Analysis of the Perovskite Solar Battery

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Abstract. As a matter of fact, the subversive photovoltaic technology of the perovskite solar cell has the benefits of high energy efficiency in conversion, low production costs, and ease of preparation in recent years. A larger number of scholars have given perovskite solar cells a lot of attention because of their advantages such as simple process, roll-to-roll production and low cost, as well as have become the most eye-catching new generation photovoltaic devices. At the same time, PSCs have enormous potential, as seen by the rise in efficiency from 3.81% to 25.7% in just a decade. On this basis, the perovskite solar cells' mechanism of operation and device architecture are described and discussed in this study. To be specific, its fabrication is also summarized and discussed accordingly. According to the analysis, the future perovskite solar cell development issues and difficulties are also anticipated and demonstrated at the same time. Overall, these results shed light on guiding further exploration of solar cells.

Keywords: Perovskite; solar cells; photovoltaic fabrication.

1. Introduction

The history of the solar cell began in the 19th century when the photovoltaic effect was discovered [1]. Alexandre-Edmond Becquerel observed that when exposed to light, certain materials could generate an electric current. However, the development of solar cell technology progressed slowly in the following decades, as scientists experimented with various materials and shapes to increase the cells' effectiveness and stability. Researchers in 1954 created the first usable silicon solar cell, with a 6% efficiency. The public and the industry were more interested in solar energy as a result of this discovery., especially for space applications. Since then, solar cell technology has advanced significantly, with the introduction of various types of cells, such as thin-film, multi-junction, concentrator and organic solar cells [2-4]. The efficiency of solar cells has also increased dramatically, reaching over 40% for some laboratory prototypes. Solar cells are now widely used for various purposes, such as power generation, communication, lighting, heating and transportation [5]. Since the solar cells emerge as a promising research area, researchers are trying increase the effectiveness of solar cells. With the introduction of perovskite type organometallic halide semiconductor as light-absorbing materials, perovskite solar cells (PSCs) emerge as a viable replacement for traditional photovoltaic systems made of silicon.

PSCs use a perovskite-structured substance as the light-absorbing layer. In recent years, PSCs have improved greatly in the performance and stability. From 3.8% in 2009 to over 25% in 2020, the power conversion efficiency (PCE) of PSCs has increased, surpassing that of traditional silicon solar cells. As first observed in 2009 [6], the PCE of PSCs are roughly 3-4%. In 2011, by improving the perovskite coating conditions, the PCE was doubled. Then, by using a liquid electrolyte in place of the solid hole conductor, PCE increases to around 10%. Moreover, using inexpensive organometal halide perovskite components, PCE is able to value over 20%. As of right now, PSC efficiency is 25.5%, exceeding that of CIGS solar cells and getting close to that of crystalline-Si solar cells. This is accomplished by enhancing the composition, shape, and interface of the charge transport and perovskite absorber layers, as well as introducing functional groups and additives to enhance the crystallization and passivation of the perovskite film. The stability of PSCs has also greatly increased. After 1000 hours of nonstop use in artificial sunlight, several gadgets showed no signs of damage. Significant progress has been made in PSC stability by using various strategies, such as engineering the perovskite structure and composition, developing stable charge transport materials and electrodes, encapsulating the devices with robust materials, and reducing the lead leakage from the perovskite

layer. Some PSCs have shown excellent stability under various stress conditions, like excessive heat, humidity, light exposure, mechanical bending [6]. Moreover, PSCs can be fabricated by low-temperature and solution-based methods, which can reduce the manufacturing cost and environmental impact. In this overview, the fundamentals of PSCs and their operational concept are presented. In addition, mainstream fabrication in recent years is also mentioned.

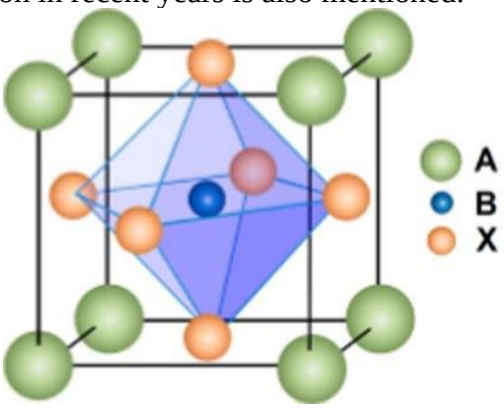

Fig. 1 Basic structure of ABX3 perovskite.

