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Perovskite photovoltaic effect and its application on solar cell

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Abstract. Significant attention has been attracted by perovskite photovoltaic materials due to their excellent monochromatic incident photon-to-electron conversion efficiency. This article will provide an overview of the fundamental principles of perovskite photovoltaic effects, the various types of perovskite photovoltaic materials, their optoelectronic properties, key factors influencing the performance of perovskite photovoltaics, and the current situation as well as future challenges of perovskite solar cells. It emphasizes that the continuous tunability of perovskite structure is pivotal in achieving highly efficient photoelectric materials. Doping and interface design plays a substantial role in enhancing the performance of perovskite solar cells. Finally, the article offers a glimpse into the prospects of commercial applications and potential research directions of perovskite photovoltaic materials. This article serves as a valuable reference for further comprehension and development of efficient and stable perovskite photovoltaic materials, paving the way for advancements in renewable energy technology.

Keywords: perovskite, perovskite photovoltaics, perovskite solar cells.

1. Introduction

The photoelectric effect is one of the earliest and most widely applied phenomena in the field of quantum mechanics. The development based on the photoelectric effect has led to continuous discoveries and applications in the areas of photovoltaics and photoelectronic imaging. Photonic materials not only form the foundation of the modern information society but also play a pioneering role in the information technology revolution. Therefore, research on materials related to the photoelectric effect is at the forefront of contemporary scientific development, exhibiting immense creativity and challenges. Simultaneously, photonic materials hold a decisive position within the entire field of optics. The relevant optoelectronic devices and products find applications in various industries such as information acquisition, processing, transmission, storage, and display.

In recent years, perovskite materials have emerged as a frontier research direction in the field of new optoelectronic materials, owing to a range of advantages including high photoluminescence quantum yield, strong charge carrier mobility, extended carrier lifetimes, tunable bandgaps, and strong light absorption capabilities [1]. Currently, significant attention has been garnered by perovskite materials in various applications such as solar cells, photodetectors, and light-emitting diodes [2]. Its characteristics have demonstrated enormous potential applications in energy conversion, optical communication, and

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optical information processing. Additionally, research on perovskite materials has given rise to many innovative technologies and devices, injecting new vitality into the field of optoelectronics.

Overall, the extensive utilization of perovskite materials in the realm of optoelectronics not only underscores their pivotal contribution to contemporary technological progress but also catalyzes substantial momentum for innovation and industrial growth in a multitude of industries. This widespread adoption showcases their versatility and potential to revolutionize various fields of technology. Perovskite is a category of materials characterized by a cubic crystal structure known as ABX_3. In this structure, element A and B occupy the corners of the cube, while element X is situated at the center of each face [3]. surrounded by 12 ions and forms a coordination cubic octahedron, with a coordination number of 12, as illustrated in Figure 1. In this structure, In the ABX_3 structure, A is typically an organic cation. B represents metal cations like Pb^{2+} or Sn^{2+}. X stands for halide anions including Cl^-, Br^-, I^-, and so on. Perovskite materials exhibit exceptional efficiency in converting sunlight into electricity, and they offer flexibility in composition adjustments along with the advantage of cost-effective preparation. The photovoltaic effects of perovskites and their applications in highly efficient and cost-effective next-generation solar cells have resulted in their widespread adoption. The goal of this paper is to give a thorough review of the fundamental principles behind perovskite photovoltaics and how they are utilized in solar cell technology.

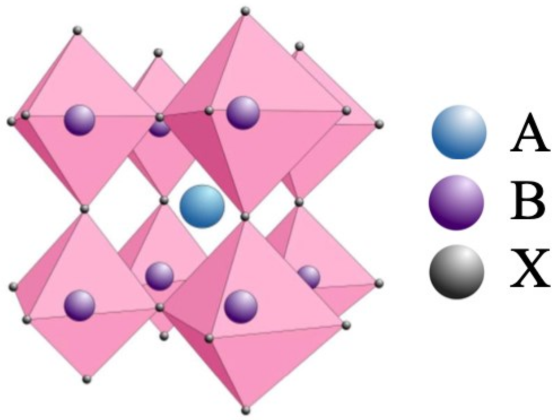

Figure 1. A schematic diagram of the ABX_3 structure.

