Perovskite Solar Cells Stability Factors And Encapsulaiton For Performance Enhancement

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Abstract: Perovskite solar cells, which are considered the third generation of new concept solar cells, are known for their high photoelectric conversion efficiency, low cost, and flexible processing advantages, and have been rapidly development in recent years. its photoelectric conversion efficiency is gradually comparable to that of silicon cells and has been close to the level required for industrial applications. However, the main problem with the industrial application of perovskite solar cells is their stability. Researchers need to solve the biggest problem of how to maintain high efficiency for a long time in perovskite solar cells. Encapsulation is currently being widely studied as a solution to the external stability issue of perovskite solar cells. A good encapsulation can not only solve the stability problem of the device but also ensure the safety of the device and extend the service life. The stability of perovskite solar cells and the conditions for testing it are briefly described in this paper. In the end, the various encapsulation structures, techniques, and materials for perovskite solar cells are explained. The continuous advancement of encapsulation research will lead researchers to optimize and solve existing problems, leading to the eventual industrialization of perovskite solar cells on a large scale.

Key words: perovskite solar cell; stability of device; encapsulation material; industrialisation application

CLC number: TM914.4 **Document code:** A **DOI:** 10.13725/j.cnki.pip.2024.01.003

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Received date: 2023-10-6
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I. INTRODUCTION

Global energy consumption continues to rise year on year, and the limited availability of fossil fuels necessitates vigorous research into sustainable and renewable energy sources. In this century, solar energy has become an important source of unconventional energy to meet the energy needs of a country's overall development [1-4]. Therefore, the development of efficient photovoltaic (PV) cells to harness solar energy has become important. Solar cells have a long history of development. Perovskite solar cells (PSCs), recognized as third-generation PV technology, have more advantages over other types of photovoltaic cells due to their outstanding photoelectric conversion efficiency (PCE) [5-6]. In 2009, researchers first used methylamine (MA) lead halide perovskite compounds $MAPbBr_3$ and $MAPbI_3$ as visible photosensitizers in dye-sensitized solar cells, demonstrating a PCE of 3.8%. A variety of technologies have been developed to improve the performance of perovskite solar cells, including solvent engineering, interfacial engineering, bandgap engineering, etc. To date, the maximum certified efficiency of single-junction perovskite solar cells has reached 25.7%, which is close to the PCE of commercial crystalline silicon solar cells [7-9]. Meanwhile, perovskite solar cells also offer the advantages of low extraction binding energy, high optical cross-section, superior bipolar charge transfer, tunable band gap, and low-cost fabrication [10-13]. At present, however, traditional silicon solar cells are still the preferred choice of the photovoltaic industry, mainly due to their long life (20–25 years) and non-toxicity [14]. With the development of perovskite solar cell research, the demand for industrialization has become the key issue that researchers are focusing on. Lifetime is the biggest problem for the industrialization of perovskite solar cells, and the stability of perovskite solar cells affects lifetime. Researchers have done a lot of work on this. The degradation mechanism of the perovskite functional layer and the interaction between the interface of each functional layer of the perovskite solar cell are discussed in detail [15-17]. The researchers found that perovskite solar cells are extremely sensitive to their environment, and their stability is mainly affected by ultraviolet radiation [18-19], high temperatures, Oxygen, and moisture [20-21]. These factors affecting the stability of perovskite solar cells are very important and will be discussed in detail below [22]. As a photovoltaic device, perovskite solar cells can often work in harsh environments, and the failure of perovskite solar cells due to stability factors makes it impossible to ensure that it has the same service life as conventional silicon solar cells, which is very fatal for the industrialization of perovskite solar cells. Compared with higher photoelectric conversion efficiency, people want to have stable and long-term photovoltaic devices. To improve the stability of perovskite solar cells, researchers are currently working on two main approaches. Firstly, the fabrication of perovskites that are inherently more stable, as well as other functional layers, is a means of improving stability in itself. Secondly, encapsulation has become an important means of improving the stability of perovskite solar cells to overcome the influence of the external environment [23-24].

Encapsulation is the process of wrapping the functional layers of perovskite solar cells with other materials to isolate them from the potential influence of the external environment on the stability of perovskite solar cells, as shown in figure 1. For the validity of the encapsulation, wang et al. [25] say that the encapsulation of the device will play a role in the industrialization of perovskite solar cells, as unencapsulated devices typically show severe degradation after hours of continuous light exposure, while encapsulation devices last longer. The current encapsulation strategy mainly involves the use of waterproof and Oxygen-blocking materials to encapsulate the perovskite solar cell devices, while at the same time not compromising the integrity of the protective encapsulation, so that the positive and negative electrodes of the perovskite solar cell can be used normally [26]. The purpose of encapsulation is to enable perovskite solar cells to maintain their initial efficiency over time. Li et al. [27] devel-

oped and used an environmentally friendly ultraviolet (UV) curing material that takes only 1 minute to UV cure for encapsulation. Since the cured encapsulation material has a refractive index similar to glass, which has a non-destructive effect on perovskite, the performance of the encapsulation device improves as the current density increases. Device stability tests, including immersion in water and weak acids, outdoor exposure, −35 °C, and 60 °C/85% RH environments, show initial efficiencies over 90% after 1 000 hours. To maintain high efficiency over time, encapsulation research has focused on overcoming the factors that affect the stability of perovskite solar cells. Due to different environments of use and commercial requirements, encapsulation materials should have the characteristics of low cost, high transparency, high stability and good ductility, the most important point is to be inert to perovskite to ensure that it does not react with perovskite. Moreover, in the structure of perovskite solar cells, the thermal stability temperature of a part of some hole transport materials is lower than 85 °C, while $MAPbI_3$, a widely used perovskite absorption layer, decomposes above 120 °C, and the thermal stability improvement of triple cationic perovskite compounds mixed with inorganic Cs^+ is limited [28]. The above problems indicate that the encapsulation temperature of perovskite devices is limited by many conditions. At present, the research direction of perovskite solar cell encapsulation is mainly carried out from two aspects: reducing the encapsulation temperature of encapsulation materials and exploring low-temperature encapsulation technology [25,29-32]. Ma et al. [29] developed a low-temperature (below 100 °C) encapsulation technique using nonpolar, low-cost paraffin wax as an encapsulant. The results show that the low melting point paraffin can remove residual Oxygen, water, and delay the release of volatiles after perovskite decomposition [33-34]. Under this encapsulation condition, the phase segregation and vacancy defects of the perovskite absorption layer are greatly reduced, thus inhibiting the decomposition of the film and significantly improving the thermal and water stability of the device. Finally, the synthesized device achieved superior long-term stability, maintaining 80% of its initial efficiency after more than 1 000 hours of maximum power point tracking (MPPT). In addition, large-area encapsulation technology is one of the current research directions. There are more and longer-lasting encapsulation technologies and materials. After many years of research into encapsulation, researchers have found that many materials and different encapsulation technologies can be used for encapsulation, and these different encapsulations have their advantages and disadvantages, which will have different effects on the final stability and lifetime of perovskite solar cells.

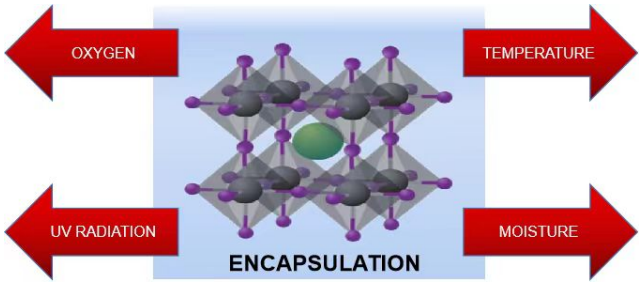

Fig. 1. Factors to consider for perovskite encapsulation.

In this article, we will introduce the fabrication process of perovskite solar cells and briefly describe their advantages and disadvantages. It focuses on current encapsulation strategies for perovskite solar cells, including encapsulation types, encapsulation techniques, and encapsulation materials, and explains their contribution to improving the stability of perovskite solar cells. Finally, the problems facing the development and industrialization of perovskite solar cells and the importance of good encapsulation for perovskite solar cells are summarised, and a better control scheme for the uncertainties of perovskite solar cells is proposed.

II. POTENTIAL APPLICATIONS OF PEROVSKITE SOLAR CELL

Perovskite solar cells will have a wider range of applications than silicon solar cells due to their excellent properties such as lightness, transparency, and flexibility. To realize the industrial application of perovskite solar cells, they are made into modules to meet the needs of the terminal. This includes the possibility of replacing silicon cells in the future for solar

power generation or building-integrated photovoltaics (BIPV) and car-integrated photovoltaics (CIPV)[35].

Taking BIPV as an example, according to previous reports, the market share of BIPV is expected to reach about 11 billion euros, and the installed capacity will reach 16 GW in 2021, accounting for 13% of the current total photovoltaic market, and the value will continue to grow, and it is predicted that it will continue to expand at an annual growth rate of 40% in the next decade. An important feature of BIPV is the solar window, which not only needs to generate electricity but also needs to have good transparency for viewing the landscape. This is something that traditional silicon solar cells cannot do, and it is also a unique advantage of perovskite solar cells, because of its translucent and color-adjustable characteristics, making the BIPV market a potential application environment for it[35-37]. In addition, the flexibility of perovskite solar cells makes them very promising in wearable or portable electronic devices, indoor chargers, etc., and further exploration is needed.

III. PERVOSKITE SOLAR CELLS STRUCTURE AND FABRICATION METHODS

A. Structure of perovskite solar cells

Perovskite solar cells mainly consist of an electron transport layer (ETL), a hole transport layer (HTL), and an active perovskite layer. The active perovskite layer is sandwiched between the ETL and the HTL[38-41]. After the incident light through the glass, photons with energy greater than the forbidden bandwidth are absorbed, generating excitons, which are then separated in the absorption layer of perovskite, turning into holes and electrons and injected into the transport material respectively[42-43]. Among them, the hole is from the perovskite into the HTL, and finally collected by the metal electrode; the electron is from the perovskite into the ETL and finally collected by the ITO/FTO[44-45]. Current is generated through a circuit connecting the ITO/FTO and the metal electrode[46-47]. When light passes through an ETL and there is a transparent conductive layer in front of the ETL, it is called an n-i-p structure as shown in figure 2(b). In contrast, p-i-n is used, as shown in figure 2(c). Mesoporous is another structure of perovskite solar cells as shown in figure 2(a)[19,48,50-54].

1. planar structure

The planar structure of perovskite solar cells is mainly divided into n-i-p and p-i-n structures. The n-i-p structure is one of the most widely used structures for the fabrication of high-performance perovskite solar cells. As shown in figure 2(b), the n-i-p structure consists of a conductive glass electrode (ITO or FTO), an electron transport layer (ETL, consisting of a dense TiO_2 layer 150–200 nm thick, and a mesoporous TiO_2/Al_2O_3 layer 150–200 nm thick), 300–500 nm thick perovskite layer, hole transport layer (HTL, Spiro-OMeTAD) and 50–100 nm thick hot vapour deposited gold-plated metal electrodes (Au, Al, Ag). The n-i-p structure typically consists of a dense ETL layer about 150 nanometres thick, which can be SnO_2 and TiO_x. The n-i-p structure has relatively high V_{oc} and J_{sc} values, but the hysteresis of the device is severe.

In the p-i-n structure, the HTL layer is below the perovskite layer, as shown in figure 2(c). A P-type semiconductor polymer, such as PEDOT: PSS, is spun onto an ITO/FTO conductive substrate with a thickness of about 30-50 nm, then a perovskite layer is spun on top of the HTL, followed by an ETL layer of about 40-60 nm, usually PCBM or C_{60}. Finally, a metal layer (Au, Ag, Al) is vapour-deposited as an electrode. Since PEDOT: PSS is acidic and carnosic, which will destroy the stability of perovskite devices, PEDOT: PSS is gradually being replaced by other inorganic p-type semiconductor materials, such as NiO_x and CuO, and because of the use of inorganic p-type semiconductors, the p-i-n structure perovskite solar cells show very good light stability. The p-i-n fabrication process is simpler and cheaper, lower temperature, and is also suitable for combining with traditional solar cells to cascade solar energy, so it has attracted more and more attention from researchers. Compared with the n-i-p structure, the main problem of p-i-n structure perovskite solar cells is low efficiency. Improving the effi-

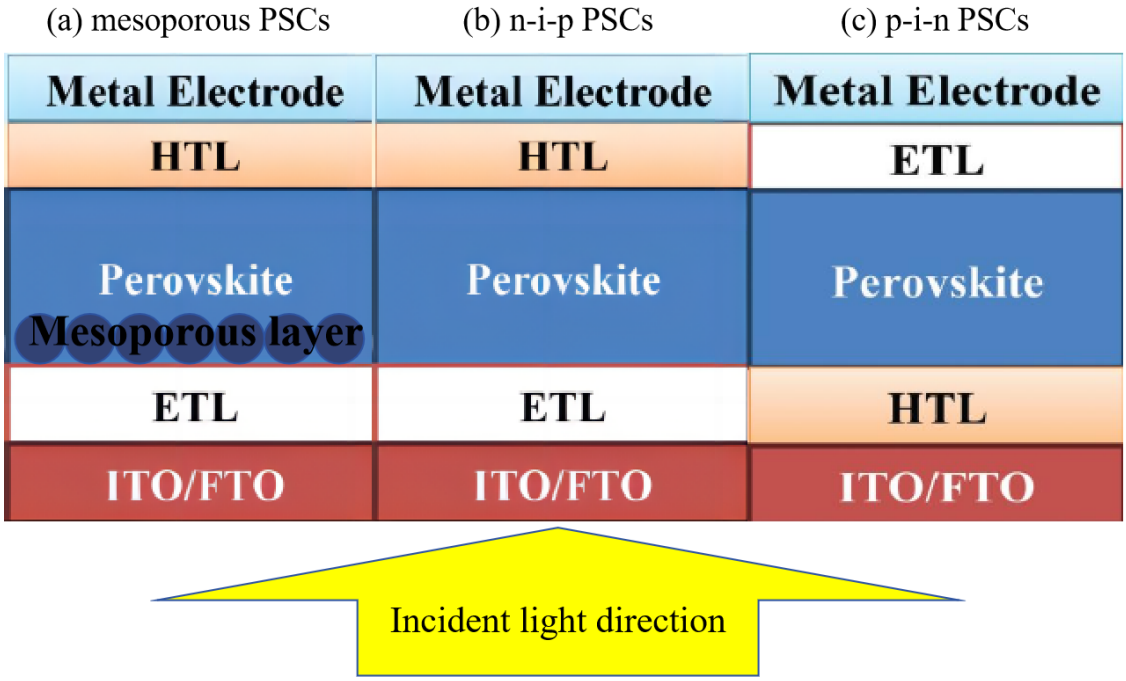

Fig. 2. Schematic representation of the structure of (a) mesoporous PSCs; (b) n-i-p PSCs; (c) p-i-n PSCs.

ciency of p-i-n perovskite devices is the focus of current research.

2. Mesoporous structure

Mesoporous perovskite solar cells are derived from dye-sensitized solar cells (DSSCs) and use traditional mesoporous structures. In this structure, the mesoporous TiO_2 (m-TiO_2) layer is deposited on the dense TiO_2 (c-TiO_2) layer, which acts as a scaffold to better extract electrons from the perovskite layer. Then, in most cases, HTLs (spiro-OMeTAD) and the back electrode (gold, silver, etc.) are sequentially deposited on the perovskite layer.

