

Analysis on future development of solar cells focusing on materials and devices

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Abstract. In recent times, solar cells have garnered significant attention due to their numerous advantages. These include continuously improving energy conversion efficiency, a simple solution preparation method, flexibility, lightweight design, wearability, suitability for ultra-lightweight space applications, and low-cost material components. Perovskite solar cells have achieved impressive efficiencies of over 25% by using high-quality perovskite films synthesized at low temperatures and by making advancements in compatible interface and electrode materials. Moreover, the stability of cells has become a major focus of research. This paper analyzes the development history, material system, device structure, challenges, and future development direction of perovskite solar cells. The unique photoelectric properties and tunable band gap of materials have made them a hot topic in the field of solar cells. In this paper, the basic characteristics and synthesis methods of perovskite materials are introduced before discussing the device structure, interface engineering, and stability of perovskite solar cells in detail. Finally, it prospects on the future development trend of perovskite solar cells.

Keywords: perovskite solar cells, photoelectric conversion efficiency, interface engineering.

1. Introduction

The depletion of non-renewable energy has led to environmental issues, spurring the advancement of renewable energy technologies. Solar energy is particularly significant as a renewable resource due to its abundance, cleanliness, and inexhaustibility. In recent years, various methods have been developed to harness solar energy [1, 2]. The capacity of photovoltaics to directly transform sunshine into electricity via the photovoltaic effect has garnered a lot of attention among them.

Three generations are commonly used to categorize solar cells as wafer-based, thin-film technology, and organic components. The high cost, complex manufacturing procedures, and less eco-friendly nature have limited popularity of the previous two generation solar cells. As a result, scientists are looking into innovative, reasonably priced, and ecologically benign materials for solar cells. Third-generation silicon solar cells, which have a power conversion efficiency (PCE) of 25–26%, currently control the market. With a PCE of up to 22.1%, third-generation perovskite solar cells provide a viable substitute [3, 4].

This paper aims to introduce the fundamental characteristics and working principles of perovskite materials. It also seeks to explore the device structure, interface engineering, and stability. Finally, it aims to anticipate the challenges and future development trends in this field.

2. Device structure and working mechanism

The excellent photovoltaic performance of perovskite solar cells can be attributed to their remarkable intrinsic properties [5]. Compared to conventional organic and inorganic semiconductors, OHIP materials exhibit unique optical and electrical characteristics [6]. These attributes make organic-inorganic hybrid-perovskite (OHIP) materials very appealing for highly efficient and cost-effective solar cells.

Typically, perovskite solar cells feature an absorber layer and when exposed to light, and it absorber generates electron-hole pairs, with electrons moving into the n-type carrier transport materials and holes into the p-type materials, creating free charge carriers, as shown in fig.1. To create

current, the holes go in the direction of the counter-electrodes and mix with electrons. The quantity of current produced is determined by the thickness of the perovskite material [7].

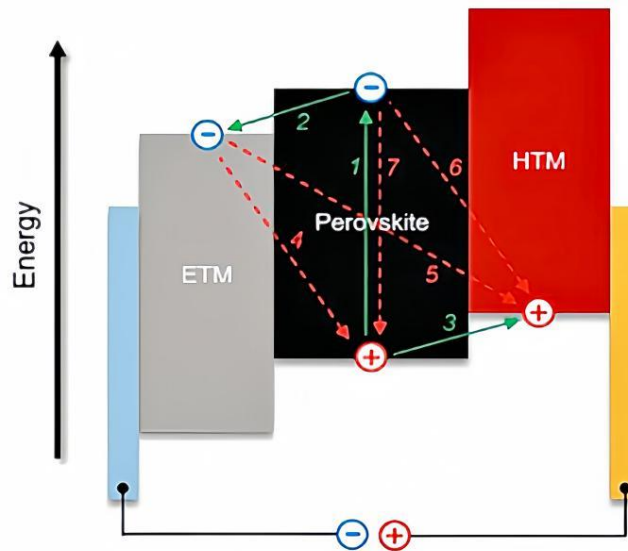


Fig 1. The working process [7]

The fundamental layers of perovskite solar cells include a transparent conducting layer (such as ITO on glass or plastic), an electron transport layer, a hole transport layer, a perovskite absorption layer, and a metal electrode (such as gold or silver). Hole Transport Layer (HTL) separates the metal electrode and the absorption layer. By blocking the passage of electrons, it transfers photogenerated holes from the perovskite layer to the electrode. The perovskite layer absorbs sunlight, which provides energy to excite electrons.

3. Interface engineering

Interface engineering aims to optimize the interface between different functional layers to increase the efficiency of charge extraction and transmission and reduce charge recombination at the interface. Through interface engineering, the band structure can be adjusted, the contact between layers can be improved, and the overall performance can be improved, as shown in fig.2.

