Research Progress of Perovskite Quantum Dot Optoelectronic Devices

Xiran Bai
The College of Physics and Materials Science, Tianjin Normal University, Tianjin, 300387, China

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Abstract: Perovskite quantum dot optoelectronic devices show great potential in improving photoelectric conversion efficiency. In recent years, researchers have continuously studied and solved many problems related to the limited properties of perovskite quantum dots, laying the foundation for their future extended applications. This paper takes perovskite quantum dots as the core material to sort out the research in solar cells, photovoltaic cells, display fields, and other fields, and looks forward to the exploration of future research directions and the evolution of development trends. In the direction of batteries, even though the improvement of existing technology has led to an increase in the photoelectric conversion efficiency of related devices, the existing technology still requires high equipment accuracy and is difficult to reduce cost issues. Although it is highly efficient and low-cost in the display field, it is difficult to achieve further breakthroughs and new developments in this direction. Due to the rapid development of artificial intelligence at present, it is possible to combine AI-driven intelligent manufacturing with the manufacturing of perovskite quantum dot devices in the future, injecting new vitality into more new fields under the current trend of energy transformation.

1 INTRODUCTION

Perovskite quantum dots play an indispensable role in the field of optoelectronic devices. It features high luminous efficiency, adjustable wavelength, and excellent carrier transport performance, making it a core material for enhancing the key performance of optoelectronic devices such as luminescence and photoelectric conversion. It is a nanoscale luminescent material based on the perovskite crystal structure, with ABX3-type perovskite as its basic skeleton and quantum confinement effect as its dominant factor, due to the programmability of its unique structure and the controllability of dynamic defects. It has demonstrated revolutionary advantages in the field of optoelectronics. Its ultra-high quantum efficiency provides a new way to improve the performance of quantum dot LEDs (Pi et al., 2021).

In recent years, the application of perovskite quantum dots in solar cells has received widespread attention. Based on the improvement of the stability performance and the extension of the lifespan of solar cells, Liang (2024) further investigated the degradation mechanism of all-inorganic perovskite (QDSCs), and obtained the results of enhancing the performance and stability of this type of cell from the perspective of defect passivation of perovskite quantum dots. Obtained a photoelectric conversion efficiency (PCE) of 18.78%, and after being stored in a certain environment for 600 hours, the battery efficiency only decreased to 93% of the initial value. Perovskite quantum dots have the property that the band gap can be adjusted by changing their chemical composition and size to give them a wide color gamut. The devices composed of them can present rich and vivid colors (Wang et al., 2020). At the same time, it also has good solution processability. Long et al. (2025) can precisely control the film thickness and uniformity of quantum dots through processing technology. Broadcasting Service Television (BT) with a color range of 96% has been achieved, and higher production efficiency has been achieved in applications such as inkjet printing. Based on the above research results, this article has conducted an in-depth exploration of its field.

This article introduces its research progress in the field of photoelectric conversion batteries, display fields, and other fields. Intended to provide innovative research ideas for researchers and readers

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in this field, and to help expand their horizons in this field.

2 PREPARATION AND PROPERTIES OF PEROVSKITE QUANTUM DOTS

2.1 Specific Properties

Due to the highly flexible and stable crystal structure, surface modifiability, and high ion substitutability of perovskite quantum dots, they possess a wide range of excellent properties. Due to its adjustable crystal structure and high surface activity, its constituent ions can be relatively easily arranged and combined under different conditions and interact with surrounding ligands or solvent molecules. In its optical performance, high defect tolerance and high carrier mobility are the key advantages with the greatest potential for application. The research of Tang et al. (2023) indicates that the photoluminescence quantum yield of perovskite quantum dots can reach over 90%, approaching 100%, and they can still maintain efficient luminescence performance even in the presence of defects. In addition, Wei et al. (2023) pointed out in their study on charge transfer in optoelectronic devices that the mobility of the material was increased to 2.66 × 10-3cm2V-1s-1, which improved the efficiency of optoelectronic devices.