B. Fabrication technology of perovskite solar cells

1. Fabrication of perovskite functional layer

Perovskite solar cells are composed of several functional layers, among which the role of the perovskite layer is to absorb photons, generate electron-hole pairs, and separate charge carriers, which is the most important part of perovskite solar cells. Currently, the main fabrication methods include blade coating, groove coating, spraying, inkjet printing, screen printing, electrodeposition, physical vapour deposition (PVD), and chemical vapour deposition (CVD). To make the photovoltaic device more efficient, it is necessary for the perovskite layer to fully absorb photons, produces high-quality carriers, and complete carrier transport, and it is necessary to obtain high crystallinity and uniformly dense perovskite film during the fabrication of the perovskite layer. In particular, the uniformity of large-area perovskite films must be ensured for future industrialization [55-59].

2. Fabrication of other functional layers

Other functional layers of perovskite solar cells can still be prepared by liquid phase and deposition methods, such as polybis(4-phenyl)(2,4,6-trimethylphenyl)amine (PTAA), self-assembled monolayer (SAMs) materials, and metal oxide nanoparticles (SnO_2, TiO_2) can be deposited by solution methods, while other materials such as insoluble organic compounds and inorganic oxide can adopt vapour phase deposition.

IV. STABILITY OF PEROVSKITE SOLAR CELLS

Although the current power conversion efficiency of perovskite solar cells has become increasingly high, poor stability is one of the main challenges hindering the industrialization of perovskite solar cells (PSCs)[12,25]. The degradation of the perovskite layer and the HTL and ETL affect the performance of the device. In this chapter, we will discuss the effects of thermal, stress, moisture, and ultraviolet illumination on the stability of the perovskite layer.

A. Key factors for stability

1. Thermal stability

In general, organic-inorganic hybrid perovskites are generally particularly prone to decomposition at high temperatures because the organic components are inherently more volatile and only weakly bonded to the inorganic PbI_6 framework[60-61]. Therefore, it is of great importance to develop a feasible method to improve the thermal stability of perovskite[62]. The commonly used perovskites undergo a continuous phase transition for low temperatures (T <162.2 K) distorting the oblique cross state to the medium temperature (162.2–327.4 K) tetragonal phase, and then, ideally, the cubic phase >327.4 K. When the temperature is further elevated, the perovskites decompose into volatile methylamines and HI compounds[63].

While the mixed halide/cationic perovskite improves the performance index of perovskite solar cells, some researchers have also investigated its thermal stability. Yang et al.[64] carried out a systematic study on the thermal stability and degradation mechanism of mixed cationic (Cs/FA/MA) mixed halide (I/Br) perovskite at 85 °C. They found that after 12 h, 24 h, and 48 h heat treatment of mixed cationic perovskite film fabricated into a complete device, found that the device efficiency gradually decreased from the initial 15.06% to 13.24%, 11.70%, and 8.37%, and the open circuit voltage, short circuit current, filling factor, and device EQE showed a considerable degree of attenuation. To further investigate the changes in the perovskite layer, the researchers performed SEM morphology characterization and XRD and photoelectron spectroscopy tests on the perovskite layer. The study found that the thermal degradation of the perovskite started from the surface layer by layer down, which was caused by the intrinsic defects on the surface and the suspension bonding, which reduced the activation energy required for degradation. MA and I ions showed a synergistic effect and jointly led the degradation technology of perovskite, while Cs, FA, and Br ions showed good stability at 85 °C[65-66]. The reaction of temperature-induced perovskite degradation can be expressed as follows.

$$CH_3NH_3PbI \rightarrow PbI_2 + CH_3NH_2 + HI. \quad (1)$$

Since the effect of heat on the performance of perovskite solar cells is almost unavoidable, researchers have tried to enhance the thermal stability of perovskite solar cells in certain ways. Typically, they will use solvent engineering and device engineering methods to improve the thermal stability of perovskite solar cells[67-69]. For organic perovskite, Uddin et al.[70] demonstrated that a mixture of crystalline thermoplastic polymer additives, such as polyethylene oxide (PEO, 100 000 MW) and polyethylene glycol (PEG, 12 000 MW), can improve the thermal stability of $CH_3NH_3PbI_3$ ($MAPbI_3$) perovskite, thereby improving device stability. As a result of the thermoplastic shield and Lewis base acid reactions between the hydroxy groups in the PEO+PEG mixture and the uncoordinated Pb^{2+} in the $MAPbI_3$ perovskite, PEO+PEG-based PSCs exhibit increased thermal stability at 85 °C in ambient air compared to the control device. Thus, this approach could be employed to stabilize different kinds of perovskite-based photoelectric device topologies. Thus, this approach could be used to stabilize different types of perovskite-based photoelectric device topologies. In addition to solvent engineering, some researchers have tried different encapsulation methods to achieve thermal stability in perovskite solar cells. Shi et al.[60] proposed an encapsulation strategy for thermoplastic polyurethane (TPU), an inexpensive encapsulation method that not only greatly reduces the photoluminescence (PL) intensity loss but also improves the thermal stability of perovskite solar cells.

In the fabrication process of perovskite solar cells,

the high fabrication temperature of each functional layer can directly lead to the degradation of the perovskite active layer. During operation, factors such as light and ion/electron transport and leakage current increase the temperature of the photovoltaic module; in the future industrialization process, the mismatch between the thermal expansion coefficients of different materials and the uneven temperature distribution during operation will cause the large-area perovskite solar cells to generate different thermal stresses, leading to thermal stress failure, thus affecting their stability. As the main factor affecting the performance of perovskite solar cells, heat should be the focus of future research. For the encapsulation of perovskite solar cells, thermal stability requires that the encapsulation technologies and the materials themselves have good heat resistance, and good chemical stability at high temperatures, it is best to have good heat dissipation capacity, and the heat that can degrade the perovskite is not generated during the encapsulation process.

2. Stress stability

The residual stress produced in the technology of perovskite fabrication is one of the factors affecting the life of perovskite solar cells, but it is often overlooked[71]. Because the material defects disrupt the arrangement of the atoms and cause their displacement to change, the particle orientation and tilt are opposite to cause deformation, resulting in residual stress. The residual stress of the stretched perovskite film can exceed 50 MPa, a level sufficient to deform copper. These stresses can cause the perovskite layer to crack, generate leakage current, or cause the perovskite film to be uneven. Wang et al.[72] investigated the perovskite lattice distortion of residual stress (and strain) in polycrystalline films. The results show that the residual stress is concentrated at the surface of the prepared film, and an effective method of releasing the interfacial stress by A-position cation alloying is proposed. This leads to a lattice reconstruction of the surface of the polycrystalline film, resulting in a low modulus of elasticity. As a result, a "bone-joint" structure is formed at the interface between the absorber and the carrier transport layer, which greatly improves the performance of the device.

In addition to the residual stress that occurs during perovskite fabrication, thermal stress caused by heat during the operation of perovskite solar cells should also be a concern. Pisoni and colleagues[73] investigated the mechanism of mechanical stress and failure within the perovskite layer due to light heating and found that heat from light does not dissipate well because $MAPbI_3$ ($CH_3NH_3PbI_3$) has very low thermal conductivity for both larger monocrystalline and polycrystalline forms. This means that heat from light deposits inside perovskite does not spread out as quickly, resulting in mechanical stresses that limit the lifespan of photovoltaic equipment[73-74].

In general, studies of the stress stability of perovskite are few and complicated. The influence of force exists not only at the microscopic scale of the perovskite but also at the large scale of the perovskite. This includes perovskite layers, metal electrodes, and hole/electron collection layers. To overcome the effects of stress on perovskite solar cells, future researchers should focus on the fabrication method of perovskite and the matching the thermal expansion coefficients of different parts of the material. The strength of the encapsulation materials should be sufficient to protect the functional layers of the perovskite solar cell from damage by external forces, and its modulus of elasticity should be adequate to ensure not only stiffness after encapsulation but also some flexibility.

3. Moisture stability

Moisture is deadly to perovskite solar cells because the cations in perovskite dissolve well in water, at the same time, the most common ammonium ion in $MAPbI_3$ can also react with water Lewis acid-base[75-77], water deprotonates the methylammonium ion to form methylamine[78-79]. The stability of perovskite solar cells in wet environment is a challenging problem[80]. Due to its importance, researchers have made many studies on the mechanism of water acceleration of perovskite degradation. Frost et al.[81] proposed a reasonable degradation pathway for $MAPbI_3$ in the presence of water, which undergoes a similar water-assisted degradation technology in which methy-

lamine groups are lost through sublimation to form lead iodide. Previous studies have reported that perovskite solar cells are severely affected by environmental sensitivity to water and oxygen due to the degradation of perovskite by hydrolysis reactions, which is represented by the following chemical equation[25].

$$CH_3NH_3PbI_3(s) \xrightarrow{H_2O} PbI_2(s) + CH_3NH_3I(aq), \quad (2)$$

$$CH_3NH_3I(aq) \longrightarrow CH_3NH_2(aq) + HI(aq), \quad (3)$$

$$4\,HI(aq) + O_2 \longrightarrow 2\,I_2(s) + 2\,H_2O(aq), \quad (4)$$

$$4\,HI(aq) \xrightarrow{h\nu} H_2(g) + I_2(s). \quad (5)$$

Although three-dimensional (3D) perovskite solar cells have a high power conversion efficiency (PCE), they are unstable under humidity, oxygen, and ultraviolet light[82]. In recent years, 2D perovskite solar cells have begun to receive attention for their better stability[80,83-84]. The hydrophobicity of two-dimensional perovskite organic space and its relatively stable structure improve the stability of perovskite solar cells[25]. The above method can be called chemical structure engineering method[85], which can also use mixed halide compositions[86-87], cation substitution[88-89]. Improving moisture stability can also be done using interface engineering methods. Yu et al.[80] used a different type of spacer cation, 1,4-butanediamonium Fabrication of perovskite precursor by (BDA^{2+}) and 2-phenylethylammonium (PEA^+), formula $(BDA)_{1-a}(PEA_2)_aMA_4Pb_5X_{16}$. They found that the crystallinity and vertical orientation of two-dimensional perovskite $(BDA)_{0.8}(PEA_2)_{0.2}MA_4Pb_5X_{16}$ films could be improved by using mixed spacer cations. In addition, complementary humidity and thermal stability are achieved due to the enhanced interlayer interaction of BDA^{2+} and the improved moisture resistance of the hydrophobic groups of PEA^+. After 500 hours of storage in ambient air at 40±5% relative humidity or 100 hours of storage in nitrogen at 60 °C, the encapsulated device retained over 95% and 75% of its initial efficiency, respectively. Finally, stability can also be improved through the encapsulation device[90]. As shown in the figure 3, Wang et al.[91] took into account the water vapor transmittance and process temperature through organic-inorganic alternating layer encapsulation. At 50 °C encapsulation temperature, the water vapor transmittance was only 1.3×10^{-5} $g{\cdot}m^{-2}{\cdot}d^{-1}$). After exposure at 30 °C and relative humidity of 80% for 2000 h, the device retained 96% of the initial effectiveness (17.01%). After 300 min underwater, the sealer retained 95% of the initial efficiency.

Moisture stability can be said to be the most critical factor affecting the stability of perovskite solar cells, so researchers have done a lot of research and sought some solutions. For the industrialization of perovskite solar cells, encapsulation is still the simplest, cheapest, and most effective way to achieve moisture stability. The encapsulation materials and encapsulation technologies can ensure that the perovskite solar cell is not damaged by water as long as it has good water resistance performance.

4. Photostability

The study found that the UV-light illumination of perovskite is another serious problem in the application of perovskite solar cells[93]. The perovskite active layer will be damaged by long-term exposure to ultraviolet light in the environment, resulting in an increase of defects in the perovskite layer and eventually degradation of the perovskite layer[78,93-94]. To assess the photostability of perovskite solar cells, the light soaking test in IEC 61215 can be referred to. Due to the working environment of photovoltaic modules, the decrease in the stability of perovskite solar cells brought by light must be considered[95]. The chemical equation of the reaction of the $MAPBI_3$ perovskite layer in a descending light state is as follows:

$$CH_3NH_3PbI_3(s) \xrightarrow{h\nu} PbI_2(s) + CH_3NH_2(g) + HI(g), \quad (6)$$

$$2I^- \xrightarrow{h\nu} I_2(s) + 2e^-, \quad (7)$$

$$CH_3NH_3^+(s) \xrightarrow{h\nu} 3CH_3NH_2(g) + 3H^+(g), \quad (8)$$

$$I^- + I_2(s) + 3H^+ + 2e^- \longrightarrow 3HI(g). \quad (9)$$

Some researchers believe that the method of surface passivation of perovskite is the key to improving the photostability of perovskite solar cells. A good passivation agent can significantly improve the durability of the perovskite layer. Kanda et al.[95] applied fluorinated passivation to improve photostability and found that fluorinated passivation can prevent the for-

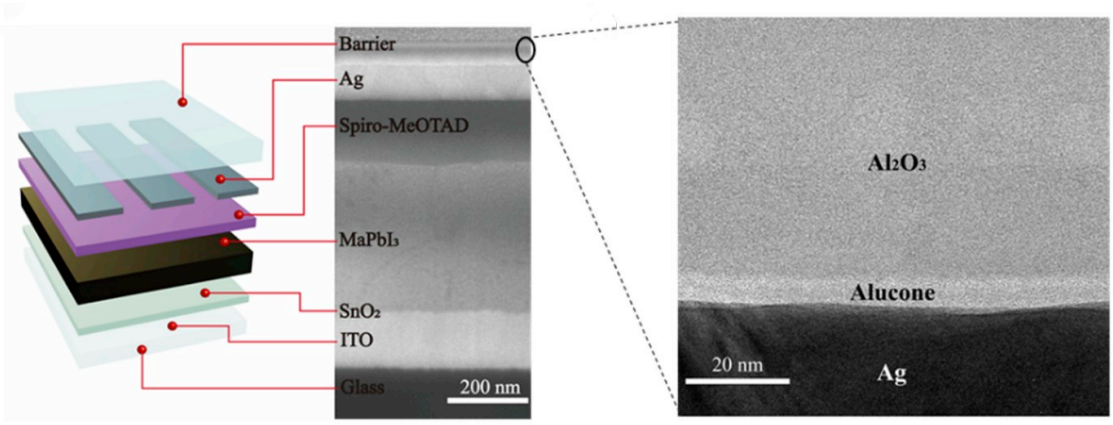

Fig. 3. Schematic diagram of the structure of the PSC and a cross section scanning electron microscope image of the PSC with the enclosing layer and a transmission electron microscope image of the barrier layer on the PSC[91].

mation of Pb on the perovskite surface, thereby inhibiting defection-induced recombination and improving the durability of perovskite solar cells. At the same time, in the XRD results, the diffraction pattern is shown in figure 4[95], with peaks at 100, 110, 111, and 200 reflections, corresponding to a cubic structure. Before light immersion, the diffraction pattern did not change with or without PFOTES, indicating that the passivation material did no effect on the crystal structure of perovskite. Other researchers have proposed that the photostability of the perovskite layer is affected by the other functional materials in the perovskite solar cell. Yang et al.[93] believe that the TiO_2 layer is a kind of photocatalyst, which will accelerate the decomposition of perovskite film under UV irradiation, but the efficiency of the perovskite solar cells will be significantly reduced if the TiO_2 layer is removed. Therefore, they inserted a layer of Bphen between the ITO substrate and perovskite film through chemical engineering technology. A TiO_2-free PC was been developed with good photostability and an average PCE of about 18.53%. Therefore, a stable ETL should be a prerequisite for the long-term operation of perovskite solar cells.

