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A Review on Quantum Dot Solar Cells

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Abstract. As an emerging photovoltaic technology, quantum dot solar cells (CQD-SCs) demonstrate significant application potential due to their excellent optoelectronic properties, low-cost fabrication processes, and broad-spectrum absorption capabilities. This paper reviews recent progress in CQD-SCs, focusing on advances in quantum dot synthesis methods, surface modification techniques, efficiency enhancement strategies, and device structure optimization. Unique properties of quantum dots, such as tunable bandgaps and multiple exciton generation (MEG), offer new possibilities for improving power conversion efficiency. Nevertheless, CQD-SCs still face challenges in material stability, scalability of synthesis processes, and efficiency bottlenecks. In particular, environmental concerns related to lead-based quantum dots have driven research into lead-free alternatives. Future research will focus on developing new quantum dot materials, optimizing multijunction architectures, engineering interfaces, and integrating photovoltaic systems. With continued advancements in materials and processes, CQD-SCs are expected to achieve commercial viability in the coming years, contributing to global energy transition and the development of the photovoltaic industry.

Keywords: quantum dot, optoelectronic properties, multiple exciton generation, lead-free materials

1. Introduction

With the global demand for clean energy increasing, solar energy has become a key solution to the energy crisis and climate change as a green energy source. Traditional silicon-based solar cells face limitations in both efficiency and cost, and their manufacturing process is complex and energy-intensive [1]. To overcome these bottlenecks, quantum dot solar cells (CQD-SCs) have gained significant attention as a promising new photovoltaic technology. Quantum dots can precisely tune their bandgaps by adjusting their size, enabling broader spectrum absorption, improved power conversion efficiency, and the potential for low-cost, large-scale production. Although quantum dot materials exhibit remarkable optoelectronic advantages, challenges such as stability, efficiency, and synthesis techniques remain. This review explores the current state, development trends, and key challenges in CQD-SC research, with a particular focus on synthesis methods, surface modification strategies, performance enhancement, and device structure optimization. Furthermore, it analyzes approaches to overcome existing issues of stability and efficiency bottlenecks, proposing future

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research directions to provide theoretical support for the advancement and commercialization of CQD-SCs.

2. Background of quantum dot solar cell research

2.1. Unique advantages of quantum dot materials

Quantum dot (CQD) materials are semiconductor nanoparticles at the nanoscale, whose unique quantum confinement effect grants them electronic and optical properties distinct from conventional semiconductors. The bandgap and light absorption characteristics of quantum dots can be precisely controlled by adjusting their size, giving quantum dot materials great flexibility in photovoltaic applications. Moreover, quantum dots can absorb a broad range of the solar spectrum, especially in the near-infrared (NIR) region, which significantly enhances the power conversion efficiency of quantum dot solar cells. Another key advantage of quantum dot materials is their capability for large-scale production through solution-based processes. Compared to the high-cost manufacturing processes of traditional silicon-based solar cells, CQD solar cells can be fabricated using low-temperature solution methods, significantly reducing both material and production costs. This low-cost and high-efficiency manufacturing approach broadens the application prospects of CQD solar cells in large-scale photovoltaic systems, especially in emerging areas such as building-integrated photovoltaics (BIPV) and wearable electronics, where CQD solar cells show great potential.

2.2. Current research achievements and challenges

Research on quantum dot solar cells began in the early 2000s, initially focusing on the basic exploration of quantum dot synthesis methods and their optoelectronic properties. Conventional semiconductor quantum dot materials such as PbS, CdSe, and PbTe have been widely applied. Techniques like surface passivation and ligand exchange have significantly enhanced their optoelectronic performance [2].

Despite these advancements, CQD solar cells still face several challenges. First, the stability of quantum dot materials, particularly lead-based ones such as PbS and PbSe, is a major issue, as they tend to oxidize or hydrolyze easily under humid and high-temperature conditions, compromising long-term performance. Second, the synthesis methods for quantum dots are not yet fully mature. Although existing techniques, such as solution processing and vapor deposition, can produce high-quality quantum dots at the laboratory scale, their complexity and cost hinder their application in large-scale manufacturing.

2.3. Future research directions

Although the research on quantum dot solar cells still faces numerous challenges, their potential for improving efficiency, reducing cost, and enabling large-scale production makes this field one of the most promising in solar technology. Future research should focus on the following key areas: Firstly, the development of lead-free and environmentally friendly quantum dot materials has become a critical direction. Tin-based quantum dots (SnQDs) and zinc-based quantum dots (ZnQDs), as lead-free alternatives, possess good optoelectronic properties and environmental compatibility, making them current research hotspots [3].