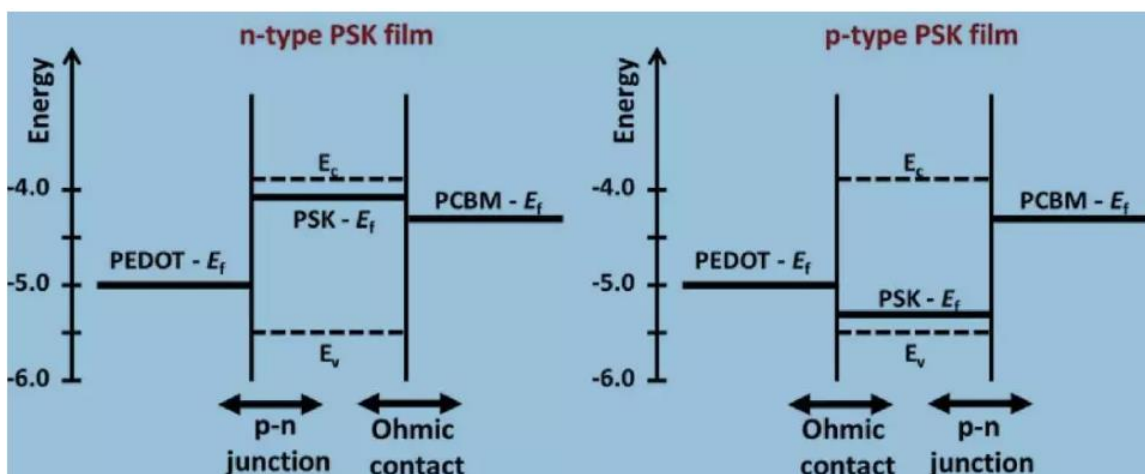


Fig 2. Change of the ohmic contact between layers to make the energy levels more matched [8]

The implementation methods of interface engineering are as follows. Additional buffer layers or additives are introduced to improve the chemical and physical properties. The surface of electron-transport layer (ETL) or hole transport layer (HTL) is treated by chemical or physical methods to enhance its affinity with the perovskite layer. The conductivity and stability of ETL or HTL materials

are improved by doping modification. Design new structures: such as porous structures or nanostructures to increase interface area and improve charge transport channels.

The buffer layer materials for interface modification can be selected such as TiO_2 , SnO_2 , ZrO_2 , etc. These materials can be used as buffer media to improve interface contact. Organic molecules and polymers can be selected such as Spiro-OMeTAD, PTAA, etc. These materials can be used as HTLs, and can also be used for interface modification to improve interface properties. Inorganic materials such as metal oxides, sulfides, etc., can be used for ETL or HTL interface modification to improve the conductivity and stability of the interface. The surface of ETL or HTL can be functionalized by SAMs to improve the interface bonding with the perovskite layer [9].

The importance of interface engineering is reflected in improving charge separation efficiency, improving energy level matching, enhancing device stability and reducing interface defects. The interface engineering can effectively promote the separation of photogenerated charges in the ETL and HTL, reduce charge recombination, and improve the overall efficiency of the battery. The improvement of energy level matching is through interface engineering, which can achieve better energy level matching, and promote effective charge transport. The stability of the device is enhanced because reasonable interface modification can reduce the penetration of water and oxygen bringing a better long-term stability. Interface engineering plays a crucial role in reducing defects and trap states at the interface, as well as minimizing non-radiative recombination. Additionally, it has been found to significantly improve the photoelectric conversion efficiency of the battery [10]. Reasonable interface modification can prevent the erosion of perovskite materials by water vapor and oxygen, and improve the environmental stability and long-term stability of the battery [11].

4. Improvement of perovskite solar cells

4.1. Stability improvement

Perovskite materials are easy to absorb moisture and degrade in humid environment, and may face problems of thermal stability and light stability in long-term operation [12]. The stability improvement can be improved in the following ways. Packaging technology is used to isolate water and oxygen to reduce the impact of environmental factors on battery performance. The long-term stability of the battery is conducted by simulating the accelerated aging test under actual use conditions. Outdoor tests were conducted to evaluate the performance and durability under real environmental conditions [13].

4.2. Efficiency improvement

The following strategies can be used to improve battery efficiency. By synthesizing new perovskite materials or improving the chemical composition of existing materials, the photoelectric conversion efficiency can be improved. If a new type of electron and hole transport layer is used, or an interface modification layer is introduced, the efficiency of charge extraction and transmission can be improved, and charge recombination can be reduced. The use of laminated structure or multi-junction battery design is another effective method for improving efficiency [14]. Furthermore, advancements in manufacturing processes such as solution treatment, vapor deposition, or printing technology can greatly enhance the quality and uniformity of perovskite films, leading to improved battery performance. Through careful optimization of annealing and post-treatment steps, the crystallinity of the perovskite crystal and overall device performance can be significantly enhanced [15].

5. Commercialization prospects, challenges and further outlook

Firstly, the production cost is low, which makes them have great potential in commercialization. With the continuous advancement of technology, the photoelectric conversion efficiency has now reached or even surpassed that of traditional solar cells. The manufacturing process is expected to achieve large-scale production and meet the large-scale demand for renewable energy in the market.

At the same time, there are some problems. The long-term stability is a key problem to be solved before commercialization. Moreover, the lead content in perovskite batteries may have an impact on the environment, and it is necessary to develop lead-free or low-lead perovskite materials [16].

The potential of perovskite solar cells is truly impressive, with laboratory efficiency reaching over 25%, comparable to the silicon-based solar cells currently on the market. Additionally, the manufacturing cost is low. The solution processing characteristics of perovskite materials offer the possibility of reducing production costs for solar cells [17]. Moving forward, research will focus on developing lead-free or low-lead perovskite materials to minimize environmental impact. Furthermore, efforts will be made to enhance stability and efficiency through optimization of the interface layer [18].

6. Conclusion

Perovskite solar cells have performed much better recently thanks to a variety of fabrication techniques and new perovskite compounds. However, even with all this progress, there are still several significant challenges. Transport and collection losses, for example, need to be reduced, and charge separation needs to be improved. One of the most important aspects of this development is optimizing charge carrier injection and collection properties, which are closely related to the interfacial characteristics. It is well-known that interface material properties have a critical impact on the performance of the cells. Researchers are continuously striving to overcome these challenges and develop new types of cells with improved power conversion efficiency and long-term stability.

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