2.2 Preparation

Hot injection and ligand-assisted reprecipitation are common preparation methods for perovskite quantum dots. Different preparation methods will affect their properties exhibited in different environments, which, to some extent, determines the cost of related optoelectronic devices. It has the ability of rapid nucleation and growth, which enables it to be synthesized using the thermal injection method. Dong et al. (2025) found that by controlling the temperature and injection rate during the process, the size of quantum dots can be precisely adjusted, allowing for rapid synthesis of large quantities of quantum dots with high synthesis efficiency and ease of large-scale production.

The chemical activity of the constituent ions of perovskite quantum dots is relatively high, and there are many differences in their solubility in different solvents. Therefore, ligand-assisted reprecipitation is a commonly used preparation method for it (Zhang, 2017). This method can enhance the stability and luminescence efficiency of quantum dots, making their surface properties relatively good. It is not only simple to operate, but also has a wide range of applications. Different ligands will affect the growth direction of quantum dot crystals, and thus, the appearance of the obtained perovskite quantum dots is not the same. Meanwhile, under the action of ligands, quantum dots can precipitate out of solution in a highly controllable manner, and achieving the preparation and purification of quantum dots. In addition, there are also common methods such as ion exchange, high-temperature melting, and supersaturation.

3 APPLICATION OF PEROVSKITE QUANTUM DOTS IN OPTOELECTRONIC DEVICES

3.1 Sensitized Solar Cells

Solar cells are a new type of solar cell based on perovskite quantum dot materials, composed of electrode layers, transport layers, and sensitization layers. They utilize their unique photoelectric properties to convert solar energy into electrical energy. Guijarro et al. (2019) studied the introduction of colloidal lead halide perovskite quantum dots (CsPbl3QDs) as the third component into the active layer of solar cells (OSCs). Due to the increase in the loading of quantum dots Quantum Dot(QD), the power conversion efficiency of the device increased from 7.94% in the control group to 10.8%. The use of this quantum dot in ternary OSCs has achieved efficient charge separation and recombination suppression, with a photoelectric conversion efficiency (PCE) of 10.8% and no significant change in its absorption spectrum. This achievement fully verifies that quantum dots (QD) interact with the organic mixture bulk heterojunction(BHJ), which can improve the conversion efficiency. However, due to the excessive number of QDs, their interface becomes clustered, triggering new recombination paths and resulting in a decrease in their performance.

There have also been many new discoveries in lead-free aspects. Saifee et al. (2025) designed a lead-free double perovskite solar cell based on the FTO/TEO structure. Its absorption layer selected the non-toxic and stable double perovskite $Cs_2AsBiBr_6$ instead of the traditional lead-based materials. Make it have a wide band gap (1.2 eV) and better humidity stability. By using TiO_2 as the electron transport layer, the efficiency of electron extraction was further improved, and the thickness of its absorption layer was optimized to 1.2×10^{-6}m. At the same time, the doping density and defect density were improved, and the charge separation efficiency was enhanced. This process has optimized parameters through machine learning and design, but there are still significant engineering gap challenges.

3.2 Photovoltaic Cells

Based on the fundamental principle of the photovoltaic effect, it achieves the conversion of light energy into electrical energy. In Salimet al.'s (2024) study, various optimization strategies were proposed to improve photovoltaic performance. At the interface energy level, a new nanocomposite material is constructed using inorganic PbS quantum dots and lead halide perovskite. By adjusting the surface shell, the order of electronic energy levels at the interface can be precisely controlled, improving the path of charge transport and ultimately reducing energy loss. Meanwhile, in terms of lattice strain, researchers introduced PbS quantum dots into Fapi-based and Mapi-based perovskites, respectively. By means of lattice contraction and expansion, they enhanced phase stability and mitigated anisotropic changes, ultimately achieving an improvement in the uniformity of the thin film. However, reducing carrier loss will increase volatile organic compounds. Therefore, striking a balance between performance improvement and stability is the key to achieving efficient perovskite solar cells (PSCs).

In addition, the regulation of the doping concentration of PbS quantum dots is also extremely important. Rao (2022) found that the best performance was achieved when 0.6mg/ml PbS quantum dots were doped in $MAPBI_3$. However, excessive doping would lead to a decrease in the decomposition ability of perovskite, resulting in a decline in performance. For the $FAPBI_3$ system, even low-concentration doping may lead to an extremely low efficiency due to a significant reduction in the filling factor. In solvent engineering, the use of the ethyl acetate anti-solvent method can increase the crystallization rate of perovskite and further improve the density of the film through high-temperature annealing, ultimately achieving the goal of enhancing the stability of the device. Although the use of cinnamic acid to replace traditional oleic acid in the research process can prepare more stable $MAPbBr_3$ quantum dot nanocrystals, further research is needed in terms of quantum yield, fluorescence lifetime, and stability performance.

