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Application Progress of Perovskite Quantum Dot Materials in Photoelectric Conversion

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Abstract. Perovskite quantum dot materials have become a research hotspot in the field of photoelectric conversion due to their unique photoelectric properties, such as high quantum efficiency, narrow half-peak width, and adjustable band gap. This paper reviews the application progress of perovskite quantum dot materials in photoelectric conversion, including their working principles and performance improvement strategies in devices such as solar cells and photodetectors. At the same time, the challenges faced by the material in terms of stability, toxicity, and the large-scale preparation process were analyzed. In terms of stability, the material is highly sensitive to light, oxygen, temperature, and humidity. In terms of toxicity, the lead element contained in the material is easily migratable in the environment, endangering the ecosystem through water and soil, and may also pose a threat to human health through inhalation or skin contact. In the large-scale preparation process, the high-temperature hot injection method has high equipment requirements and a complicated operation. This paper also discusses the corresponding solutions. Finally, this paper looks forward to the future trend of perovskite quantum dot materials in composite applications with other emerging materials, new device structure exploration, and potential new application field expansion.

Keywords: Perovskite quantum dots, Photoelectric conversion, Solar cells, Photodetectors, Stability

1. Introduction

Photoelectric conversion technology is very important in the field of modern energy and communication. With the increase in energy demand and the depletion of fossil energy, the development of efficient and sustainable photoelectric conversion materials has become the key. Halide perovskite quantum dots have attracted much attention due to their unique photoelectric properties. They have excellent light absorption coefficient, narrow emission characteristics, and adjustable band gap structure, which make them show broad application prospects in photovoltaic cells, photodetectors, and other photoelectric conversion devices [1].

Perovskite quantum dots are highly sensitive to external environments such as light, heat, and humidity, and are prone to decomposition failure, and the stability problem is prominent [2]. The problem of lead toxicity has aroused widespread concern. Against the background of increasing

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environmental awareness, how to reduce or eliminate the potential harm of lead to the environment has become a key issue [3].

This paper reviews the application progress of perovskite quantum dot materials in photoelectric conversion, including their working principles and performance improvement strategies in devices such as solar cells and photodetectors. The challenges faced by the material in terms of stability, toxicity, and the large-scale preparation process were analyzed, and the corresponding solutions were discussed. The aim is to provide reference and direction for the further development of perovskite quantum dot materials in the field of photoelectric conversion.

2. Perovskite quantum dot material foundation

2.1. Structure and properties

Perovskite quantum dots have a unique crystal structure, and their chemical formula is ABX3. The A-site cations (such as Cs^+ or $CH_3NH_3^+$), B-site cations (such as Pb^{2+}), and X-site anions (such as Cl^-, Br^-, or I^-) constitute a three-dimensional cubic lattice structure [1]. This highly symmetrical structure endows perovskite quantum dots with excellent optical properties, including high quantum efficiency, narrow half-peak width, and tunable band gap characteristics [1,4]. For example, all-inorganic perovskite quantum dots (such as $CsPbX_3$) are ideal materials for optoelectronic devices due to their high fluorescence quantum yield (up to 95%) and extremely narrow emission peak half-width (12 ~ 42 nm) [5,6].

2.2. Optical properties

Perovskite quantum dots have attracted much attention due to their unique optical properties. The tunability of luminescence spectrum, high quantum efficiency, and narrow half-peak width make them ideal materials in the field of photoelectric conversion. Liu et al. have shown that the emission wavelength of perovskite quantum dots can be precisely controlled by changing their size and halogen composition. The emission wavelength range can be extended from the ultraviolet region to the near-infrared region (about 410-760 nm), and the half-peak width can be narrowed to 12-42 nm, showing excellent color purity [5].

2.3. Electrical properties

The electrical properties of perovskite quantum dots are also crucial for their application in the field of photoelectric conversion. In particular, the parameters such as carrier mobility and conductivity directly affect the device performance. Shi et al. have shown that perovskite quantum dots have high carrier mobility, which is mainly due to the highly ordered atomic arrangement and weak electron-phonon coupling effect in their crystal structure [7].

2.4. Synthesis method

The synthesis methods of perovskite quantum dots include the thermal injection method, the one-step reaction method, and the anion exchange method. High-temperature hot injection method can form uniform and monodisperse quantum dots in a short time by rapidly injecting precursor solution under high temperature conditions, but its operation is complex and requires high equipment [5]. In contrast, the one-step reaction method simplifies the experimental steps. The target product can be obtained by mixing and heating all precursors at the same time, but this method has certain

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limitations in controlling the size and morphology of quantum dots [8]. The anion exchange rule realizes the dynamic regulation of the optical properties of quantum dots by changing the type of halogen ions in the reaction system, but this process may introduce impurities and affect the stability of the final product [5].