2. The Basic Principles of Perovskite Photovoltaic Effect

The perovskite photovoltaic effect can be summarized as follows. Light excitation creates electron-hole pairs, which are then transported to the electrodes and separated, generating a current [4]. Specifically, when the energy of incident photons exceeds the bandgap of the perovskite, they will be absorbed by the material, causing valence band electrons to transition to the conduction band while generating holes in the valence band. The excited state's lifetime is on the order of tens of nanoseconds, allowing electrons and holes to move in different directions within the material, achieving spatial separation. The perovskite crystal itself possesses a long-range charge transport length, which facilitates the migration of charges to the electrode interface. Finally, the electrons and holes that reach the two ends are respectively collected by the conductive substrate and the transparent conductive oxide layer, resulting in the generation of photocurrent output. By comparing with the ideal photovoltaic device power, one can readily obtain the general definition of the photovoltaic conversion efficiency. If the incident light power is P_{in}, the photovoltaic energy conversion efficiency η is expressed with V_{oc}, J_{sc} and FF as follows

$$\eta = \frac{V_{oc} j_{sc} FF}{P_{in}}. \quad (1)$$

The high-efficiency photoelectric conversion of perovskite can be attributed to its wide absorption spectrum, high absorption coefficient, and favorable charge carrier transport properties [5]. Modulating the composition and structure of perovskite can optimize these key factors, leading to higher photoelectric conversion efficiency. The photoelectric effect in the semiconductor is shown in Figure 2 [6].

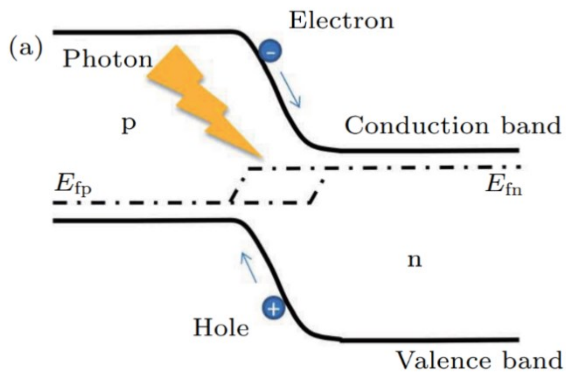

Figure 2. The photoelectric effect in the semiconductor [6].

3. Types and Photoelectric Characteristics of Perovskite Photovoltaic Materials

3.1. Hybrid Organic-Inorganic Halide Perovskites

Hybrid organic-inorganic halide perovskite $APbX_3$ (A = CH_3NH^{3+}, $CH(NH_2)^{2+}$, Cs^+; X = Cl^-, Br^-, I^-) has a wide spectral absorption range and high carrier mobility, characteristics of high absorption coefficient. Thanks to these properties, the application of perovskite solar cells has developed rapidly. At the same time, hybrid organic-inorganic halide perovskites also play a pivotal role in optoelectronic devices such as radiation detectors, photodetectors, and energy storage. Regarding the photoelectric properties of hybrid organic-inorganic halide perovskites, the bandgap width of the perovskite can be directly adjusted by changing the halogen element at the X position, thereby tuning its absorption range. For example, gradually replacing Cl elements with I elements can adjust the absorption range of perovskite, achieving a broad-spectrum absorption from 2.3eV to 1.5eV. In addition, the electron-hole pairs in this material have a relatively long lifetime, which helps to enhance the efficiency of charge separation and transport, thereby improving photoelectric conversion efficiency.

3.2. All-inorganic perovskite

The basic structure of all-inorganic perovskites is a perovskite compound composed of unstable organic cations such as methylammonium ions (MA^+) replaced by inorganic cations such as cesium ions (Cs^+) and inorganic anions. The classic all-inorganic perovskite is oxide perovskite (perovskite), whose chemical formula is usually ABX_3, where A represents a larger cation (such as chromium ion), B represents a smaller cation (such as titanium ion), and X represents an anion. (Usually oxygen ions, but can also be other halide ions such as fluorine, chlorine, etc.). A typical representative is $CsPbI_3$.

Comparing the photoelectric properties of hybrid organic-inorganic halide perovskites, all-inorganic perovskites have the following four advantages. Firstly, it has better thermodynamic stability and can work under high temperature conditions. Secondly, it has stronger chemical stability and less prone to pollution and degradation. Thirdly, the energy gap range is wider and the absorption from visible light to near-infrared light can be tuned. Finally, the structure is more uniform, which is conducive to obtaining high-quality films.

3.3. Two-dimensional perovskite

In recent years, two-dimensional perovskite has been proven to be a novel semiconductor material, and its excellent properties make it have great development potential in the field of optoelectronic devices. Its manifestations are usually solution-processed films, single crystals and nanosheets. Figure 3 schematically illustrates the layer-by-layer self-assembly process of two-dimensional perovskites. This results in thinner thicknesses and observable changes in electronic structure and optical tunability, providing promise for new optoelectronic applications [7,8].