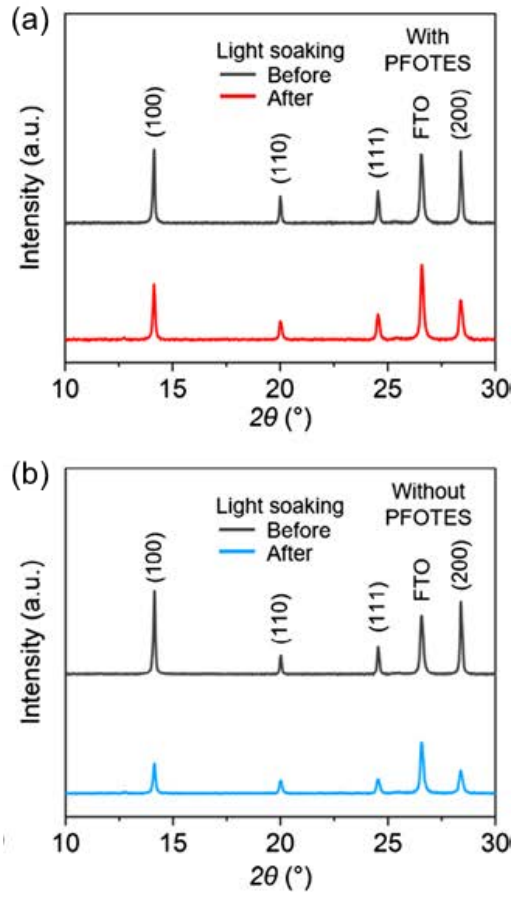

Fig. 4. (a) XRD with PFOTES passivation on perovskite layer comparing before and after light soaking. (b) XRD without PFOTES. Concentration of PFOTES solution was 10 vol%[95].

Since encapsulated devices are generally effectively insulated from moisture and oxygen, light-induced instability of perovskite solar cells has become another problem to be solved by encapsulation. Sunlight irradiation to the earth's surface and its ultraviolet irradiation intensity of an average of 4.61 mW/cm^2, despite the protection of the ozone layer can be removed from the sunlight in some of the bands of ultraviolet light, but there are still strong ultraviolet rays, including UVA (320–400 nm) and UVB (280–320 nm) can be

irradiated to the earth's surface, of which the UVB band of ultraviolet light has the strongest destructive ability, and it is very easy to degrade the perovskite, thus affecting the photoelectric conversion efficiency as well as the photostability of the device. To alleviate the impact of ultraviolet light on perovskite solar cells, the current use of ultraviolet filters added to the light source, to avoid the use of titanium dioxide and other materials with ultraviolet degradation, or to add materials with the nature of the upconversion, absorption or filtration of ultraviolet wavelengths in the source of light and other ways. In the process of practical application, the encapsulation method to reduce the impact of ultraviolet rays on the calcium titanium ore solar cells should be the most simple.

B. Measures of perovskite solar cells stability

The previous article mentioned that the industrialization demand for perovskite solar cells is similar to that of traditional silicon solar cells, which require long-term stability, and summarised some important factors affecting the stability of perovskite. As a photovoltaic product, perovskite solar cells need to undergo some specific harsh environmental stability tests and accelerated simulator aging to infer the potential long-term operating performance of the module. Among these, the International Electrotechnical Commission (IEC) test standards are the most authoritative and comprehensive performance tests for photovoltaic products. Test conditions and details of pass requirements are collected as IEC 61215 standards[96-98]. Figure 5[98] and table I[97] show simplified flow charts and protocols for module stability testing based on IEC61215. To date, the stability of perovskite solar cells has been tested by most researchers using the method in this standard.

According to IEC 61215:2016, perovskite samples should pass a series of tests based on external inputs, temperature, humidity, or UV exposure, specifically targeting the main causes of perovskite degradation that commonly occur. The test items include the basic characteristics of perovskite solar cells during operation, stress test, wet heat cycle test, and mechanical stability test (hail test and mechanical load test). The most important is the humid heat test, the thermal cycling test, the light soaking test, and the UV precondition test, each of which characterizes the influence of several key stability factors on perovskite solar cells in the next chapter. It can also be improved by encapsulation.

Currently, the British Standards Institute (BSI) is proposing the more specific specification IEC TR 63228:2019, which summarises current thinking on the performance evaluation of emerging photovoltaic technologies, in particular, OPV, DSC, and PSC devices. This is very useful for the development of research into the stability of perovskite solar cells. Due to their unique material properties, perovskite solar cells require more detailed and stringent test standards to evaluate their performance.

V. ENCAPSULATION

Photovoltaic (PV) power generation devices are used as a clean energy source, and the operational life of the modules is usually required to be more than 20 years. Taking traditional silicon solar cells as an example, once the adhesive film and back sheet of the battery module start to yellow and crack, the battery will easily fail and be scrapped, so the encapsulation material plays a crucial role in improving and guaranteeing the quality of photovoltaic modules. Unlike traditional photoactive materials such as silicon, perovskite materials exhibit significant ionic properties, which limits the long-term stability of perovskite materials due to the relatively low activation energy of ion migration within the perovskite layer[99].

The above-mentioned tests are required for photovoltaic devices, as well as several factors affecting the stability of perovskite solar cells. With the demand for the commercial development of perovskite solar cells, which requires a larger photovoltaic area and longer stable operation[100], the encapsulation method will provide a protective barrier for perovskite solar cells to prevent the above-mentioned factors that can affect the stability of perovskite solar cells from affecting photovoltaic devices[101-105]. In this paper, the perovskite encapsulation is divided into three parts, namely encapsulation structure, encapsulation technol-

TABLE I. According to IEC 61215 photovoltaic module test items and conditions.

Test	Conditions
Measurement of temperature coefficients	Temperature coefficients for the current (a), voltage (β) and peak power (δ).
Measurement of nominal module operating temperature	Module operating near maximum power point Total solar irradiance: 800 W/m^2 Ambient temperature: 20 °C Wind speed: 1 m/s
Performance at low irradiance	Cell temperature: 25 °C Irradiance: 200 W/m^2 with IEC 60904-3 reference solar spectral distribution
Light soaking test	Cell temperature: 50±10 °C 800–1 000 W/m^2 with IEC 60904-9 reference solar spectral distribution or a class CCC or better simulator
UV precondition test	15 kWh/m^2 total UV irradiation in the wavelength range from 280 nm to 400 nm with 3% to 10% UV irradiance in the wavelength range from 280 nm to 320 nm at 60±5 °C
Thermal cycling test	50 or 200 cycles from −40 °C to 85 °C with current as per technology specific part up to 80 °C
Damp heat test	1 000 h at +85 °C, 85% RH
Humidity freeze test	10 cycles from 85 °C, 85% RH to −40 °C with circuitry continuity monitoring
Hot-spot endurance test	Exposure to 1000 W/m^2 irradiance in worst-case hot-spot condition

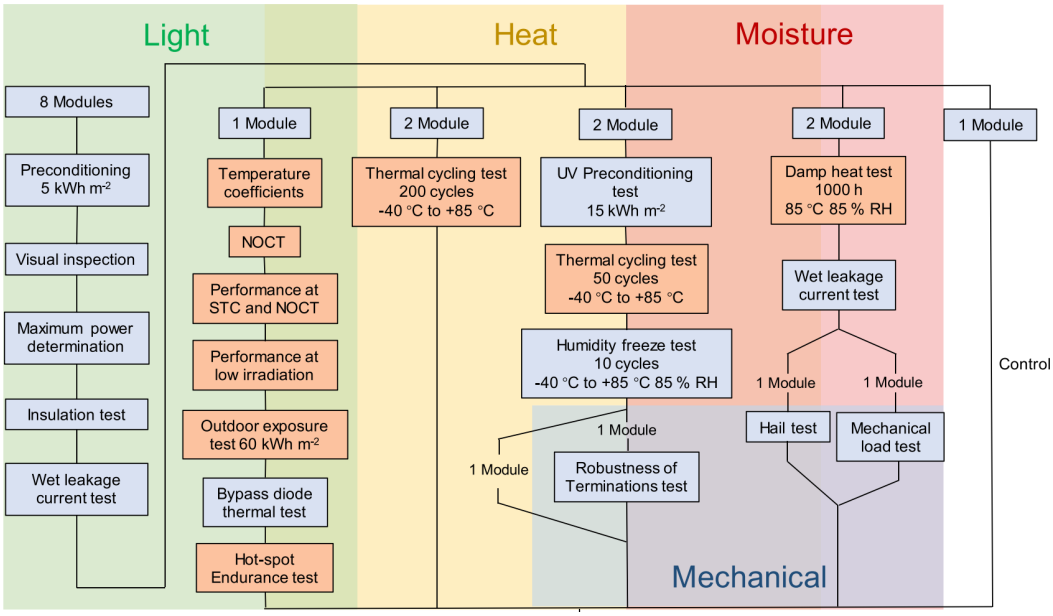

Fig. 5. Full test flow for design qualification and type approval of PV modules [98].

ogy, and encapsulation materials. At the same time, some research results in recent years are presented, as well as the impact of this research on perovskite solar cell encapsulation.

A. Encapsulation structure

Encapsulation structure refers to the composition type of the encapsulation as a whole, which can be simply divided into full coverage encapsulation and edge encapsulation in perovskite solar cell encapsulation, these two encapsulation structures are the most common in perovskite encapsulation. Common encapsulation methods can be roughly divided into two categories, figure 6(a) is full coverage encapsulation, which usually fabricates the encapsulation layer at the top of the module, and figure 6b is edge encapsulation [106], this encapsulation structure typically uses glass-glass

encapsulation technology and encapsulant is applied around the module.

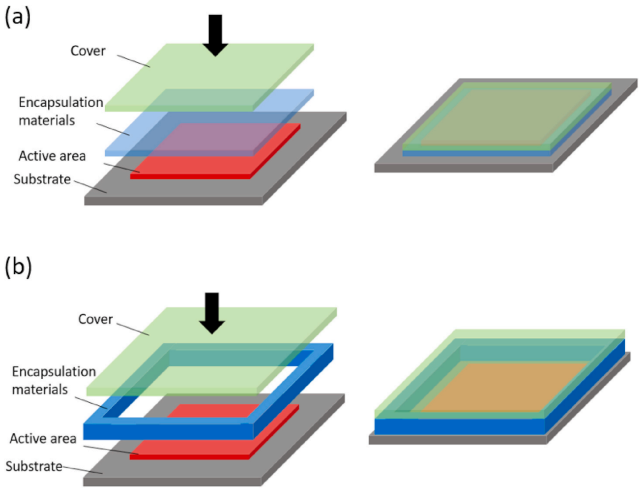

Fig. 6. (a) Full coverage encapsulation diagram; (b) edge encapsulation diagram.

1. Full coverage encapsulation

The full coverage encapsulation method is in direct contact with the perovskite solar cell device, which has high requirements for the encapsulation material and technology, first of all, it should have high light transmission, and at the same time can block ultraviolet radiation. Encapsulation materials need to be chemically inert to the perovskite functional layer, to ensure that it does not affect the performance of the functional layers. Full coverage encapsulation greatly improves the stability of perovskite solar energy, this structure resists the maximum amount of water oxygen. For perovskite solar cells to maintain stability, usually use a polymer as an encapsulation material or use atomic layer deposition to fabricate water-oxygen insulation film[107].

2. Edge encapsulation

Edge encapsulation structures are shown in figure 6(b). The advantage of edge encapsulation is to reduce the contact with each functional layer and reduce the possibility of encapsulation materials and perovskite reaction, but the effect of encapsulation can be correspondingly reduced, to further increase the effect of water resistance, which can add desiccant in the technology of edge encapsulation[108]. Due to the simple operation of edge encapsulation structure, many options of encapsulants, and low price, edge encapsulation has been widely studied at present, mainly focusing on the improvement of encapsulants, and researchers are committed to finding more long-term, stable encapsulants with less impact on perovskite. Some commonly used encapsulants are described below.

B. Encapsulation technology

We divide the most common encapsulation techniques into glass-glass encapsulation, organic material encapsulation such as polymer encapsulation and inorganic thin-film encapsulation such as atomic layer deposition (ALD) and plasma-enhanced chemical vapour deposition (PECVD)[109-110,112-113].

1. Glass-glass encapsulation

Glass-glass encapsulation is a typical edge encapsulation as shown in figure 6b and it has two critical components, one edge encapsulant and the other one is glass. The Glass encapsulant must have good light transmission and the edge encapsulant is mainly used to isolate water and oxygen[114]. Currently, this technology is the most common encapsulation method for all types of solar cells, which is one of the most widely used strategies to improve the long-term stability of perovskite solar cell equipment. Silicon solar cells can operate stably for up to 20 years using a glass-glass encapsulation[104,115-116]. This encapsulation technology is usually performed at ($\geq$100 °C), and the temperature sensitivity of perovskite makes glass-glass encapsulation not ideal for perovskite solar cells. To avoid degradation of perovskite during encapsulation and curing, lower temperature encapsulants and UV-curable encapsulants have been developed, such as ethylene vinyl acetate (EVA), butyl rubber and polyisobutylene (PIB), epoxy resins or epoxy adhesives, and different edge encapsulants such as butyl rubber, PIB or UV epoxy adhesives[117-121,123-124]. Considering the application of photovoltaic devices, glass-glass encapsulation are not suitable for use in flexible devices, which

limits many application scenarios for perovskite solar cells.

2. Organic thin-film encapsulation

Because glass-glass encapsulation technology requires materials such as encapsulant and glass, each step can lead to a reduction in the lifetime of perovskite solar cells. The researchers began using organic thin-film encapsulation to encapsulate perovskite solar cells. As an encapsulation layer, organic materials have the advantages of high flexibility, bendability, and low cost, and are suitable for the encapsulation of rigid or flexible devices[125-127]. Organic thin-film encapsulation is mainly polymer encapsulation, and many studies in recent years have shown that the low cost and easy availability of polymer encapsulation technology make it attractive in the fields of dye-sensitive solar cells (DSSCs)[128-130], organic polymer solar cells (OPVs), etc[131-132]. For flexible perovskite solar cells, organic film encapsulation technology has great potential, especially in large-scale encapsulation, its fabrication process and the diversity of raw materials make it a major choice for perovskite commercial encapsulation[133-135]. Several types of organic materials can be used for this purpose, examples include polymethyl methacrylate (PMMA), polyethylene terephthalate (PET), polytetrafluoroethylene (PTFE), polycarbonate (PC), polydimethylsiloxane (PDMS), ethylene vinyl acetate (EVA), polyethylene naphthalate (PEN), flexible polymer-based hybrid multilayers, and polymer composites Material. The encapsulation of organic materials needs a low water vapour transmission rate (WVTR), high light transmission, good thermodynamic properties, and chemical inertness to the functional layers of the solar cell[113,116].