3. Photoelectric conversion principle

3.1. Photoelectric effect

The core mechanism of photoelectric conversion is based on the photoelectric effect, that is, the carrier separation and transmission process generated by the interaction between photons and matter. Perovskite quantum dot materials show significant advantages in this process due to their unique photoelectric properties. When the incident photon energy is higher than the band gap of the material, the photon is absorbed and the electrons are excited to transition from the valence band to the conduction band, and holes are left in the valence band to form electron-hole pairs [4]. These photogenerated carriers are separated and migrated to the electrode under the action of the internal electric field, thereby completing the photoelectric conversion process. The high absorption coefficient and narrow band gap characteristics of perovskite quantum dots enable them to efficiently capture photons of different wavelengths, thereby improving the photoelectric conversion efficiency.

3.2. Band theory

The band theory provides an important theoretical framework for understanding the mechanism of perovskite quantum dots in photoelectric conversion. The conduction band bottom and valence band top of perovskite materials are composed of different orbitals, respectively. This special band structure determines its excellent photoelectric properties [9]. For example, the conduction band of $CsPbX_3$ quantum dots is mainly contributed to by the 6p orbital of Pb, while the valence band is dominated by the np orbital of X (such as Cl, Br, or I). This orbital hybridization makes the perovskite quantum dots have direct band gap characteristics, thereby enhancing the light absorption capacity.

4. Quantum confinement effect principle

The quantum confinement effect is the key characteristic of perovskite quantum dots at the nanoscale. The core is that when the particle size is reduced to be equivalent to or smaller than the exciton Bohr radius, the movement of electrons and holes is limited in a limited space, and then shows a significant quantization behavior [10]. This phenomenon is essentially related to the wave-particle duality of electrons, that is, the wave nature of electrons in a confined space leads to the discretization of energy distribution [11].

The confinement of electrons and holes in quantum dots is mainly due to the potential well effect: when the size of quantum dots is much smaller than the characteristic length of bulk materials, the wave function will be localized to form a quantized energy level structure, and this confinement degree is directly related to the size and shape of quantum dots [11]. By changing the energy distribution of electrons and holes, the quantum confinement effect will further lead to the energy level separation and band gap widening of quantum dots. When the size of quantum dots is reduced to below the exciton Bohr radius, the wave function overlap of electrons and holes increases, the Coulomb interaction is enhanced, and the band gap width between the conduction band and the

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valence band is significantly increased, which ultimately affects the optical properties of the material.

5. Application of perovskite quantum dot materials in different photoelectric conversion devices

5.1. Application in solar cells

Perovskite quantum dots have shown excellent application potential in the field of solar cells due to their unique photoelectric properties, mainly as light absorption materials and passivation materials.

As a light absorption material, perovskite quantum dots achieve efficient coverage of the solar spectrum by adjusting the band gap, which significantly improves the light absorption efficiency. Studies have shown that the band gap tunability comes from the substitution of anions or cations in the crystal structure. For example, by changing the proportion of halogen ions, light absorption from ultraviolet to near-infrared regions can be achieved [12]. In addition, the high absorption coefficient of perovskite quantum dots enables them to achieve the same light absorption effect as traditional silicon-based materials at an extremely thin thickness, which provides the possibility for the preparation of lightweight and flexible solar cells [9].

As a passivation material, perovskite quantum dots play an important role in reducing interface defects. Interface defects in solar cells usually lead to non-radiative recombination and reduce device performance. Perovskite quantum dots can effectively suppress the non-radiative recombination process of carriers by filling surface trap states and passivating grain boundary defects. In the literature, it is pointed out that after introducing it into the interface layer of solar cells, the open circuit voltage and fill factor of the device are significantly improved, indicating that the passivation effect is of great significance to improve the overall performance of the battery [9,12].