2. Basic Descriptions of PSCs

PSCs are one type of solar cell that uses a perovskite-structured substance as the light-absorbing layer. Generally, the structure of perovskite material is ABX3, where the A position is a monovalent cation, the B position is a divalent metal cation, and the X position is a halogen anion [7]. The A cation occupies the center of the cubic unit cell, the B cation occupies the body-center position, and the X anion occupies the face-centered positions. The crystal structure of a perovskite is shown in Fig.1. Halide perovskites exhibit better ionic crystallinity than oxide perovskites as an ionic crystal because of the strong ionicity of halide anions. Charge neutralization in the lattice structure is produced by the coordination of many cations and anions, bits. The perovskite structure is very versatile and can accommodate a wide range of elements, leading to diverse properties and applications. Perovskites are found in nature as minerals, in the Earth's mantle, in meteorites, and in stars.

PSCs are mainly composed of 5 parts: a transparent conductive substrate, an electron transport layer (ETL), a perovskite active layer, a hole transport layer (HTL) and a top electrode, as shown in Fig. 2. The transparent conductive substrate is an important component for sunlight and carrier transmission. Its transmittance, surface roughness, surface resistance and other characteristics will directly affect the device performance. ETL plays a role in extracting and transporting electrons and blocking holes in the device. High-performance ETL should have appropriate Fermi level, excellent conductivity and electron mobility, etc. The perovskite active layer can absorb sunlight within a certain wavelength range and promote the dissociation and transport of photogenerated carriers. The function of HTL is to transfer holes to the contact electrode, obstruct reverse electron transit, and lessen recombination. As for the top electrode, the material can be metal such as Au and Ag. According to the direction of charge transfer, perovskite solar cells can be classified into n-i-p structure and p-i-n structure. Based on the structure of ETL, n-i-p type solar cells can be divided into mesoporous structure and planar structure. In the n-i-p structure, incident light is absorbed and collected from the ETL side by the perovskite, and electrons and holes are collected by the front electrode and the back electrode respectively. The p-i-n structure are obtained by replacing the positions of ETL and HTL on the n-i-p structure. It has the opposite direction of charge transfer to the formal device. The preparation process of planar p-i-n type structure is simple and low-cost. It can be used for the preparation of perovskite stacked devices, and the hysteresis phenomenon is almost negligible. However, compared to the n-i-p structure, the biggest problem of the p-i-n structure PSCs is that the efficiency is not that high.

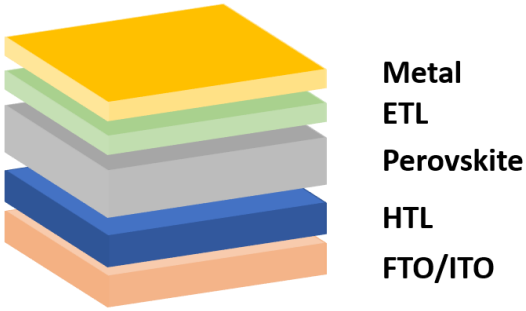

Fig. 2 Typical structure of PSC

3. Principle

PSCs are devices that can convert solar energy directly into electrical energy. Its working principle is based on the photovoltaic effect of semiconductors [8]. When sunlight hits the perovskite photoactive layer, the perovskite layer absorbs photons and generates electron-hole pairs. Electrons and holes are driven by the built-in electric field and are separated into the conduction band minimum (CBM) and valence band maximum (VBM) of the perovskite. When exposed to light, ETL selectively collects electrons, while HTL selectively collects holes. They serve to prevent recombination of electrons and holes and to facilitate charge extraction [9, 10].