This technology is a full coverage encapsulation and has a good effect. At the same time, similar to glass-glass encapsulation technology, organic thin-film technology mostly requires thermal curing technology, which can also make it possible to cause perovskite degradation. Therefore, low-temperature organic thin-film encapsulation technology needs to be further developed.

3. Inorganic thin-film encapsulation

Inorganic thin-film encapsulation technology has great advantages over other encapsulation technologies. Water vapour transmission rate (WVTR) and oxygen transmission rate (OTR) are very low because the encapsulation can deposit single or multilayer films directly on the perovskite device. In addition, a variety of deposition technologies are available[137]. A wide variety of materials can be used as barriers (i.e. Al_2O_3, SiO_x, TiO_2, or organic-inorganic hybrid polymer layers) and can be used for chemical or physical vapour deposition (CVD, PVD), plasma-enhanced chemical vapour deposition (PECVD), or atomic layer deposition (ALD)[138-142]. In addition to good encapsulation performance, this technology is highly adaptable to many types of hole transport layers[143].

The water resistance and oxygen resistance of inorganic film encapsulation technology are very good, but this technology is complex and expensive, and cannot be used as the first choice for large-scale commercial perovskite solar cell encapsulation, researchers are further improving the applicability of this method.

C. Encapsulation material

The main purpose of perovskite solar cell encapsulation is to prevent perovskite degradation caused by the reaction of water, oxygen, and, as well as the leakage of harmful substances in the perovskite[144-146]. One of the most important is to prevent water vapour from entering the perovskite solar device, causing perovskite degradation. To ensure a satisfactory encapsulation effect, the encapsulation material must have suitable thermal expansion properties. Its oxygen transmission rate (OTR) and water vapour transmission rate (WVTR), which represent the rates at which oxygen and water vapour are transferred through the encapsulation material, must be sufficiently low[111,147-148]. For the minimum standard of encapsulation materials, you can refer to the standard of encapsulation materials for OPV devices proposed by Ahmad et al.[149] as shown in table II. This chapter of this article will introduce the current perovskite solar cell encapsulation materials.

TABLE II. Specifications and requirements for OPV encapsulation materials.

Characteristics	Specification of Requirement
WVTR	10^{-3}–10^{-6} g·m^{-2}·d^{-1}
OTR	10^{-3}–10^{-5} cm^3·m^{-2}·d^{-1}·atm^{-1}
Glass transition temperature (Tg)	< 40 °C (during the winter in deserts)
Total hemispherical light transmission over the wavelength range from 400 nm to 1100 nm	90% of incident light
Hydrolysis	None (80 °C, 100% RH)
Water absorption	<0.5 wt% (20 °C / 100% RH)
Resistance to thermal oxidation	Stable (up to 85 °C)
Mechanical creep	None (90 °C)
Tensile modulus	<20.7 Mpa (> 3000 psi) at 25 °C
Chemical inertness	No reaction at 90 °C
UV absorption degradation	None (> 350 nm)
Hazing or clouding	None (80 °C, 100% RH)

1. Glass-glass encapsulant

Standard glass-glass encapsulation is the most commonly used method in photovoltaics. With this method, the top and bottom are perfectly protected with glass, but the edges are more vulnerable. Moisture can penetrate through the edges, so proper edge sealing must be used to fully protect the device [150-151]. In the case of flexible devices, the encapsulation architecture plays an important role in the stability of the device. Research into glass-glass encapsulation focuses on two main aspects: the choice of edge encapsulants and more advanced encapsulation technology. Matteocciet al. [119] adopted several different encapsulation methods to encapsulate PSC (the effective area is 1.05 cm^2) as shown in figure 7, and the average PCE can reach 13.6%. They studied the external degradation caused by the environment separately from the internal degradation caused by the material itself, and compared five different glass sealing methods. The best encapsulation method was based on polyimide tape sealing using UV-cured epoxy resin and edge seal adhesive together. After encapsulation, in a dark environment with 30% relative humidity, the device can maintain the initial efficiency (13.6%) for more than 1 300 h. Their proposed concept of combining full coverage encapsulation with edge encapsulation can effectively reduce the net efficiency loss caused by thermal stress and high pressure in the sealing process and has practical implications for achieving better encapsulation efficiency.

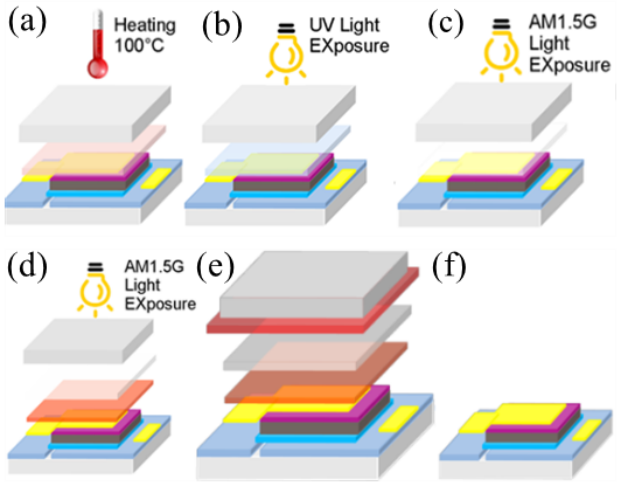

Fig. 7. (a) Encapsulation with thermoplastic sealant (Surlyn60); (b) Encapsulation with ultraviolet curing adhesive (three bond）; (c) Encapsulation with UV curable epoxy resin; (d) Encapsulation with polyimide tape and UV curable adhesive; (e) Use polyimide tape as primary seal, UV curable adhesive glass as secondary seal, and the most additional edge seal of three adhesive; (f) Unencapsulated blank sample.

This section summarises some of the material parameters used as adhesives in glass-glass encapsulation shown in table III.

2. Organic encapsulation materials

Organic encapsulation materials are mainly polymer materials used for organic thin-film encapsulation and as encapsulants for edge encapsulation [111]. As mentioned above in the section on organic thin-film

TABLE III. Properties of commonly used glass-glass encapsulant materials.

Materials	WVTR ($g \cdot m^{-2} \cdot d^{-1}$)	Application condition	Transmittance (%)	Elastic modulus (Mpa)	Long-term stability	Cost （$/ kg）	Ref.
EVA	28	140 °C, 650 mbar 20 min	91	10	40% RH, retained 95% of the original PCE after 1 000 h	3.3–4.7	[29,97,117]
PIB	10^{-2}–10^{-3}	90 °C, 300–400 mTorr 10 min	92	N/A	85 °C, 85%RH, no loss after 500 h and retain its initial PCE after 200 cycles	0.22–6.8	[97,117]
PU	16	UV light 10 min	N/A	N/A	At 18–30 °C, 28–65% RH, retain 94% of the PCE after 2 500 h	N/A	[97]
POE	N/A	150 °C, 500 mbar 8 min	90	9.1	85 °C, 85% RH, retain 60% of initial PCE after 900 h	1. 85 （DuPont 8150）	[24]
UV-cured epoxy	0.15	80 °C, 100 kPa 15 min	90	15–40	at 40 °C, 30% RH, retain 90% of the initial PCE after 45 days	20	[39,117]
Butyl rubber	10^{2}–10^{3}	90 °C, 400 mbar	92	9	N/A	N/A	[24]
PI tape	N/A	Xenon lamp at 25 °C	90	N/A	ambient atmosphere, retain 97% of the PCE for 1 000 h	N/A	[24]

encapsulation technology, the main encapsulation polymers are PMMA, PIB, EVA, etc. The following is a review of research into the encapsulation properties of organic materials[23,152].

Ethylene-vinyl acetate (EVA) is a popular encapsulant for photovoltaic modules worldwide and has been used for more than 25 years[153]. EVA has many attractive properties such as high light transmission (91%), the volume resistivity of 0.2–1.4×10^{16} Ω·cm and adhesive strength of 9–12 N/mm (90° peel). However, EVA degrades to acetic acid, which lowers the pH and generally increases the rate of surface corrosion. EVA also undergoes a glass transition, starting at around −15℃, making its use in environments below −15 °C questionable. Despite these drawbacks, EVA has proven to be a good encapsulant material for silicon solar cells. However, perovskite solar cells are more sensitive to external conditions than silicon solar cells. It can be used not only for organic thin-film encapsulation but also as an encapsulant for edge encapsulation. The thermal expansion coefficient of perovskite is 10 times higher than that of the glass substrate or transparent conductive oxide. Therefore, mechanical stress caused by temperature changes accelerates the degradation of these layers through delamination. Cheacharoen et al.[154] calculated the fracture toughness of a perovskite solar cell stack in a temperature cycle from −40 °C to 85 °C, using EVA as the encapsulant between two 3 mm thick pieces of glass, and using polyisobutylene encapsulant at the edges. As shown in figure 8(a), after 200 thermal cycles, the EVA encapsulated device still retains 90% of its initial performance, and they conclude that due to the low modulus of EVA, the device strain caused by heat is dissipated by EVA. However, the upper-pressure temperature of EVA (>130 °C) is dangerous for perovskite materials. Therefore, EVA does not appear to be an efficient encapsulant for perovskite solar cells[104].

Surlyn is DuPont's ionomer resin copolymer of ethylene and methacrylate. It has good chemical inertness and electrical insulation properties and has a low water vapour transmission rate (WVTR)[155-156]. Surlyn has been used as an encapsulant for almost all organic electronic devices, such as OLeds[157] and OPVs[158]. Cheacharoen et al.[154] also conducted the encapsulation experiment of Surlyn, mainly because the mechanical properties of Surlyn and EVA are very different. The modulus of elasticity of EVA is 10 Mpa and that of Surlyn is 394 Mpa. As a result of Surlyn's high modulus of elasticity, the encapsulation structure

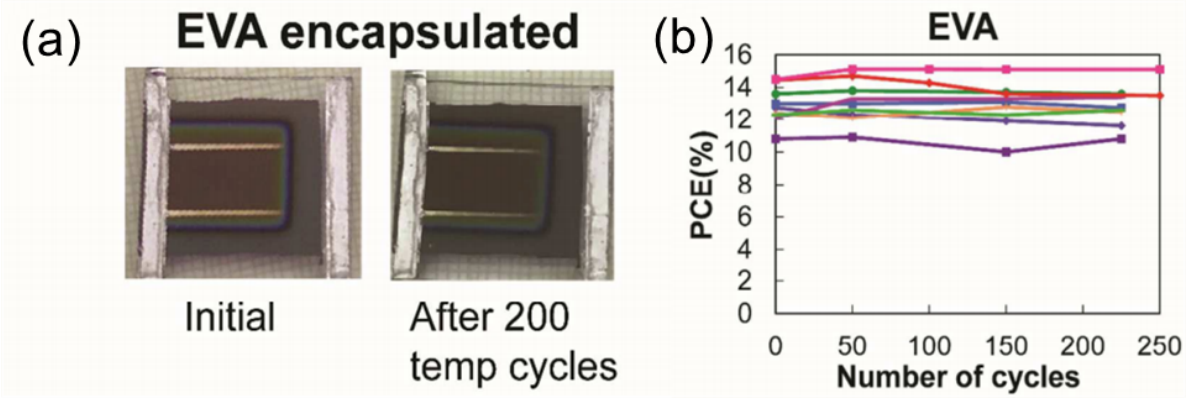

Fig. 8. (a) EVA encapsulated devices and (b) normalized PCE.

creates subtle defects under temperature changes, providing a path for water and oxygen to enter the device, resulting in serious performance degradation during testing.

Polyisobutylene (PIB) is a vinyl polymer with a low WVTR (10^{-2}–10^{-3} gm^{-2}·d^{-1})and a low glass transition temperature (−75 °C), of elastic modulus is 9 Mpa. which makes PIB also a popular encapsulation material for photovoltaic modules[127]. PIB is mainly used as encapsulant for edge encapsulation. Shi et al.[117] tested encapsulated perovskite solar cells using PIB as an encapsulant and found that PIB-encapsulated perovskite solar cells can operate stably for at least 200 days. Current-voltage measurements were taken under the damp heat cycle test standard of IEC 61215 and AM 1.5 G sunlight to monitor the change in PCE. After 540 hours of heat and humidity testing and 200 thermal cycles, the efficiency is still good. They believe that PIB as an encapsulation material can effectively ensure the stability of perovskite solar cells.

Epoxy resin is a thermosetting polymer with unique mechanical, electrical, and optical properties. Compared with EVA, epoxy resin has a lower operating temperature. The properties of epoxy resins are mainly determined by the formulation of their monomers and their additives[151,159]. Shi et al.[117] compared with PIB, ethylene-vinyl acetate copolymer (EVA), and UV-curable epoxy resin, PIB has the best encapsulation effect, which can effectively prevent the entry of external water and oxygen, and inhibit the volatilization of internal decomposition products. At the same time, they designed three different encapsulation structures (figure 9) PIB was used for edge encapsulation in both methods 1 and 2. The difference was that in method 1, the gold film layer was used as the positive contact, and the FTO layer was used as the negative contact. In method 2, the positive and negative contacts are provided by the FTO layer. Method 3 uses PIB for the complete coverage encapsulation, and the positive and negative contacts are provided by the FTO layer. The results show that method 3 has the best encapsulation effect, and the PSC of the encapsulation remains at 90% of the initial efficiency (8.7%) after 540 h of the damp heat test at 85 °C and 85% relative humidity. Under the condition of 85% relative humidity, after 200 freeze-wet cycles (−40–85 °C), 90% of the initial efficiency can be maintained. Epoxy resin is a widely used encapsulation material at present, but it tends to age and discolor, which reduces light transmission. In addition, because it is not flexible, it is easy to crack in the hot and cold cycles. Luo et al.[160] tested perovskite films and solar cell seals against commercial polyisobutene-based sealants (PVS, day seals), EVA (silicon) and AB epoxy adhesives (Aibida 6 005) as encapsulation materials, systematically studying the water resistance of packaged devices at high temperatures (very harsh environments) for the first time. The aging process of perovskite films and solar cells was recorded as a function of time and the reliability of these perovskite PV packaging technologies was carefully evaluated. They found that EVA had poor encapsulation performance compared to the other two materials under extremely harsh conditions, and the encapsulation structure was destroyed during the test.