5.2. Application in photodetectors

Perovskite quantum dots have excellent performance in the field of photodetectors due to their excellent photoelectric properties, especially in terms of high response speed and wide spectral response. High response speed is one of the key performance indicators of photodetectors, and the high carrier mobility of perovskite quantum dots provides an important guarantee for achieving this goal. Studies have shown that the carrier mobility of perovskite quantum dots can reach tens to hundreds of square centimeters per volt-second, which is much higher than that of traditional semiconductor materials [7]. This high mobility enables perovskite quantum dots to complete carrier transport and collection at the picosecond level, thereby significantly improving the response speed of the detector. In addition, the low trap state density of perovskite quantum dots further reduces the capture and recombination of carriers, which helps to improve the sensitivity and signal-to-noise ratio of the detector.

Wide spectral response is another important feature of perovskite quantum dot photodetectors. Its response range can extend from ultraviolet to the near-infrared region, even covering the short-wave infrared band. This characteristic is mainly attributed to the tunable band gap and strong photoluminescence effect of perovskite quantum dots. Zhang et al.pointed out that by adjusting the size and composition of perovskite quantum dots, a sensitive response to different wavelengths of light can be achieved to meet the needs of multi-scenario applications [9]. For example, in the visible light range, perovskite quantum dot detectors can be used for environmental monitoring and

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image sensing; in the near-infrared region, they can be applied to the field of biological imaging and communication technology [7].

5.3. Application in other photoelectric conversion devices

In addition to solar cells and photodetectors, perovskite quantum dots also show broad application prospects in other photoelectric conversion devices such as light-emitting diodes (LEDs) and fluorescent concentrating cells (LSC). In the field of LED, perovskite quantum dots are regarded as the core material of next-generation display technology due to their high quantum efficiency and narrow half-peak width. Studies have shown that by embedding perovskite quantum dots into a polymer matrix, LED devices with high color purity and uniform brightness can be prepared, and their external quantum efficiency has exceeded 20% [1]. In addition, the tunable emission wavelength characteristics of perovskite quantum dots enable them to cover the entire visible spectral range, thereby meeting the needs of full-color display. In the field of fluorescent concentrating batteries, perovskite quantum dots are used as fluorescent materials to absorb and re-emit sunlight, thereby improving the light energy utilization of the battery. Zhang et al. pointed out that the wide absorption range and efficient fluorescence conversion ability of perovskite quantum dots make them ideal fluorescent concentrating materials [9]. By integrating perovskite quantum dots into fluorescent concentrating batteries, not only can the light capture efficiency be enhanced, but also the battery cost can be effectively reduced.

6. The challenges and solutions of perovskite quantum dot materials in photoelectric conversion applications

6.1. Core challenges

Titanium quantum dot materials face multiple key challenges in photoelectric conversion applications. The first is the problem of insufficient stability. The material is highly sensitive to environmental factors such as light, oxygen, temperature, and humidity, which directly lead to performance degradation and shortened service life. For example, all-inorganic perovskite quantum dots (IPQDs) are prone to decomposition or aggregation in polar solvents. Long-term illumination may also degrade their structure, and changes in temperature and humidity can also significantly destroy their stability [2,4].

The second is the hidden danger of toxicity. The lead element contained in perovskite quantum dot materials is toxic and poses a potential threat to the environment and human health. Lead ions are prone to migrate in the environment and may enter the ecosystem through water and soil and causing toxicity to organisms. At the same time, its toxicity can also endanger human health by inhalation or skin contact [4].

In addition, there are also problems of cost control and process consistency in large-scale preparation. At present, the common synthesis methods of this material include the high temperature hot injection method, one-step reaction method, anion exchange method, and so on. However, when these methods are applied to large-scale production, they not only need high equipment cost, but also face a complex operation process. It is more difficult to ensure that the prepared materials meet the requirements in consistency and uniformity, which further restricts their industrial application in the field of photoelectric conversion [5,8].

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6.2. Solutions to challenges and research progress

In order to improve the stability, Lyu et al. used ion doping and surface passivation technology [2]. For example, Mn doping can increase the quantum yield of $CsPbI_3$ from less than 5% to 27% [2]. Surface passivation technology covers the surface of quantum dots by organic or inorganic ligands to suppress non-radiative recombination and improve the optical stability of materials. For example, after 2 hours of ethanol treatment, the fluorescence intensity of TOPO-$CsPbBr_3$ quantum dots only decreased by 5%, while the fluorescence intensity of CsPbBr3 quantum dots using traditional oleic acid / oleylamine as ligands decreased by 87%.