3.3 Display Domain

3.3.1 Light Emitting Diodes

The material cost of perovskite quantum dot light-emitting diodes is relatively low. Its preparation method is also highly flexible to a great extent and has made significant progress in current research. In response to a series of problems such as low efficiency, insufficient brightness, and spectral instability in red halide perovskite quantum dot light-emitting diodes, various optimization strategies have been proposed in recent years. By introducing a double-layer hole transport layer, Lu (2024) balanced the transport of charge carriers while reducing the operating voltage, increasing the external quantum efficiency to 11.7%, and improving the maximum brightness. In addition, the research also reconstructed the surface of perovskite films. While passivating the defects of the thin film with small ions (GA^+, Na^+, SCN^-), it can also suppress the loss of energy transfer, increase the quantum yield of photoluminescence of the thin film to 95.1%, and make the external quantum efficiency(EQE) of the device exceed 24.5%. Although research has achieved efficient, high brightness, and spectral stability in the preparation of PQDLEDs, more stable operation is needed. Perovskite quantum dots (PQDs) are more environmentally friendly and still face significant challenges in large-scale production.

3.3.2 Inkjet Printing/Printing

Traditional perovskite quantum dot inks are prone to agglomeration and have a large solvent contact Angle, which may cause the printed film to exhibit a "coffee ring effect". Trace amounts of oil amine (OAM) ligands can be introduced to improve the dispersion of quantum dots while suppressing storage condensation. On this basis, Li et al. (2020) used dodecane to optimize the mixed solvent to achieve the purpose of balancing the surface tension and also eliminate the situation of uneven film caused by capillary flow. To avoid the problems of high cost, low efficiency, and low material compatibility in traditional photolithography, in-situ inkjet printing can achieve efficient patterned preparation of perovskite quantum dots (Shi et al. 2019). It can be directly sprayed onto polymer substrates (such as PAN, PMMA, etc.) in the precursor solution, and the in-situ crystallization of perovskite can be induced by the method of solvent evaporation. This process does not require pre-synthesis of PQDs, avoiding the problems of quantum dot aggregation and poor stability in traditional inkjet printing. Meanwhile, this method can be compatible with various perovskites and multiple types of polymer substrates, breaking the limitations of traditional hydrophilic materials.

3.3.3 Ultra-High-Definition Pure Red Light Perovskite Electroluminescent LED Devices

Due to the unique property of tunable bandgap luminescence of $CsPbI_3$ perovskite quantum dots, they have always been an ideal material for manufacturing pure red LEDs. However, due to the defect of insufficient stability of the material itself, this difficult problem has not been overcome either. It was not until Zhou et al.(2025) first utilized the all-solution method and achieved the preparation of large-area in-situ controllable inhibition junctions through perovskite van der Waals epitaxy technology. This innovative technology has successfully overcome the dual challenges of history, not only improving the stability performance of materials but also enhancing the performance of devices and developing pure red perovskite electroluminescent devices (LEDs) with excellent stability and high efficiency. This breakthrough provides a new direction for the future research and development of optoelectronic devices.

3.3.4 Other Development Areas

The research scope of perovskite quantum dots is extremely extensive, and new developments have also emerged in the field of fluorescent probes. Patel et al. (2025) developed a novel fluorescent probe based on europium-doped strontium molybdate perovskite quantum dots (Eu^{3+}: SMO PQDs), which can be used for efficient detection of hypoxanthine (HX) and iron ions (Fe^{3+}). This probe can be detected through the unique mechanism of fluorescence "turn-off". In the presence of HX, the fluorescence intensity is reduced, but the addition of Fe^{3+} restores the fluorescence state. Experiments have also shown that this probe has good sensitivity, low detection limit (LOD), and selectivity, and can detect HX and Fe^{3+} in complex biological samples such as plasma and urine. This method provides a low-cost, efficient, and easy-to-use detection method for clinical diagnosis and environmental detection, etc. It provides a broader application scope for the further optimization of multiple detection capabilities in the future.