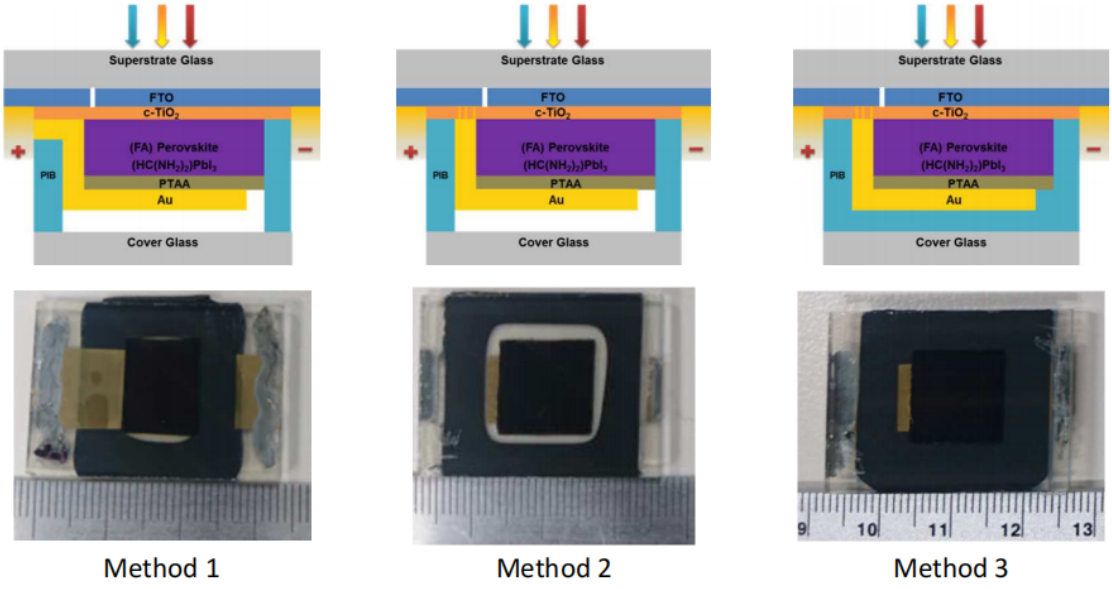

Fig. 9. Cross-sectional schematics and plan view photographs from the FTO glass side of PSCs encapsulated by three methods (not to scale). In Method 1, PIB is applied over a thin gold film which is the positive electrical feedthrough for the cell. In Methods 2 and 3, both electrical feed through are provided by the FTO layer. Methods 1 and 2 use PIB as an edge seal whereas in Method 3, PIB blankets the entire area under the cover glass.

Polymethyl methacrylate (PMMA) is an acrylic-based polymer with strong bending strength, transparency, and UV resistance linearity. It is also currently used as a perovskite solar battery encapsulant[133]. McKenna et al.[135] discussed the effects of four polymers PMMA, polycarbonate (PC), ethyl cellulose (EC), and poly (4-methyl-1-pentene) (PMP) on the thermal stability of encapsulated PSC. PMMA encapsulation had the best effect and the encapsulation layer showed no obvious degradation at 60, 80, and 100 °C after 384 h. PMMA is also used as an interlayer and passivation layer to increase the lifetime of the device[1,161-162]. Soo et al.[163] improved thermal stability by spinning PMMA onto $MAPbI_3$ films fabricated under environmental conditions as an encapsulation layer as shown in figure 10. The grain boundary defects at the film/air interface were passivated by the PMMA layer during the annealing of the encapsulated perovskite film, and degradation signs started to appear after 3 h of annealing. After annealing for 5 h, only a small amount of $MAPbI_3$ was thermally degraded to PbI_2. These studies demonstrate that PMMA can effectively protect the stability of perovskite solar cells. However, studies have shown that PMMA can be decomposed by hydrolysed ester groups of water molecules[161], indicating that PMMA cannot effectively protect perovskite solar cells from water damage.

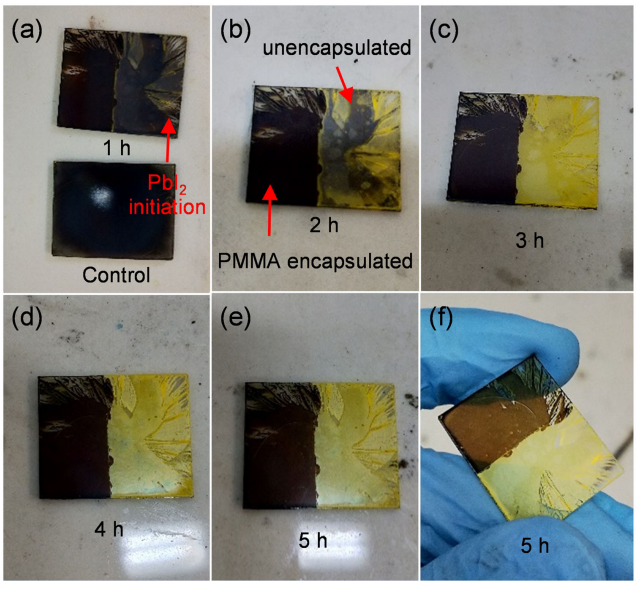

Fig. 10. Physical appearances of $MAPbI_3$-tracking films (with left portion encapsulated with PMMA and right portion unencapsulated) annealed at 150 °C for various times: (a) control film (annealed at 100 °C for 10 min) and 1 h (the arrow pointed to PbI_2 initiation region), (b) 2 h, (c) 3 h, (d) 4 h, (e) 5 h, and (f) tilted view of 5 h film to show the bleaching of initial dark brown color.

Polydimethylsiloxane (PDMS) was an important encapsulant for silicon photovoltaic devices in the 1960s and 1970s due to its high stability against thermal and ultraviolet light induction[156,164]. Liu et al.[165] used PDMS as an encapsulant to isolate water oxygen in the air and avoid the degradation of perovskite as shown in figure 11, and the equipment showed excellent stability during the test period of 3 000 h.

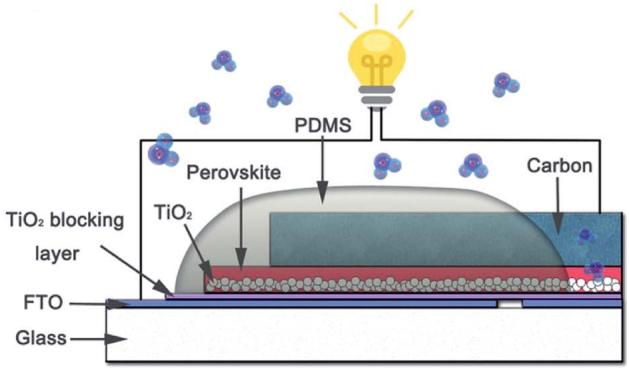

Fig. 11. Schematic diagram of PDMS encapsulation device.

Thermoplastic polyurethane (TPU) is a copolymer made by reacting polyols (short-chain and long-chain diols) with diisocyanates. Its structure and properties can be modified by changing the ratio. At the same time, TPU is the only encapsulant that adheres to the surface of polyester without any surface treatment. TPU has been widely used in the encapsulation of various electronic devices[162,166-167]. Due to its chemical properties, it can be used as a thin-film encapsulant[168-169]. Shi et al.[60] used TPU to encapsulate inorganic perovskite quantum dots to improve their thermal degradation and moisture resistance. After soaking in water for 72 hours, the polymer film still maintained the initial green light emission. This demonstrates the potential of polyurethane for the encapsulation of inorganic perovskite solar cells. Toniolo et al.[170] investigated two alternative packaging polymers for packaging perovskite/silicon series into micro-modules: thermoplastic polyurethane (TPU) and thermoplastic polyolefin (TPO) elastomers. To assess their impact on series module performance and stability, they performed two internationally recognized accelerated module stability tests (IEC 61215): wet heat exposure and thermal cycling. Finally, To better understand the thermodynamic properties of these two types of packaging and their relationship with the thermal cycle of packaging, dynamic mechanical thermal analysis was carried out. They found that TPU has a higher energy dissipation capacity than TPO, especially in the relevant temperature range of the module thermal cycle, and more effectively avoids microfracturing and delamination of perovskite/silicon series devices.

PU is an economical, lightweight, and thermally stable material whose mechanical, chemical, and physical properties can be easily adjusted by selecting the right precursor. PU film has excellent resistance to moisture and oxygen, which can prevent degradation of the perovskite film to PbI_2, improving the stability of the device. According to Bonomo et al.[171] PU encapsulated devices retain over 94% of their initial efficiency after 2 500 hours of storage in a laboratory environment. PU encapsulation is well suited to flexible perovskite solar cells, avoiding expensive and complex encapsulation methods. However, it is also difficult to use as a long-term encapsulation material because it degrades under long-term exposure to ultraviolet light, resulting in encapsulation failure.

In addition to the above types of organic encapsulation materials, some scholars have also conducted a small amount of research on other organic materials to explore their feasibility for perovskite solar cell encapsulation. Wu et al.[172] introduced polystyrene (PS) into perovskite solar cells as a buffer layer between SnO_2 perovskite, shown in figure 12, which releases residual stress in the perovskite during annealing due to its lower glass transition temperature. Stress-free perovskite has less recombination, a larger lattice and a lower tendency for ion migration, resulting in significantly improved cell efficiency and device stability. In addition, so-called internally encapsulated perovskite solar cells are produced by adding another PS coating layer on top of the perovskite. When the steady-state PCE is 21.5%, the photoelectric conversion efficiency (PCE) is as high as 21.89%.

An et al.[173] investigated a new cross-linked fullerene derivative (FPPS) for the encapsulation of PSC as shown in figure 13. The highest PCE after encapsulation was 17.82%, while the PCE without cross-linked devices was only 16.99%. Under the condi-

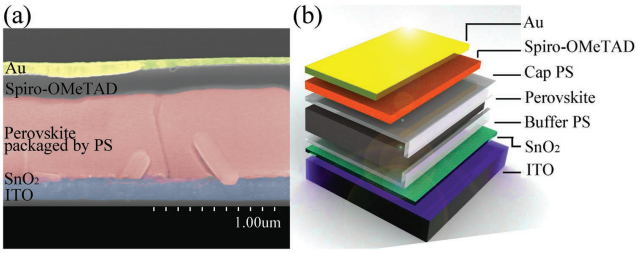

Fig. 12. (a) Schematic diagram of inner-encapsulated PSCs' structure; (b) Cross-sectional SEM image of the perovskite cell.

tion of 50%-60% relative humidity at dark room temperature, 80% of the initial efficiency can be maintained after 300 h.

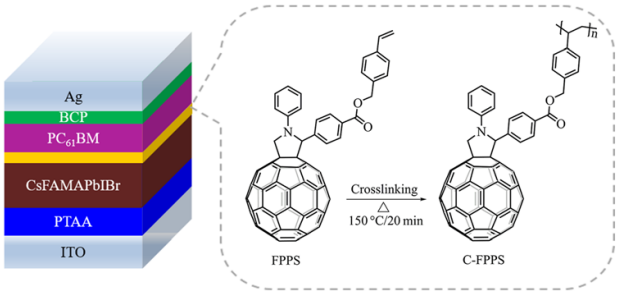

Fig. 13. Illustration of the device architecture with FPPS cross-linked to C-FPPS.

After a long period of research has shown that a large number of organic polymer materials can be used to encapsulate perovskite solar cells and that they have different properties and defects. Organic materials as perovskite solar cladding materials, should first consider the chemical inertness between it and other functional layers; And the process temperature at the time of encapsulation, the appropriate temperature should not cause damage to the perovskite functional layer after the completion of encapsulation; Finally, its light transmission and ability to block water oxygen. As a material that can be used for complete encapsulation, researchers are still trying to study organic encapsulation materials with good encapsulation properties and economic and long-term stability.

3. Inorganic encapsulation materials

Inorganic materials (silicon nitride, metal oxide, alumina, alumina, tin oxide, silicon oxide, oxide, etc.)[174]. It has been widely used as an encapsulant in OLED, OPV and dye-sensitised solar cells (DSSCs)[175]. To create high-performance barrier films, inorganic materials are deposited often using vacuum processes such as sputtering, ALD, and CVD.

Al_2O_3 has excellent resistance to water and oxygen. Its OTR is 1.9×10^{-3} g· m^{-2}·d^{-1} and WVTR is 9.0×10^{-4} g· m^{-2}·d^{-1} [141,176]. Ghosh et al.[177] deposited Al_2O_3 encapsulation layer on one side of the metal gold electrode of hybrid perovskite $[(FA_{0.83}MA_{0.17})_{0.95}Cs_{0.05}PbI_{2.5}Br_{0.5}]$ photovoltaic device, which inhibited the photo-induced degradation of the device. The short circuit current (JSC) of the original device drops sharply, dropping to 48% of the initial value (from 20 mA/cm^2 to 9.70 mA/cm^2) within 3 h. The encapsulation device retained nearly 92% of its initial value (from 20.7 mA/cm^2 to 19 mA/cm^2) after 3 h.

SnO_x film is a material with perfect barrier properties under high-humidity and high-temperature conditions, which can resist the influence of harmful factors such as water and oxygen, its WVTR is 7×10^{-5} g·m^{-2}·d^{-1}, thus effectively protecting the operating stability of the device. Zhao et al.[178] deposited two layers of SnO_x and added an ultrathin Ag layer in the middle as shown in figure 14, so that the SnO_x formed a conductive barrier to protect the silver electrode from moisture damage, while the SnO_x under the ultrathin Ag layer protected the silver electrode from halide leakage. The efficiency of perovskite solar cells is higher than 11%, with an average transmittance of about 70% in the near-infrared region ($\lambda > 800$ nm) and 29% at $\lambda = 400$–900 nm. Regardless of whether they are exposed to the ambient atmosphere or high temperatures, these devices have shown amazing stability over more than 4 500 hours.

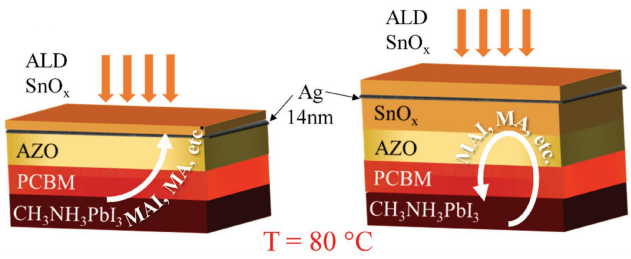

Fig. 14. Schemes of capping process via ALD for AZO/Ag and AZO/SnO_x/Ag samples.

In addition to the traditional Al_2O_3 and SnO_x inorganic encapsulation materials, there are some other inorganic encapsulation materials. Koiry et al.[179] investigated paraffin wax as an encapsulant for perovskite solar cells. The encapsulation does not affect the photovoltaic performance of the device. Moreover, under the environmental conditions of continuous exposure to relative humidity in the range of 70-85%, the photovoltaic performance of the encapsulated perovskite solar cells remains unchanged even after 2 160 h. Even after soaking in water or heating at 85 °C, the performance is still good. Therefore, paraffin has the potential to be used as a low-cost encapsulation material for perovskite solar cells.

Although the inorganic encapsulation film has the advantage of a simple fabrication process, the cracks and pinhole defects on the surface of the inorganic film are inevitable. In addition, they are not suitable for flexible devices because thicker inorganic films can cause cracking when bent. Water vapour and oxygen rapidly diffuse through these defects, further accelerating the degradation of perovskite solar cells. For high-performance encapsulation barriers, these inherent defects should be reduced or passivated. In addition, inorganic encapsulants require expensive encapsulation equipment such as CVD and ALD. These process conditions can damage the active material of perovskite solar cells and reduce their performance[104].

VI. CHALLENGES AND PERSPECTIVES

A. Fabrication process

As mentioned above, the biggest problem with perovskite solar cells is instability. There is a hidden danger of not being able to work for a long time at a high PCE. Thermal, stress, moisture, and ultraviolet radiation can all lead to the failure of the perovskite device. Therefore the stability problem is the first problem that must be solved for the industrialisation of perovskite solar cells.

The first problem to overcome is the fabrication of perovskite, which cannot yet be fabricated on a large scale in indoor environments. Since perovskite is very sensitive to water and the environment, the entire fabricating process must be carried out in an inert environment (glove box). The stability problem in the application process depends on better encapsulation technology and encapsulation materials.