For example, electron transfer layer helps the excited electrons move from the perovskite active layer to the front electrode. Additionally, it aids in preventing holes from entering the front electrode. On the contrary, electron transfer layer facilitates the movement of excited holes and block the release of electrons. Electrons are transported from CBM of the perovskite to the CBM of ETL, and then to FTO anode. Holes are correspondingly transported from the VBM of the perovskite to the VBM of HTL, and are then collected by the metal anode through ohmic contact. The electrons then flow through the external circuit and combine with holes to form a complete closed circuit. In order to effectively extract the charges in the perovskite active layer, there must be a certain energy level difference between the charge transport layer and the perovskite layer. Therefore, to transmit electrons, the CBM of the electron transport material and the perovskite must coincide. In order to achieve the hole transfer, the highest occupied molecular orbital (HOMO) energy level of the hole transport material must be higher than the VBM of the perovskite.

In perovskite solar cells, there are other recombination processes in addition to the separation and movement of carriers, including as radiative recombination, non-radiative recombination, and interface recombination. Non-radiative recombination will take place at the perovskite interface and throughout the body as a result of the mismatched band gaps between perovskite and HTL and ETL, which will impact the PCE of devices. Therefore, improving device performance requires lowering ETL/HTL interface recombination in the perovskite active layer. Non-radiative recombination can be divided into Auger recombination, trap-assisted recombination, electron-phonon interaction and carrier-carrier scattering. Fig. 3 demonstrates the pathways for carrier recombination inside PSCs devices.

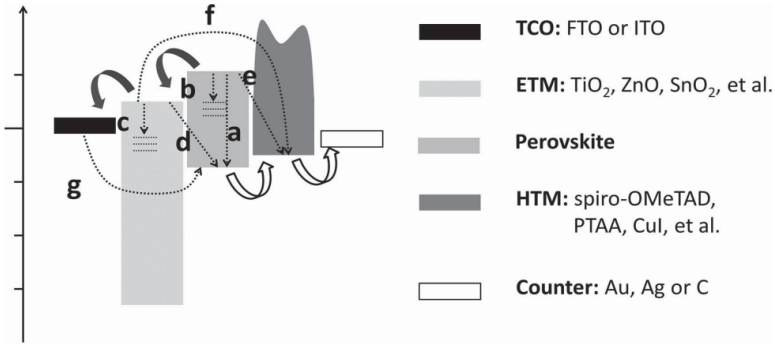

Fig. 3 Working principle and path of carrier recombination inside PSCs devices.

4. Fabrication

As mentioned before, PSCs are composed of transparent conductive substrate, ETL, perovskite photoactive layer, HTL and top electrode. The primary component of the device is the conductive substrate of PSCs acting as the electrode. It typically consists of a transparent conductive oxide with good heat resistance, low resistivity, and high optical transmittance. Early PSC development and research was done on surfaces made of hard glass. In addition to rigid substrates, PSCs uses flexible substrates to prepare flexible devices for use in wearable devices [11]. In most cases, flexible substrates are made of polymer materials, which offer the advantages of being flexible, foldable, scalable, and lighter than metal in general. The following materials are frequently used: polyimide, polyether sulfone, polyimide, and polyethylene terephthalate.

In mesoporous PSCs, ETL generally consists of a dense layer and a skeleton layer. The dense layer serves two purposes: first, it transports the perovskite layer's photogenerated electrons to a transparent conductive substrate, and second, it blocks the direct contact between HTL and the conductive substrate, contributing in preventing the recombination of holes and electrons in the conductive substrate. The semiconductor materials in the dense layer mainly include TiO2, ZnO, SnO2, CdS, etc. The chemical preparation methods of the dense layer include sol-gel method, dipping and pulling method, and electrochemical deposition method. The physical preparation methods of dense layers include spray pyrolysis, magnetron sputtering, electron beam evaporation deposition, and atomic layer deposition. The skeleton layer usually serves as a scaffold layer for the perovskite light-absorbing layer. The primary components of the skeleton layer include TiO2, Al2O3, ZrO2, SnO2, and ZnO, etc. One-dimensional structured nanorods are also frequently employed as the framework material in ETL in addition to the nanogranular mesoporous structure that can be used in this role.