In order to solve the problem of toxicity, Wang et al. proposed to develop lead-free or lead-free perovskite quantum dot materials [4]. For example, tin-based perovskite quantum dots have the potential to replace traditional lead-based materials. The co-doping of lead and other metal elements by an alloying strategy can reduce the lead content and maintain the photoelectric properties of the material. However, due to the inherent defects of the crystal structure and the easy oxidation of Sn^{2+} to Sn^{4+}, these materials are significantly inferior to $CsPbX_3$ in optical performance and long-term stability [4].

In order to realize the large-scale preparation of perovskite quantum dot materials, Liu et al. improved the traditional synthesis method and optimized the production process [5,8]. For example, by precisely controlling the synthesis process, the one-step reaction method first prepares the cesium oleate precursor and the lead halide precursor respectively, and then mixes them and heats them to a specific temperature range (50 ~ 170°C) for reaction. After rapid cooling to room temperature in an ice water bath and centrifugal separation, quantum dot materials were successfully prepared. By systematically adjusting the reaction temperature parameters and flexibly changing the type and ratio of halogen anions, the emission wavelength of quantum dots can be adjusted in a wide range of 360-700 nm, and the fluorescence quantum yield can reach up to 87% [5]. The target mixed halogen $CsPb(XY)_3$ quantum dots were successfully synthesized by mixing the prepared single halogen $CsPbX_3$ quantum dots and adjusting the ratio of the stock solution at room temperature by anion exchange method [8]. The obtained CsPbBr1.5I1.5 quantum dots exhibit longer fluorescence lifetime and better luminescence properties than similar materials prepared by the thermal injection method. It was further applied to LED devices, and the color stability and performance of the device did not decrease significantly after 3600 hours of continuous operation without packaging and an average humidity of 60%, confirming its excellent long-term stability [8].

7. The future development trend of perovskite quantum dot materials in the field of photoelectric conversion

Perovskite quantum dots can improve photoelectric properties by compounding with other materials and exploring new device structures. At the same time, their application fields are also expanding. In terms of material compounding, compounding with emerging materials, metal-organic frameworks (MOFs) and other semiconductor materials is the core path: when compounding with two-dimensional materials (such as graphene oxide) and metal nanostructures, for example, the composite hole transport layer constructed by GO and Spiro-OMeTAD is applied to $CH_3NH_3PbI_3$ perovskite solar cells, and the power conversion efficiency (PCE) is 53% higher than that of pure Spiro-OMeTAD devices [13]. Metal nanostructures can also enhance light absorption and regulate local electromagnetic fields by surface plasmon resonance effect; the pore structure of MOFs can slow down the performance degradation caused by ion migration or surface defects, and its high conductivity can also improve the carrier transport efficiency [14]. Combined with ZnO, TiO_2, and

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other semiconductor materials, the efficiency and stability of the device can be improved by adjusting the energy band structure to efficiently utilize sunlight and inhibit non-radiative recombination [7].

In the optimization of device structure, the exploration of new structures such as vertical stacking, porous network, and three-dimensional heterojunction aims to shorten the carrier transmission distance and improve the charge collection efficiency [9]. For example, the vertical stacking structure achieves higher light absorption efficiency and lower energy loss by accurately controlling the thickness and arrangement order of the functional layer.

In terms of application fields, the potential of perovskite quantum dots in new fields such as bio-optoelectronics and smart sensors has attracted much attention. In the field of bio-optoelectronics, it can be used for fluorescence imaging, photodynamic therapy, and biosensing [15]. For example, the MAPbI3 @ PCN-221 (Fe_x) (x = 0 ~ 1) composite photocatalytic material constructed with iron-based MOF (PCN-221) as the encapsulation matrix exhibits a continuous working stability of the aqueous phase for more than 80 hours in the photocatalytic CO_2 reduction reaction [15].

8. Conclusion

Perovskite quantum dot materials have great potential in the field of photoelectric conversion due to their unique optical properties and tunable band gap characteristics. Its application research in solar cells and photodetectors has made remarkable progress, especially in improving efficiency, response speed, and stability. However, the material is faced with poor environmental stability, toxicity controversy, and large-scale preparation problems. Researchers have improved stability through ion doping and surface passivation, developed lead-free materials to reduce toxicity, optimized synthesis methods to control costs, and ensure process consistency. These achievements have promoted basic research and provided theoretical support and technical support for photoelectric conversion technology. Although perovskite quantum dot materials have made remarkable achievements in the field of photoelectric conversion, future development still needs to overcome bottlenecks and explore new directions. It is necessary to carry out interdisciplinary research to achieve breakthroughs in order to promote the development of this field and the sustainable development of energy and the environment.

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