Photodetectors that span across the ultraviolet, visible, and near-infrared ranges have significant application value in the fields of optical communication, imaging, and astronomy. In recent years, two-dimensional materials have attracted much attention due to their excellent photoelectric properties. However, because of their poor thermal stability and sensitivity to water, how to obtain stable and lead-free wideband photodetectors has become a research trend. Lead-free perovskite Cs_2SnI_6 brings new directions for research due to its excellent stability, environmental friendliness, broadband absorption characteristics, and ultra-high detection sensitivity. Xie et al. (2024) successfully synthesized 2D Cs_2SnI_6 thin films on mica substrates using chemical vapor deposition (CVD) technology, exhibiting a single crystal structure and a long photoluminescence lifetime. Based on this, an ultra-high response rate (6.25×105A/W), external quantum efficiency, and fast response time within a wide spectrum ranging from 365nm to 1342nm were fabricated. This research has promoted the development of green electronic technology.

Ultrafast spectroscopy of excitons is also one of the development directions of perovskite. At present, the dynamic behavior of excitons in layered hybrid perovskites (LPKs) can be studied by combining ultrafast optics and terahertz spectroscopy techniques. Free carriers can rapidly cool within approximately 400 femtoseconds while forming excitons, and then reorganize at a slower rate. In this process, excitons recombine through a single-molecule process (Helen et al., 2024). This study also found signs of exciton-phonon coupling, providing a new theoretical basis for further optimizing optoelectronic devices.

In quantum technology, room-temperature single-photon sources based on inorganic $CSPbI_3$ perovskite quantum dots (PQDS) embedded in tunable open optical microcavities have shown key applications. Tristan et al. (2023) achieved high-purity single photon emission in single-mode and narrowband at room temperature through the coupling of PQD and optical microcavities, with a single photon purity of up to 94%. While breaking through the limitation of traditional single-photon sources operating at low temperatures, it also provides more efficient and extensive solutions to fields such as quantum metrology and quantum information processing. Not only has it laid the foundation for the development of future quantum technology, but it also has the potential for low-cost industrialization.

4 CONCLUSION

This paper introduces the development process of perovskite quantum dots in specific optoelectronic fields. Due to its special basic framework, it has a wide range of excellent properties, and the preparation methods also have their own advantages. In the application of optoelectronic devices, due to the controllability of perovskite quantum dots, surface engineering optimization such as halogen modulation, changing surface ligands, and surface passivation, as well as controlling various conditions during the preparation process, can improve the efficiency of related devices and have great potential for application. The thermal stability of perovskite quantum dots varies due to the influence of the A-site cation, and they are also sensitive to environmental factors such as light, humidity, and oxygen, which affect their optical properties. It is difficult to control the uniformity of size and morphology during preparation, resulting in differences in surface energy, optical, and electrical properties of quantum dots. The selection of its ligands, as well as the processes of adsorption and desorption, are also difficult to precisely control, which may affect the transfer of charges between quantum dots and generate unstable factors in the subsequent processing. In addition, the existing process of large-area uniform film formation technology also requires high equipment.

Combining AI-driven intelligent manufacturing with the manufacturing of perovskite quantum dot devices, and using machine learning algorithms to analyze various data such as temperature, humidity, and solution concentration, can reduce production costs and inject new vitality into new fields such as quantum computing. Under the trend of energy transition, perovskite quantum dots have moved from single power generation to the combination of energy information and materials, with broad prospects in stacked batteries and integrated light storage hydrogen systems.

The aggregation of perovskite quantum dots can lead to a decrease in performance. This can be improved by enhancing ligands, increasing the vacancy hindrance between quantum dots, reducing aggregation, and reasonably controlling the amount of ligands used. This is to prevent too little from effectively preventing aggregation and too much from affecting photoelectric performance. The reduction of ligands can also increase volatile organic compound. By continuously optimizing the ligand structure and introducing special functional groups, the binding between the quantum dot surface and ligands can be enhanced, indirectly reducing the production of volatile organic compounds. In the subsequent processing of quantum dots, high-temperature and other treatments can be avoided, and vacuum and other methods can be used for processing.

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