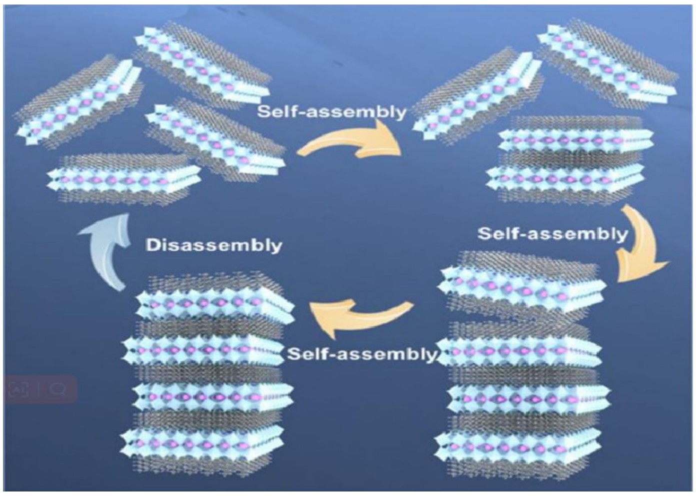

Figure 3. A schematic diagram depicting the layer-by-layer self-assembly of $C_8H_{17}NH_3$-terminated $CsPb_2Br$ nanosheets into layered $(C_8H_{17}NH_3)_2CsPb_2Br_7$ superlattice nanosheets [8].

4. The Key Factors Affecting the Photovoltaic Performance of Perovskite Material

The photovoltaic performance of perovskite material is primarily evaluated through photovoltaic conversion efficiency and external quantum efficiency. The key factors that generally affect the photovoltaic performance of perovskite include the following issues. Chemical Stability of Perovskite Materials: This primarily encompasses the stability of the perovskite crystal structure, thermal stability, and resistance to moisture. Stability of Device Structure: Including the selection of materials for the electron transport layer (ETL) and hole transport layer. Impact of Environmental Conditions: This includes the effects of factors such as humidity, oxygen exposure, and exposure to ultraviolet (UV) light that are impacted by environmental conditions [8].

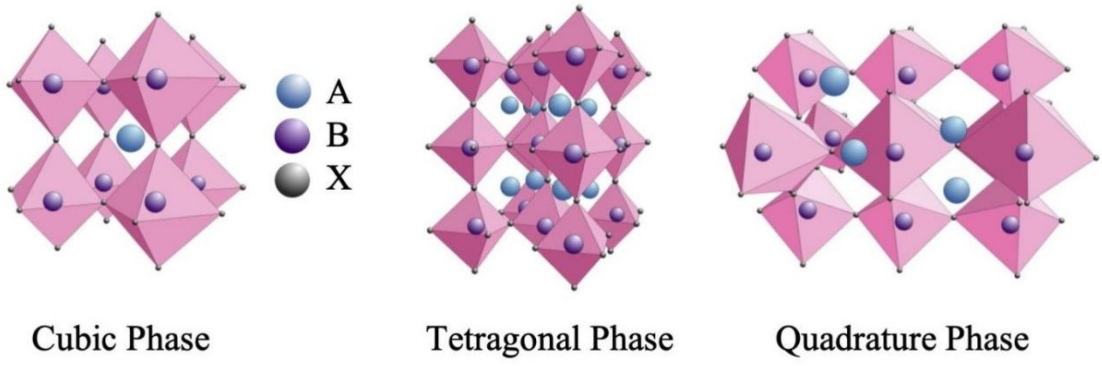

Figure 4. Crystal structure of hybrid perovskite material

4.1. Crystal Structure and Composition

Perovskite materials refer to a class of organic-inorganic hybrid materials with the same crystal structure as $CaTiO_3$, with a chemical formula of ABX_3. In this formula, A typically represents organic cations like $CH_3NH_3^+$ or $HN{=}CH(NH_3)^+$, B represents divalent metal ions, and X represents halide ions. In cubic phase structure, B and X form a regular octahedral symmetry, with A at the center of the octahedron, resulting in a cubic symmetry of BX_6. A is distributed at the center of the octahedral structure, forming a cubic structure, thus forming a three-dimensional periodic arrangement.

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Different combinations of ions can lead to varying charge distributions and bond strengths, thereby influencing the stability of the material. The different crystal structures and compositions can affect the structural stability, thermal stability, and humidity stability of perovskite materials. For example: cubic phase, tetragonal phase and quadrature phase (see Figure 4 for illustration).