B. Application challenges

At present, silicon cells dominate the photovoltaic products on the market due to their excellent photoelectric performance and mature manufacturing technology. However, its high manufacturing cost is preventing further popularisation and application, and it is still unable to shake off the status of traditional fossil energy. The main challenge for solar cells is therefore to reduce costs. This is also a major challenge in the industrialization process of perovskite solar cells, in addition to stability issues. To reduce the cost, improving the power conversion efficiency of solar cells is one of the most effective methods. At present, conventional single-junction silicon solar cells have achieved an efficiency of $> 25\%$ in experiments[180-182]. However, due to the Shockley-Queisser limit, the efficiency of single-junction solar cells cannot exceed 33.16%[183], regardless of material or complex design. Therefore, to achieve a breakthrough in conversion efficiency, a series module consisting of multiple single-junction solar cells is required.

To improve the efficiency of perovskite solar cell modules, the width of each subunit, the GFF, the line width, the electrode and the transmission loss of each single-junction solar cell link should be taken into account. In laminated series perovskite solar cells, the incident light passes through different cells from top to bottom, and the photons are absorbed more completely, which reduces the internal contradiction between the maximum absorption amount of photons and minimizes the thermal relaxation loss. Therefore, the theoretical limit of two-subunit series devices is increased to 42%, and for infinite small-subunit series devices, it can be further increased to 68%.

For planar series perovskite solar cells, high GFF is important to improve module utilization. GFF can be increased by increasing the subcell width, but this may introduce additional resistance losses. Therefore,

the loss caused by balancing resistance and dead zones is crucial to maximizing module PCE, requiring precise optimization of parameters such as subcell width, line width, and electrode design. In addition, the efficiency can be improved by replacing the highly conductive TCO and improving the laser marking accuracy.

C. Strategies for dealing with stability challenges

Solving the stability problem of perovskite is key to achieving sustained efficiency from perovskite solar cells. Although environmental stability, especially water stability, has been a widespread concern, the moisture stability of perovskite can be improved after proper passivation, and effective encapsulation can block water well. Ion migration also poses challenges for the stability of perovskite solar cells. Some studies indicate that the fabrication of perovskite films composed of larger grains is one method of inhibiting ion migration. For this reason, the researchers believe that the single-crystal perovskite film has good development prospects, and another strategy is to add additives to the perovskite film. Appropriate choice of additives can inhibit ion migration in halide perovskite and improve the operational stability of perovskite solar cells[184-185].

In the long term, perovskite solar cells or newer photovoltaic technologies will gradually replace the current silicon photovoltaic technology, but researchers need a deeper understanding of the degradation factors and mechanisms to overcome the current problems of perovskite solar cells. The ability to control stability issues will determine whether the technology can be industrialized.

VII. CONCLUSIONS

Perovskite solar cells have been widely studied as an economical and efficient new photoelectric device, and their industrialization has become a hot topic for the future. The results of the current study show that perovskite solar cells operating in outdoor conditions are susceptible to UV light, temperature and humidity, and thus become unstable. How to improve efficiency while maintaining long-term stability is therefore a major challenge, which is also the focus of the industrialization of perovskite solar cells. Encapsulation of perovskite solar cells can effectively improve their long-term stability. This is because it can act as a barrier layer by limiting the diffusion of oxygen, moisture and ion migration, thus protecting the device interface and active layer from degradation. Through some encapsulation, the life of perovskite solar cells can be up to 5 years, but most of the research results are still at the laboratory level, as well as small size single-junction solar cells, and most of the encapsulation technology is not suitable for large-scale fabrication, can not meet the needs of industrialization. Many researchers are currently working on the encapsulation of perovskite solar cells. Many encapsulation methods and encapsulation materials are gradually being discovered. For example, simple glass-glass encapsulation, organic thin-film encapsulation with many materials and processes, and expensive inorganic thin-film encapsulation. Each encapsulation technology and encapsulation material has its own advantages performance and disadvantages, so there is no single encapsulation for perovskite solar cells. Future research needs to focus on materials that can protect perovskite solar cells from elements such as water, oxygen and ultraviolet light. At the same time, it should have good thermodynamic properties, and the encapsulation material itself should have a long lifetime, be able to adapt to the external environment and minimize lead leakage. Finally, for perovskite solar cells to be commercialized on a large scale, these encapsulation materials and technologies should be reproducible, economical and suitable for large-scale fabrication. In addition to encapsulation, the development of perovskite solar cells also requires the establishment of uniform performance test standards and characterization techniques to accurately assess the effect of encapsulation on the performance and stability of perovskite solar cells.

REFERENCES

[1] HABISREUTINGER S N, LEIJTENS T, EPERON G E, et al. Carbon nanotube/polymer composites as

a highly stable hole collection layer in perovskite solar cells[J]. Nano Lett., 2014, 14(10): 5561.

[2] LI G, ZHU R, YANG Y. Polymer solar cells[J]. Nat. Photonics, 2012, 6(3): 153.

[3] WU T, QIN Z, WANG Y, et al. The main progress of perovskite solar cells in 2020-2021[J]. Nanomicro Lett., 2021, 13(1): 152.

[4] FUKUDA K, YU K, SOMEYA T. The future of flexible organic solar cells[J]. Adv. Energy Mater., 2020, 10(25): 2000765.

[5] ZHOU Q, DUAN J, DU J, et al. Tailored lattice "tape" to confine tensile interface for 11.08%-efficiency all-inorganic $CsPbBr_3$ perovskite solar cell with an ultrahigh voltage of 1.702 V[J]. Adv. Sci. (Weinh), 2021, 8(19): e2101418.

[6] TONG G, SON D-Y, ONO L K, et al. Removal of residual compositions by powder engineering for high efficiency formamidinium-based perovskite solar cells with operation lifetime over 2 000 h[J]. Nano Energy, 2021, 87: 106152.

[7] YANG D, ZHOU X, YANG R, et al. Surface optimization to eliminate hysteresis for record efficiency planar perovskite solar cells[J]. Energ. Environ.l Sci., 2016, 9(10): 3071.

[8] YANG L, WANG J, LEUNG W W. Lead iodide thin film crystallization control for high-performance and stable solution-processed perovskite solar cells[J]. ACS Appl. Mater. Interfaces, 2015, 7(27): 14614.

[9] DUAN J, LIU Y, CHEN X, et al. Efficient and stable mesoporous perovskite solar cells using p-type poly (9-vinylcarbazole) modified the interface of perovskite/mesoporous TiO_2 layers[J]. Org. Electron., 2020, 82: 105737.

[10] LI H, XIAO Z, DING L, et al. Thermostable single-junction organic solar cells with a power conversion efficiency of 14.62%[J]. Sci. Bull., 2018, 63(6): 340.

[11] SALADO M, IDIGORAS J, CALIO L, et al. Interface play between perovskite and hole selective layer on the performance and stability of perovskite solar cells[J]. ACS Appl. Mater. Interfaces, 2016, 8(50): 34414.

[12] XIAO Z, JIA X, DING L. Ternary organic solar cells offer 14 power conversion efficiency[J]. Sci. Bull., 2017, 62(23): 1562.

[13] ZHU J, PARK S, GONG O Y, et al. Formamidine disulfide oxidant as a localised electron scavenger for >20% perovskite solar cell modules[J]. Energ. Environ.l Sci., 2021, 14(9): 4903.

[14] CICCIOLI A, LATINI A. Thermodynamics and the intrinsic stability of lead halide perovskites $CH_3NH_3PbX_3$[J]. J. Phys. Chem. Lett., 2018, 9(13): 3756.

[15] LIU H, FU W, ZONG B, et al. A high stability, hole-conductor-free mixed organic cation pervoskite solar cells based on carbon counter electrode[J]. Electrochim. Acta, 2018, 266: 78.

[16] FATEMA K, AREFIN M S. Enhancing the efficiency of Pb-based and Sn-based perovskite solar cell by applying different ETL and HTL using SCAPS-ID[J]. Opt. Mater., 2022, 125.

[17] XIAO K, HAN Q, GAO Y, et al. Simultaneously enhanced moisture tolerance and defect passivation of perovskite solar cells with cross-linked grain encapsulation[J]. J. Energy Chem., 2021, 56: 455.

[18] WANG Y, ZHENG X, LIU X, et al. A study of different central metals in octamethyl-substituted phthalocyanines as dopant-free hole-transport layers for planar perovskite solar cells[J]. Org. Electron., 2018, 56: 276.

[19] LI W, ZHANG W, VAN REENEN S, et al. Enhanced UV-light stability of planar heterojunction perovskite solar cells with caesium bromide interface modification[J]. Energ. Environ. Sci., 2016, 9(2): 490.

[20] HUANG J, TAN S, LUND P D, et al. Impact of H_2O on organic-inorganic hybrid perovskite solar cells[J]. Energ. Environ. Sci., 2017, 10(11): 2284.

[21] HU Y, QIU T, BAI F, et al. Enhancing moisture-tolerance and photovoltaic performances of $FAPbI_3$ by bismuth incorporation[J]. J. Mater. Chem. A, 2017, 5(48): 25258.

[22] CHOWDHURY T A, BIN ZAFAR M A, SAJJAD-UL ISLAM M, et al. Stability of perovskite solar cells: issues and prospects[J]. RSC Adv, 2023, 13(3): 1787.

[23] AITOLA K, GAVA SONAI G, MARKKANEN M, et al. Encapsulation of commercial and emerging solar cells with focus on perovskite solar cells[J]. Solar Energy, 2022, 237: 264.

[24] CROS S, DE BETTIGNIES R, BERSON S, et al. Definition of encapsulation barrier requirements: a method applied to organic solar cells[J]. Sol. Energ. Mat. Sol. C., 2011, 95: S65.

[25] WANG R, MUJAHID M, DUAN Y, et al. A review of perovskites solar cell stability[J]. Adv. Funct. Mater., 2019, 29(47): 1808843.

[26] JIAO Y, LV Y, LI J, et al. Exploring electronic and optical properties of$CH_3NH_3GeI_3$ perovskite: insights from the first principles[J]. Computat. Theor. Chem., 2017, 1114: 20.

[27] LI R, XU Q, SHI B, et al. UV encapsulated monolithic perovskite/silicon tandem solar cells for hundred-watt power system[J]. ACS Energy Lett., 2023, 8(5): 2414.

[28] JAGADAMMA L K, BLASZCZYK O, SAJJAD M T, et al. Efficient indoor p-i-n hybrid perovskite solar cells using low temperature solution processed NiO as hole extraction layers[J]. Sol. Energ. Mat. Sol. C., 2019, 201: 110071.

[29] MA S, BAI Y, WANG H, et al. 1000 h operational lifetime perovskite solar cells by ambient melting encapsulation[J]. Adv. Energy Mater., 2020, 10(9): 1902472.

[30] DUALEH A, TÉTREAULT N, MOEHL T, et al. Effect of annealing temperature on film morphology of organic-inorganic hybrid pervoskite solid-state solar cells[J]. Adv. Funct. Mater., 2014, 24(21): 3250.

[31] MENG L, SUN C, WANG R, et al. Tailored phase conversion under conjugated polymer enables thermally stable perovskite solar cells with efficiency exceeding 21[J]. J. Am. Chem. Soc., 2018, 140(49): 17255.

[32] YE T, HOU Y, NOZARIASBMARZ A, et al. Cost-effective high-performance charge-carrier-transport-layer-free perovskite solar cells achieved by suppressing ion migration[J]. ACS Energy Lett., 2021, 6(9): 3044.

[33] HUANG C, LIU C, DI Y, et al. Efficient planar perovskite solar cells with reduced hysteresis and enhanced open circuit voltage by using PW12-TiO_2 as electron transport layer[J]. ACS Appl. Mater. Interfaces, 2016, 8(13): 8520.

[34] LIU D, KELLY T L. Perovskite solar cells with a planar heterojunction structure prepared using room-temperature solution processing techniques[J]. Nat. Photonics, 2013, 8(2): 133.

[35] BING J, CARO L G, TALATHI H P, et al. Perovskite solar cells for building integrated photovoltaics—glazing applications[J]. Joule, 2022, 6(7): 1446.

[36] POLO J, MARTÍN-CHIVELET N, SANZ-SAIZ C BIPV. modeling with artificial neural networks: towards a BIPV digital twin[J]. Energies, 2022, 15(11).

[37] SHUKLA A K, SUDHAKAR K, BAREDAR P. Recent advancement in BIPV product technologies: a review[J]. Energy Build., 2017, 140: 188.

[38] MATSUI T, SEO J Y, SALIBA M, et al. Room-temperature formation of highly crystalline multication perovskites for efficient, low-cost solar cells[J]. Adv. Mater., 2017, 29(15): 4173.

[39] JEON N J, NOH J H, KIM Y C, et al. Solvent engineering for high-performance inorganic-organic hybrid perovskite solar cells[J]. Nat. Mater., 2014, 13(9): 897.

[40] ALISHAH H M, CHOI F P G, KURUOGLU F, et al. Improvement of fill factor by the utilization of Zn-doped PEDOT:PSS hole-transport layers for p-i-n planar type of perovskite solar cells[J]. Electrochim. Acta, 2021, 388.

[41] JENG J Y, CHIANG Y F, LEE M H, et al. $CH_3NH_3PbI_3$ perovskite/fullerene planar-heterojunction hybrid solar cells[J]. Adv. Mater., 2013, 25(27): 3727.

[42] SUN K, CHANG J, ISIKGOR F H, et al. Efficiency enhancement of planar perovskite solar cells by adding zwitterion/LiF double interlayers for electron collection[J]. Nanoscale, 2015, 7(3): 896.

[43] DONG H, PANG S, ZHANG Y, et al. Improving electron extraction ability and device stability of perovskite solar cells using a compatible PCBM/AZO electron transporting bilayer[J]. Nanomaterials (Basel), 2018, 8(9): 720.

[44] SAPAROV B, HONG F, SUN J P, et al. Thin-film preparation and characterization of $Cs_3Sb_2I_9$: a lead-free layered perovskite semiconductor[J]. Chem. Mater., 2015, 27(16): 5622.

[45] SUN S, SALIM T, MATHEWS N, et al. The origin of high efficiency in low-temperature solution-processable bilayer organometal halide hybrid solar cells[J]. Energy Environ. Sci., 2014, 7(1): 399.

[46] YAO K, LI F, HE Q, et al. A copper-doped nickel oxide bilayer for enhancing efficiency and stability of hysteresis-free inverted mesoporous perovskite solar cells[J]. Nano Energy, 2017, 40: 155.

[47] MAKKARAMKOTT A, MUKHERJEE R, AVASTHI S, et al. Ambient prepared mesoporous perovskite solar cells with longer stability[J]. J. Electron. Mater., 2021, 50(3): 1535.

[48] HUANG D, LIU Q, MA Z, et al. Orientation-controlled mesoporous PbI_2 scaffold for 22.7% perovskite solar cells[J]. Science China Materials, 2023, 66(4): 1313.

[49] KIM B J, LEE S, JUNG H S. Recent progressive efforts in perovskite solar cells toward commercialization[J]. J. Mater. Chem. A, 2018, 6(26): 12215.

[50] MEI Y, LIU H, LI X, et al. Hollow TiO_2 spheres as mesoporous layer for better efficiency and stability of perovskite solar cells[J]. J. Alloys Compd., 2021, 866: 158079.

