussed. In summary, this study examines the synthesis processes utilized in the fabrication of perovskite devices, as well as the characterization techniques required to assess device structural features.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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