4.2. Doping

Doping is carried out to achieve more efficient photovoltaic performance. Specific methods include doping SnO_2 ETL with different concentrations of cesium salts [9].

One is the doping Effect. The introduction of cesium salt effectively enhances the electrical conductivity of SnO_2 (tin dioxide), promoting charge transfer. The surface roughness of the SnO_2 ETL is reduced by it, and the contact between the SnO_2 ETL and the perovskite layer is improved, enhancing the optoelectronic performance of the device. The reduction in non-radiative recombination caused by charge accumulation at the interface significantly mitigates the hysteresis phenomenon in the device. The other is the doping Effectiveness. Cesium salt doping does not exhibit a noticeable crystalline control effect on the upper perovskite layer, and it cannot improve the crystalline quality of the perovskite layer.

A typical perovskite solar cell is illustrated as follows: it consists of a glass substrate, an ETL made of SnO_2 (tin dioxide) is comprised in the device, along with a perovskite layer that was prepared from lead iodide (PbI_2), formamidinium iodide, and methylammonium chloride, a hole transport layer made of phenethylamine iodide (PEAI) and spiro-OMeTAD, and electrodes formed from molybdenum trioxide (MoO_3) and silver (Ag). In the ABX3 structure, A is typically an organic cation. B represents metal cations like Pb^{2+} or Sn^{2+}. X stands for halide anions including Cl^-, Br^-, I^-, and so on.

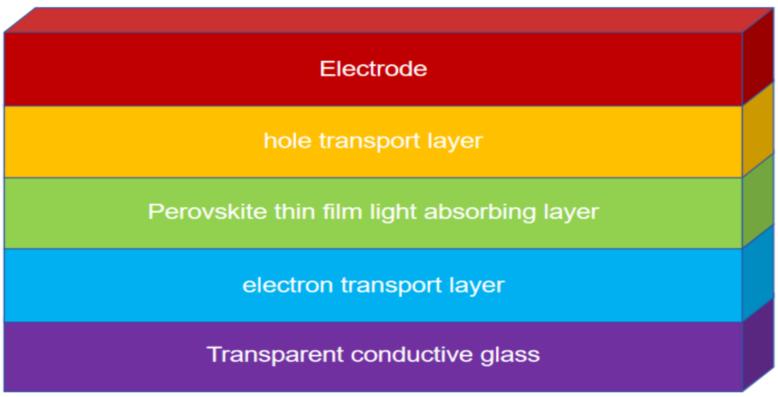

Figure 5. Perovskite solar cell structure [9].

4.3. Development status and challenges of perovskite solar cells

As a new type of photovoltaic cell, perovskite solar cells have a theoretically calculated ultimate photoelectric conversion efficiency of up to 30.5%. Since it was first developed in 2009, its photoelectric conversion efficiency has rapidly increased from 3.8% to 28%, and has gradually moved closer to the highest efficiency of silicon-based solar cells. As depicted in Figure 5, the perovskite solar cell is comprised of five components [10].

Perovskite solar cells work as follows. Firstly, energy is absorbed under sunlight. Photons in sunlight enter the light-absorbing layer. If a photon’s energy exceeds the forbidden band gap of the light-absorbing layer, it gets absorbed., as shown in Figure 5. The electrons travel through an external circuit to the cathode, while the holes move through an external circuit to the anode, forming a complete current loop. In this way, the photon energy gets converted to electric current, achieving the photoelectric conversion.

5. Conclusion

This article provides a comprehensive review of the basic principles, types, influencing factors and application development of perovskite photoelectric effects in solar cells. Perovskite solar cells are a hot research topic in solar cells today and show good development prospects. However, achieving environmental friendliness, extending service life, improving the battery performance evaluation system, improving the photoelectric conversion efficiency and stability of solar cells, and achieving large-scale industrial production are still difficult problems that future researchers need to solve. Commercial production of batteries still has a long way to go. As an emerging class of optoelectronic materials, perovskites have extremely high absorption coefficients, suitable band gaps, and long carrier diffusion lengths. They are promising materials for the development of high-efficiency and low-cost solar cells. This article systematically discusses the photoelectric conversion mechanism of perovskites, the photoelectric properties of different types of perovskites, and the multiple factors that affect their solar cell performance, including crystal structure, composition, doping, and interface control. Finally, the development status and challenges of perovskite solar cells, as well as future research directions are prospected. This review provides detailed information and reference for in-depth understanding of the photoelectric properties of perovskite and optimizing the performance of perovskite solar cells.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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