[51] MA S, PANG S, DONG H, et al. Stability improvement of perovskite solar cells by the moisture-resistant PMMA: spiro-OMeTAD hole transport layer[J]. Polymers (Basel), 2022, 14(2): 343.

[52] GRÄTZEL M. Mesoscopic solar cells for electricity and hydrogen production from sunlight[J]. Chem. Lett., 2005, 34(1): 8.

[53] HARDIN B E, SNAITH H J, MCGEHEE M D. The renaissance of dye-sensitized solar cells[J]. Nat. Pho-

tonics, 2012, 6(3): 162.

[54] SHI S, LI Y, LI X, et al. Advancements in all-solid-state hybrid solar cells based on organometal halide perovskites[J]. Mater. Horiz., 2015, 2(4): 378.

[55] FONG P W K, LI G. The challenge of ambient air-processed organometallic halide perovskite: technology transfer from spin coating to meniscus blade coating of perovskite thin films[J]. Front. Mater., 2021, 8: 635224.

[56] SUZUKI A, OKADA H, OKU T. Fabrication and characterization of $CH_3NH_3PbI_{3-x-y}Br_xCl_y$ perovskite solar cells[J]. Energies, 2016, 9(5): 376.

[57] LI Z, KLEIN T R, KIM D H, et al. Scalable fabrication of perovskite solar cells[J]. Nat. Rev. Mater., 2018, 3(4): 18017.

[58] PARK J H, YOON Y S, KIM J Y. Fabrication processes for all-inorganic $CsPbBr_3$ perovskite solar cells[J]. EcoMat, 2023.

[59] LIU P, TANG G, YAN F. Strategies for large-scale fabrication of perovskite films for solar cells[J]. Solar RRL, 2021, 6(1): 2100683.

[60] SHI J, GE W, GAO W, et al. Enhanced thermal stability of halide perovskite $CsPbX_3$ nanocrystals by a facile TPU encapsulation[J]. Advanced Opt. Mater., 2019, 8(4): 1901516.

[61] MATSUI T, YOKOYAMA T, NEGAMI T, et al. Effect of rubidium for thermal stability of triple-cation perovskite solar cells[J]. Chem. Lett., 2018, 47(6): 814.

[62] MA A. Influence of nanosemiconductor materials on thermal stability of solar cells[J]. Int. J. Anal. Chem., 2022, 2022: 6805501.

[63] CHENG Z, LIN J. Layered organic-inorganic hybrid perovskites: structure, optical properties, film preparation, patterning and templating engineering[J]. CrystEngComm, 2010, 12(10): 2646.

[64] YANG J, LIU X, ZHANG Y, et al. Comprehensive understanding of heat-induced degradation of triple-cation mixed halide perovskite for a robust solar cell[J]. Nano Energy, 2018, 54: 218.

[65] KONG W, WANG S, LI F, et al. Ultrathin perovskite monocrystals boost the solar cell performance[J]. Adv. Energy Mater., 2020, 10(34): 2000453.

[66] SONG T, GAO L, WEI Q, et al. Study on the effect of chlorine on the growth of $CH_3NH_3PbI_{3-x}Cl_x$ crystals[J]. Mater. Res. Express, 2020, 7(1): 015522.

[67] ROLSTON N, PRINTZ A D, TRACY J M, et al. Effect of cation composition on the mechanical stability of perovskite solar cells[J]. Adv. Energy Mater., 2017, 8(9).

[68] HA S R, JEONG W H, LIU Y, et al. Molecular aggregation method for perovskite-fullerene bulk heterostructure solar cells[J]. J. Mater. Chem. A, 2020, 8(3): 1326.

[69] SUPASAI T, RUJISAMPHAN N, ULLRICH K, et al. Formation of a passivating $CH_3NH_3PbI_{3/}PbI_2$ interface during moderate heating of $CH_3NH_3PbI_3$ layers[J]. Appl. Phys. Lett., 2013, 103(18): 183906.

[70] UDDIN Z, RAN J, STATHATOS E, et al. Improving thermal stability of perovskite solar cells by thermoplastic additive engineering[J]. Energies, 2023, 16(9): 3621.

[71] ROLSTON N, BUSH K A, PRINTZ A D, et al. Engineering stress in perovskite solar cells to improve stability[J]. Adv. Energy Mater., 2018, 8(29).

[72] WANG H, ZHU C, LIU L, et al. Interfacial residual stress relaxation in perovskite solar cells with improved stability[J]. Adv. Mater., 2019, 31(48): e1904408.

[73] PISONI A, JACIMOVIC J, BARISIC O S, et al. Ultra-low thermal conductivity in organic-inorganic hybrid perovskite $CH_3NH_3PbI_3$[J]. J. Phys. Chem. Lett., 2014, 5(14): 2488.

[74] ISHII M, YAMASHITA Y, WATANABE S, et al. Doping of molecular semiconductors through proton-coupled electron transfer[J]. Nature, 2023, 622(7982): 285.

[75] YI C, LUO J, MELONI S, et al. Entropic stabilization of mixed A-cation ABX3 metal halide perovskites for high performance perovskite solar cells[J]. Energ. Environ.l Sci., 2016, 9(2): 656.

[76] KWON Y S, LIM J, YUN H J, et al. A diketopyrrolopyrrole-containing hole transporting conjugated polymer for use in efficient stable organic-inorganic hybrid solar cells based on a perovskite[J]. Energ. Environ.l Sci., 2014, 7(4): 1454.

[77] YANG J, SIEMPELKAMP B D, LIU D, et al. Investigation of $CH_3NH_3PbI_3$ degradation rates and mechanisms in controlled humidity environments using in situ techniques[J]. ACS Nano, 2015, 9(2): 1955.

[78] ZHOU J, GAO Y, PAN Y, et al. Recent advances in the combined elevated temperature, humidity, and light stability of perovskite solar cells[J]. Solar RRL, 2022, 6(12): 16225.

[79] YANG J, YUAN Z, LIU X, et al. Oxygen- and water-induced energetics degradation in organometal halide perovskites[J]. ACS Appl. Mater. Interfaces, 2018, 10(18): 16225.

[80] YU H, XIE Y, ZHANG J, et al. Thermal and humidity stability of mixed spacer cations 2d perovskite solar cells[J]. Adv. Sci. (Weinh), 2021, 8(12): 2004510.

[81] FROST J M, BUTLER K T, BRIVIO F, et al. Atomistic origins of high-performance in hybrid halide perovskite solar cells[J]. Nano Lett, 2014, 14(5): 2584.

[82] ZHENG H, LIU G, CHEN X, et al. High-performance mixed-dimensional perovskite solar cells with enhanced stability against humidity, heat and UV light[J]. J. Mater. Chem. A, 2018, 6(41): 20233.

[83] AHMAD S, FU P, YU S, et al. Dion-jacobson phase 2d layered perovskites for solar cells with ultrahigh stability[J]. Joule, 2019, 3(3): 794.

[84] CHEN M, LI P, LIANG C, et al. Enhanced efficiency and stability of perovskite solar cells by 2D perovskite vapor-assisted interface optimization[J]. J. Energy Chem., 2020, 45: 103.

[85] BYRANVAND M M, KHARAT A N, TAGHAVINIA N. Moisture stability in nanostructured perovskite solar cells[J]. Mater. Lett., 2019, 237: 356.

[86] KULKARNI S A, BAIKIE T, BOIX P P, et al. Band-gap tuning of lead halide perovskites using a sequential deposition process[J]. J. Mater. Chem. A, 2014, 2(24): 9221.

[87] RYU S, NOH J H, JEON N J, et al. Voltage output of efficient perovskite solar cells with high open-circuit voltage and fill factor[J]. Energy Environ. Sci., 2014, 7(8): 2614.

[88] BERHE T A, SU W N, CHEN C H, et al. Organometal halide perovskite solar cells: degradation and stability[J]. Energ. Environ. Sci., 2016, 9(2): 323.

[89] WANG H, WANG L, REN W, et al. Synthesis and optical properties of tetragonal $CH_3NH_3PbI_xBr_{3-x}$ thin films[J]. Mater. Lett., 2015, 161: 484.

[90] WEERASINGHE H C, DKHISSI Y, SCULLY A D, et al. Encapsulation for improving the lifetime of flexible perovskite solar cells[J]. Nano Energy, 2015, 18: 118.

[91] WANG H, ZHAO Y, WANG Z, et al. Hermetic seal for perovskite solar cells: an improved plasma enhanced atomic layer deposition encapsulation[J]. Nano Energy, 2020, 69: 104375.

[92] ITO S, MIZUTA G, KANAYA S, et al. Light stability tests of $CH_3NH_3PbI_3$ perovskite solar cells using porous carbon counter electrodes[J]. Phys. Chem. Chem. Phys., 2016, 18(39): 27102.

[93] YANG Q, DETTORI R, ACHENIE L E K. A perovskite solar cell with enhanced light stability and high photovoltaic conversion efficiencies[J]. ACS Sustain. Chem. Eng., 2018, 7(1): 709.

[94] WANG P, CHAI N, WANG C, et al. Enhancing the thermal stability of the carbon-based perovskite solar cells by using a $Cs_xFA_{1-x}PbBr_xI_{3-x}$ light absorber[J]. RSC Adv, 2019, 9(21): 11877.

[95] KANDA H, USIOBO O J, MOMBLONA C, et al. Light stability enhancement of perovskite solar cells using 1H, 1H, 2H, 2H-perfluorooctyltriethoxysilane passivation[J]. Solar RRL, 2020, 5(3): 2000650.

[96] ZHANG D, LI D, HU Y, et al. Degradation pathways in perovskite solar cells and how to meet international standards[J]. Commun. Mater., 2022, 3(1): 58.

[97] HOLZHEY P, SALIBA M. A full overview of international standards assessing the long-term stability of perovskite solar cells[J]. J. Mater. Chem. A, 2018, 6(44): 21794.

[98] HU Y, CHU Y, WANG Q, et al. Standardizing perovskite solar modules beyond cells[J]. Joule, 2019, 3(9): 2076.

[99] LANGE R F M, LUO Y, POLO R, et al. The lamination of (multi)crystalline and thin film based photovoltaic modules[J]. Prog.Photovoltaics, 2011, 19(2): 127.

[100] LV Y, ZHANG H, LIU R, et al. Composite encapsulation enabled superior comprehensive stability of perovskite solar cells[J]. ACS Appl. Mater. Interfaces, 2020, 12(24): 27277.

[101] KIM Y, KIM H, GRAHAM S, et al. Durable polyisobutylene edge sealants for organic electronics and electrochemical devices[J]. Sol. Energ. Mat. Sol. C., 2012, 100: 120.

[102] XIANG L, GAO F, CAO Y, et al. Progress on the stability and encapsulation techniques of perovskite solar cells[J]. Org. Electron., 2022, 106.

[103] LI F, LIU M. Recent efficient strategies for improving the moisture stability of perovskite solar cells[J]. J. Mater. Chem. A, 2017, 5(30): 15447.

[104] SHI Y, ZHANG F. Advances in encapsulations for perovskite solar cells: from materials to applications[J]. Solar RRL, 2023, 7(7): 2201123.

[105] WEI Q, HUO X, FU Q, et al. An effective encapsulation for perovskite solar cells based on building-integrated photovoltaics[J]. J. Mater. Chem. C, 2022, 10(23): 8972.

[106] LI J, XIA R, QI W, et al. Encapsulation of perovskite solar cells for enhanced stability: Structures, materials and characterization[J]. J. Power Sources, 2021, 485: 229313.

[107] CHANG C Y, CHOU C T, LEE Y J, et al. Thin-film encapsulation of polymer-based bulk-heterojunction photovoltaic cells by atomic layer deposition[J]. Org. Electron., 2009, 10(7): 1300.

[108] CONINGS B, DRIJKONINGEN J, GAUQUELIN N, et al. Intrinsic thermal instability of methylammonium lead trihalide perovskite[J]. Adv. Energy Mater.,

2015, 5(15): 1500477.

[109] ARANDA C, GUERRERO A, BISQUERT J. Crystalline clear or not: beneficial and harmful effects of water in perovskite solar cells[J]. Chem. phys. chem, 2019, 20(20): 2587.

[110] JUILLARD S, PLANES E, MATHERON M, et al. Mechanical reliability of flexible encapsulated organic solar cells: characterization and improvement[J]. ACS Appl. Mater. Interfaces, 2018, 10(35): 29805.

[111] UDDIN A, UPAMA M, YI H, et al. Encapsulation of organic and perovskite solar cells: a review[J]. Coatings, 2019, 9(2): 65.

[112] CONTRERAS BERNAL L, ARANDA C, VALLES-PELARDA M, et al. Homeopathic perovskite solar cells: effect of humidity during fabrication on the performance and stability of the device[J]. J. Phys. Chem. C, 2018, 122(10): 5341.

[113] JIANG Y, QIU L, JUAREZ-PEREZ E J, et al. Reduction of lead leakage from damaged lead halide perovskite solar modules using self-healing polymer-based encapsulation[J]. Nat. Energy, 2019, 4(7): 585.

[114] CHEACHAROEN R, BOYD C C, BURKHARD G F, et al. Encapsulating perovskite solar cells to withstand damp heat and thermal cycling[J]. Sustain. Energ. Fuels, 2018, 2(11): 2398.

[115] YANG H, WANG H, CAO D, et al. Analysis of power loss for crystalline silicon solar module during the course of encapsulation[J]. Int. J. Photoenergy, 2015, 2015: 1.

[116] RAMANUJAM J, BISHOP D M, TODOROV T K, et al. Flexible CIGS, CdTe and a-Si:H based thin film solar cells: a review[J]. Prog. Mater. Sci., 2020, 110: 100619.

[117] SHI L, YOUNG T L, KIM J, et al. Accelerated lifetime testing of organic-inorganic perovskite solar cells encapsulated by polyisobutylene[J]. ACS Appl. Mater. Interfaces, 2017, 9(30): 25073.

[118] USH K A, PALMSTROM A F, YU Z J, et al. 23.6%-efficient monolithic perovskite/silicon tandem solar cells with improved stability[J]. Nat. Energy, 2017, 2(4): 17009.

[119] MATTEOCCI F, CINá L, LAMANNA E, et al. Encapsulation for long-term stability enhancement of perovskite solar cells[J]. Nano Energy, 2016, 30: 162.

[120] BURSCHKA J, PELLET N, MOON S J, et al. Sequential deposition as a route to high-performance perovskite-sensitized solar cells[J]. Nature, 2013, 499(7458): 316.

[121] RAMASAMY E, KARTHIKEYAN V, RAMESHKUMAR K, et al. Glass-to-glass encapsulation with ultraviolet light curable epoxy edge sealing for stable perovskite solar cells[J]. Mater. Lett., 2019, 250: 51.

[122] CASTRO HERMOSA S, TOP M, DAGAR J, et al. Quantifying performance of permeation barrier—encapsulation systems for flexible and glass-based electronics and their application to perovskite solar cells[J]. Adv. Electron. Mater., 2019, 5(10): 1800978.

[123] LEWIS J S, WEAVER M S. Thin-film permeation-barrier technology for flexible organic light-emitting devices[J]. IEEE J. Sel. Top. Quant. Electron., 2004, 10(1): 45.

[124] CASTRO-HERMOSA S, LUCARELLI G, TOP M, et al. Perovskite photovoltaics on roll-to-roll coated ultra-thin glass as flexible high-efficiency indoor power generators[J]. Cell Rep. Phys. Sci., 2020, 1(5): 100045.