For small area PSCs, the main methods for preparing perovskite layers are one-step or two-step deposition by solution method, vacuum deposition method and steam assisted solution method. One-step processing is the co-deposition of organic and inorganic components of perovskite by solution or thermal evaporation. Taking MAPbI3 as an example, the one-step solution method is to dissolve the organic component MAI and inorganic component PbI2 in the mixed organic solvent of DMF and DMSO at the same time, and then spin coating, annealing, to generate α phase perovskite. One-step thermal evaporation method uses different temperatures to heat PbI2 and MAI double evaporation sources to form perovskite films. The idea of two-step method is to prepare PbI2 layer first, and then prepare MAI layer on PbI2 film, and form perovskite film after heat treatment. At present, one-step or two-step solution method is often used for the production of small-area PSCs. Experiments have proved that the solution method has better repeatability, strong controllability, and the formed film is flatter and the crystallinity is high, and the process is simpler. However, the solution method can produce pinholes and cracks, which is not conducive to the preparation of large-scale PSCs. Therefore, the preparation of large area PSCs is more suitable for scraping, inkjet, stamping, dip coating and vacuum coating [12].

Most of the preparation methods of hole transport layer are solution spin coating. Because the preparation of inorganic hole transport layer requires high temperature annealing, which leads to degradation of the perovskite film, hole transport layer for formal devices uses organic materials. P3HT, PTAA and Spiro-OMeTAD are commonly used. The posterior electrode is the top layer of the perovskite device and is in direct contact with the external environment, so the electrode material must be strong and stable enough to slow water infiltration into the perovskite layer. The common electrodes of PSCs are Ag, Al and Au.

5. Limitations and Prospects

Perovskite solar cells have developed quickly. Its photoelectric conversion efficiency has just surpassed amorphous silicon and is on the verge of reaching polycrystalline silicon, making it one of the strongest competitors in the solar industry. Perovskite solar cells are anticipated to develop into independent clean energy sources, wearable technology, and other flexible technologies. With the

development of research, PCE of PSCs has increased rapidly, injecting new vitality into the development of future solar cells. However, it cannot be ignored that there are still many problems and challenges. For example, Pb is the primary raw material utilized in the majority of high-performance perovskites now being manufactured. Some solvents and anti-solvents that are frequently employed in the production of high-performance perovskites are hazardous and can have a negative impact on the environment. Although many studies have been done on non-lead-based perovskites and green solvents, the perovskites prepared under these circumstances still have some shortcomings in terms of stability and efficiency. Therefore, further research work in this area needs to be carried out. In addition, pinholes or other flaws in large-area perovskite films cause flexible large-area perovskite devices to perform less efficiently than other flexible solar cells. Therefore, to prepare effective and stable Flexible large-area perovskite solar cells, it is necessary to further explore various processing technologies. This also entails developing high-performance and inexpensive raw materials. Moreover, there are several restrictions on key materials. For instance, most organic electron transport materials are expensive and have unstable chemical properties, while the majority of inorganic electron transport materials still need to be annealed. Additionally, the device's core material, the perovskite material precursor, has low stability and a limited anti-solvent processing window. Low repeatability exists in the preparation of performance devices, and commonly employed hole transport materials are not only costly but also damaging to the device's long-term stability. These issues prevent the production of stable, effective, and affordable perovskite solar cells as well as their commercialization. For commercial applications, it is also necessary to consider the cost of the materials and device preparation of PSCs. To save prices, mass production technology for perovskite solar cell modules must be created. Studying on the mechanism of PSCs can surely support the further advancement of PCE because the study period on these batteries is limited and their mechanism is not yet understood. The enormous promise of perovskite solar cells cannot be overstated, despite certain significant obstacles presently standing in the way of their commercialization. The issues can be successfully resolved by additional investigation into materials and device design. Undoubtedly, perovskite solar cells will contribute greatly to the development of the photovoltaic industry.

6. Conclusion

Perovskite materials becomes more and more important among many solar cells due to their high extinction coefficient, tunable band gap, low exciton binding energy, and good polar carrier transport features. They are cheap to produce and simple to manufacture. The principle of PSCs is to convert light energy into electricity, and the main process involves exciton production, carrier separation and carrier transport. PSCs are composed of 5 different parts, and each part has its unique technique of fabrication. Although the commercialization of perovskite solar cells still faces some major challenges, their great potential cannot be ignored, and the above problems can be effectively solved through further research on the design of materials and devices. Perovskite solar cells will certainly occupy an important position in the future photovoltaic market.

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