[125] LI B, WANG M, SUBAIR R, et al. Significant stability enhancement of perovskite solar cells by facile adhesive encapsulation[J]. J. Phys. Chem. C, 2018, 122(44): 25260.

[126] LU Q, YANG Z, MENG X, et al. A review on encapsulation technology from organic light emitting diodes to organic and perovskite solar cells[J]. Adv. Funct. Mater., 2021, 31(23): 2100151.

[127] RAMAN R K, GURUSAMY THANGAVELU S A, VENKATARAJ S, et al. Materials, methods and strategies for encapsulation of perovskite solar cells: from past to present[J]. Renew. Sust. Energy Rev., 2021, 151: 111608.

[128] BELLA F, GRIFFINI G, GEROSA M, et al. Performance and stability improvements for dye-sensitized solar cells in the presence of luminescent coatings[J]. J. Power Sources, 2015, 283: 195.

[129] GRIFFINI G, BELLA F, NISIC F, et al. Multifunctional luminescent down-shifting fluoropolymer coatings: a straightforward strategy to improve the uv-light harvesting ability and long-term outdoor stability of organic dye-sensitized solar cells[J]. Adv. Energy Mater., 2015, 5(3): 1401312.

[130] BELLA F, LEFTHERIOTIS G, GRIFFINI G, et al. A new design paradigm for smart windows: photocurable polymers for quasi-solid photoelectrochromic devices with excellent long-term stability under real outdoor operating conditions[J]. Adv. Funct. Mater., 2016, 26(7): 1127.

[131] HÖSEL M, SØNDERGAARD R R, JØRGENSEN M, et al. Comparison of UV-curing, hotmelt, and pressure sensitive adhesive as roll-to-roll encapsulation methods for polymer solar cells[J]. Adv. Eng. Mater., 2013, 15(11): 1068.

[132] PINTOSSI D, IANNACCONE G, COLOMBO A, et al. Luminescent downshifting by photo-induced sol-

gel hybrid coatings: accessing multifunctionality on flexible organic photovoltaics via ambient temperature material processing[J]. Adv. Electron. Mater., 2016, 2(11): 1600288.

[133] WILDERSPIN T J, DE ROSSI F, WATSON T M. A simple method to evaluate the effectiveness of encapsulation materials for perovskite solar cells[J]. Solar Energy, 2016, 139: 426.

[134] HAN G S, YOO J S, YU F, et al. Highly stable perovskite solar cells in humid and hot environment[J]. J. Mater. Chem. A, 2017, 5(28): 14733.

[135] MCKENNA B, TROUGHTON J R, WATSON T M, et al. Enhancing the stability of organolead halide perovskite films through polymer encapsulation[J]. RSC Advances, 2017, 7(52): 32942.

[136] WANG Q, LIN Z, XU Y, et al. Chelating resin encapsulation for reduced Pb leakage in perovskite solar cells[J]. EcoMat, 2023, 5(10).

[137] KAMEL M S A, OELGEMöLLER M, JACOB M V. Sustainable plasma polymer encapsulation materials for organic solar cells[J]. J. Mater. Chem. A, 2022, 10(9): 4683.

[138] IDIGORAS J, APARICIO F J, CONTRERAS-BERNAL L, et al. Enhancing moisture and water resistance in perovskite solar cells by encapsulation with ultrathin plasma polymers[J]. ACS Appl. Mater. Interfaces, 2018, 10(14): 11587.

[139] KWON O, LEE S H. Branch length similarity entropy-based descriptors for shape representation[J]. J. Korean Phys. Soc., 2017, 71(10): 727.

[140] KIM H, LEE J, KIM B, et al. Enhanced stability of mapbi(3) perovskite solar cells using poly(p-chloro-xylylene) encapsulation[J]. Sci. Rep., 2019, 9(1): 15461.

[141] LEE Y I, JEON N J, KIM B J, et al. A low-temperature thin-film encapsulation for enhanced stability of a highly efficient perovskite solar cell[J]. Adv. Energy Mater., 2018, 8(9): 1701928.

[142] RAMOS F J, MAINDRON T, BéCHU S, et al. Versatile perovskite solar cell encapsulation by low-temperature ALD-Al_2O_3 with long-term stability improvement[J]. Sustain. Energ. Fuels, 2018, 2(11): 2468.

[143] CHOI E Y, KIM J, LIM S, et al. Enhancing stability for organic-inorganic perovskite solar cells by atomic layer deposited Al_2O_3 encapsulation[J]. Sol. Energ. Mat. Sol. C., 2018, 188: 37.

[144] LAU C F J, DENG X, ZHENG J, et al. Enhanced performance via partial lead replacement with calcium for a $CsPbI_3$ perovskite solar cell exceeding 13% power conversion efficiency[J]. J. Mater. Chem. A, 2018, 6(14): 5580.

[145] DENG K, LIU Z, XIN Y, et al. PbI_2/CH_3NH_3Cl mixed precursor-induced micrometer-scale grain perovskite film and room-temperature film encapsulation toward high efficiency and stability of planar perovskite solar cells[J]. Adv. Mater. Interfaces, 2018, 5(15): 1800499.

[146] JONES D, AN Y, HIDALGO J, et al. Polymers and interfacial modifiers for durable perovskite solar cells: a review[J]. J. Mater. Chem. C, 2021, 9(37): 12509.

[147] TIAN C, LI B, RUI Y, et al. In situ polymerizing internal encapsulation strategy enables stable perovskite solar cells toward lead leakage suppression[J]. Adv. Funct. Mater., 2023: 2302270.

[148] WANG S, ZHANG Z, TANG Z, et al. Polymer strategies for high-efficiency and stable perovskite solar cells[J]. Nano Energy, 2021, 82: 105712.

[149] AHMAD J, BAZAKA K, ANDERSON L J, et al. Materials and methods for encapsulation of OPV: A review[J]. Renew. Sust. Energy Rev., 2013, 27: 104.

[150] KYRANAKI N, PERRIN L, FLANDIN L, et al. Comparison of glass-glass versus glass-backsheet encapsulation applied to carbon-based perovskite solar cells[J]. Processes, 2023, 11(9).

[151] HAN Y, MEYER S, DKHISSI Y, et al. Degradation observations of encapsulated planar $CH_3NH_3PbI_3$ perovskite solar cells at high temperatures and humidity[J]. J. Mater. Chem. A, 2015, 3(15): 8139.

[152] KEMPE M D, MILLER D C, WOHLGEMUTH J H, et al. Multi angle laser light scattering evaluation of field exposed thermoplastic photovoltaic encapsulant materials[J]. Energ. Sci. Eng., 2016, 4(1): 40.

[153] KEMPE M D, JORGENSEN G J, TERWILLIGER K M, et al. Acetic acid production and glass transition concerns with ethylene-vinyl acetate used in photovoltaic devices[J]. Sol. Energ. Mat. Sol. C., 2007, 91(4): 315.

[154] CHEACHAROEN R, ROLSTON N, HARWOOD D, et al. Design and understanding of encapsulated perovskite solar cells to withstand temperature cycling[J]. Energ. Environ. Sci., 2018, 11(1): 144.

[155] KIM J, GODIN R, DIMITROV S D, et al. Excitation density dependent photoluminescence quenching and charge transfer efficiencies in hybrid perovskite/organic semiconductor bilayers[J]. Adv. Energy Mater., 2018, 8(35): 1802474.

[156] GRANCINI G, ROLDAN-CARMONA C, ZIMMERMANN I, et al. One-year stable perovskite solar cells by 2D/3D interface engineering[J]. Nat. Commun., 2017, 8: 15684.

[157] JUNG K, BAE J Y, PARK S J, et al. High performance organic-inorganic hybrid barrier coating for encapsulation of OLEDs[J]. J. Mater. Chem., 2011, 21(6): 1977.

[158] SEETHAMRAJU S, RAMAMURTHY P C, MADRAS G. Organic passivation layer on flexible Surlyn substrate for encapsulating organic photovoltaics[J]. Appl. Phys. Lett., 2014, 105(10): 104102.

[159] DONG Q, LIU F, WONG M K, et al. Encapsulation of perovskite solar cells for high humidity conditions[J]. Chemsuschem, 2016, 9(18): 2597.

[160] LUO Z, ZHU X, LI H, et al. Evaluation of the underwater stability of encapsulated perovskite solar cells[J]. Sol. Energ. Mat. Sol. C., 2023, 262.

[161] YOO J S, HAN G S, LEE S, et al. Dual function of a high-contrast hydrophobic-hydrophilic coating for enhanced stability of perovskite solar cells in extremely humid environments[J]. Nano Res., 2017, 10(11): 3885.

[162] PENG J, KHAN J I, LIU W, et al. A universal double-side passivation for high open-circuit voltage in perovskite solar cells: role of carbonyl groups in poly(methyl methacrylate)[J]. Adv. Energy Mater., 2018, 8(30): 1801208.

[163] SOO Y H, NG S A, WONG Y H, et al. Thermal stability enhancement of perovskite $MAPbI_3$ film at high temperature (150 °C) by PMMA encapsulation[J]. J. Mater. Sci. 2021, 32(11): 14885.

[164] ZHENG L, CHUNG Y H, MA Y, et al. A hydrophobic hole transporting oligothiophene for planar perovskite solar cells with improved stability[J]. Chem. Commun. (Camb), 2014, 50(76): 11196.

[165] LIU Z, SUN B, SHI T, et al. Enhanced photovoltaic performance and stability of carbon counter electrode based perovskite solar cells encapsulated by PDMS[J]. J. Mater. Chem. A, 2016, 4(27): 10700.

[166] YUWAWECH K, WOOTTHIKANOKKHAN J, WANWONG S, et al. Polyurethane/esterified cellulose nanocrystal composites as a transparent moisture barrier coating for encapsulation of dye sensitized solar cells[J]. J. Appl. Polym. Sci., 2017, 134(45): 45010.

[167] FU Z, XU M, SHENG Y, et al. Encapsulation of printable mesoscopic perovskite solar cells enables high temperature and long-term outdoor stability[J]. Adv. Funct. Mater., 2019, 29(16): 1809129.

[168] LA NOTTE L, POLINO G, VERZOLA P, et al. Influence of encapsulation materials on the optical properties and conversion efficiency of heat-sealed flexible polymer solar cells[J]. Surf. Coat. Tech., 2014, 255: 69.

[169] SøNDERGAARD R R, MAKRIS T, LIANOS P, et al. The use of polyurethane as encapsulating method for polymer solar cells—an inter laboratory study on outdoor stability in 8 countries[J]. Sol. Energ. Mat. Sol. C., 2012, 99: 292.

[170] TONIOLO F, BRISTOW H, BABICS M, et al. Efficient and reliable encapsulation for perovskite/silicon tandem solar modules[J]. Nanoscale, 2023, 15(42): 16984.

[171] BONOMO M, TAHERI B, BONANDINI L, et al. Thermosetting polyurethane resins as low-cost, easily scalable, and effective oxygen and moisture barriers for perovskite solar cells[J]. ACS Appl. Mater. Interfaces, 2020, 12(49): 54862.

[172] WU J, CUI Y, YU B, et al. A simple way to simultaneously release the interface stress and realize the inner encapsulation for highly efficient and stable perovskite solar cells[J]. Adv. Funct. Mater., 2019, 29(49): 1905336.

[173] AN M W, XING Z, WU B S, et al. Cross-linkable fullerene interfacial contacts for enhancing humidity stability of inverted perovskite solar cells[J]. Rare Metals, 2020, 40(7): 1691.

[174] YU D, YANG Y-Q, CHEN Z, et al. Recent progress on thin-film encapsulation technologies for organic electronic devices[J]. Opt. Commun., 2016, 362: 43.

[175] MEYER J, GöRRN P, BERTRAM F, et al. Al_2O_3/ZrO_2 nanolaminates as ultrahigh gas-diffusion barriers-a strategy for reliable encapsulation of org. electron[J]. Adv. Mater., 2009, 21(18): 1845.

[176] LV Y, XU P, REN G, et al. Low-temperature atomic layer deposition of metal oxide layers for perovskite solar cells with high efficiency and stability under harsh environmental conditions[J]. ACS Appl. Mater. Interfaces, 2018, 10(28): 23928.

[177] GHOSH S, SINGH R, SUBBIAH A S, et al. Enhanced operational stability through interfacial modification by active encapsulation of perovskite solar cells[J]. Appl. Phys. Lett., 2020, 116(11): 113502.

[178] ZHAO J, BRINKMANN K O, HU T, et al. Self-encapsulating thermostable and air-resilient semitransparent perovskite solar cells[J]. Adv. Energy Mater., 2017, 7(14): 1602599.

[179] KOIRY S P, JHA P, SRIDEVI C, et al. Improved water repellency and environmental stability of perovskite solar cells by encapsulating with paraffin wax[J]. Mater. Chem. Phys., 2022, 282: 125954.

[180] MASUKO K, SHIGEMATSU M, HASHIGUCHI T, et al. Achievement of more than 25% conversion efficiency with crystalline silicon heterojunction solar

cell[J]. IEEE J. Photovolt., 2014, 4(6): 1433.

[181] ADACHI D, HERNáNDEZ J L, YAMAMOTO K. Impact of carrier recombination on fill factor for large area heterojunction crystalline silicon solar cell with 25.1% efficiency[J]. Appl. Phys. Lett., 2015, 107(23): 233506.

[182] YOSHIKAWA K, KAWASAKI H, YOSHIDA W, et al. Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%[J]. Nat. Energy, 2017, 2(5): 17032.

[183] SHOCKLEY W, QUEISSER H J. Detailed balance limit of efficiency of p-n junction solar cells[J]. J. Appl. Phys., 1961, 32(3): 510.

[184] MEI A, SHENG Y, MING Y, et al. Stabilizing perovskite solar cells to IEC61 215:2016 standards with over 9 000 h operational tracking[J]. Joule, 2020, 4(12): 2646.

[185] CHEN Z, TUREDI B, ALSALLOUM A Y, et al. Single-crystal $mapbi_3$ perovskite solar cells exceeding 21% power conversion efficiency[J]. ACS Energy Lett., 2019, 4(6): 1258.

钙钛矿太阳能电池的稳定性因素及封装提升性能

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摘要：钙钛矿太阳能电池作为第三代新概念太阳能电池，具有光电转换效率高、成本低和加工灵活等优点，近年来发展迅速，虽然其光电转换效率逐渐可与硅电池相媲美，已接近工业应用水平，但钙钛矿太阳能电池工业应用核心问题是其稳定性。如何使钙钛矿太阳能电池长期保持高效率是研究人员需要解决的最大问题。目前，封装作为解决钙钛矿太阳能电池外部稳定性问题的手段之一已经被广泛研究，良好的封装不仅可以解决器件的稳定性问题，还可以保证器件的安全性，延长使用寿命。本文简要介绍了影响钙钛矿太阳能电池稳定性的因素及稳定性测试的条件。最后介绍了钙钛矿太阳能电池的不同封装结构、封装工艺和封装材料对封装性能的影响。随着封装研究的不断深入，研究人员将不断优化和解决存在的问题，最终实现钙钛矿太阳能电池的大规模产业化应用。

关键词：钙钛矿太阳能电池; 设备稳定性; 封装材料; 工业化应用

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