Secondly, improving the efficiency of CQD solar cells remains a core research objective. Through innovations in multijunction solar cell designs, interface engineering, and material development, it is expected that existing efficiency bottlenecks can be overcome, particularly by

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optimizing carrier recombination and energy loss. Additionally, enhancing the long-term stability of CQD solar cells will be another key research focus, especially in the context of environmental fluctuations and extended operation. Finally, scalable production technologies for CQD solar cells will be essential for promoting commercialization. By optimizing existing fabrication processes and developing low-cost, eco-friendly manufacturing methods, CQD solar cells are expected to achieve large-scale commercial deployment in the coming years.

3. Fundamental principles of quantum dot solar cells

3.1. Overview of quantum dot materials

Quantum dots (CQDs) are semiconductor nanocrystals that exhibit quantum confinement effects, typically ranging from 2 to 10 nanometers in diameter. As their size decreases, the bandgap of quantum dots increases, leading to unique optical and electronic properties that enable them to tune light absorption characteristics [2]. This feature allows quantum dots to absorb a broader range of the solar spectrum, particularly in the near-infrared (NIR) region, thus breaking through the efficiency limitations of traditional silicon-based solar cells. The high surface area of quantum dots also enhances their light absorption and electron transport capabilities, making them highly promising for photovoltaic applications.

Common quantum dot materials include PbS and CdSe, which are widely used in CQD solar cells due to their excellent optoelectronic performance. In recent years, carbon quantum dots and tin-based quantum dots have emerged as potential alternatives to lead-based materials because of their low toxicity and environmental friendliness.

3.2. Quantum dot synthesis methods

The synthesis methods of quantum dots directly affect their optoelectronic properties, stability, and cost-effectiveness, making them a crucial focus in CQD solar cell research. With the development of nanotechnology, quantum dot synthesis techniques have diversified, and researchers have been striving to improve the controllability, efficiency, and economic viability of the synthesis process. Currently, commonly used synthesis methods include solvothermal synthesis, vapor deposition, and chemical vapor deposition (CVD). The solvothermal method enables the production of small-sized quantum dots with excellent optoelectronic performance by controlling parameters such as temperature, reaction time, and precursor concentration. Vapor deposition and CVD are more suitable for large-scale production, though they involve more complex operations and higher costs. In recent years, hot-injection synthesis has gained popularity for its ability to rapidly produce high-quality quantum dots at low temperatures, particularly those with controllable sizes and uniform morphology.

Although significant progress has been made in existing synthesis methods, challenges remain for the large-scale production of quantum dots. Maintaining both cost-efficiency and high optoelectronic performance is a key issue in the commercialization of CQD solar cells.

3.3. Working principle of quantum dot solar cells

The working principle of quantum dot solar cells is similar to that of traditional photovoltaic cells: sunlight excites electron-hole pairs, which are then separated by an electric field, and the resulting charge carriers are collected by electrodes to generate current. Unlike silicon-based solar cells, the

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size of quantum dot materials is tunable, allowing them to adjust their absorption bandgap and thus more efficiently absorb a wide range of light, especially in the near-infrared (NIR) region.

When light irradiates the quantum dot active layer, photons are absorbed by the quantum dots, generating excitons that are separated via carrier transport. By integrating with an electron transport layer (ETL) and a hole transport layer (HTL), carrier mobility can be improved and recombination losses reduced, thereby enhancing efficiency. The size-tunable property of quantum dots enables absorption across different spectral ranges, particularly in the NIR region, providing a unique advantage in boosting the power conversion efficiency of solar cells [4].

The efficiency of CQD solar cells depends not only on the light absorption properties of the materials, but also on optimizing device structure, improving materials, and applying interface engineering to enhance carrier transport and suppress recombination. The use of multijunction architectures and stacked quantum dot layers can better utilize the solar spectrum, further improving device efficiency.

4. Research progress of quantum dot solar cells

4.1. Improvements and optimization of quantum dot materials

Over the past decade, research on quantum dot solar cells has made remarkable progress, particularly in the area of material optimization. The size, morphology, surface states, and synthesis methods of quantum dots directly affect the photovoltaic performance and stability of the cells. Therefore, the synthesis and optimization of quantum dot materials have become central to this research field. The surface states of quantum dots play a critical role in determining their optoelectronic performance. Typically, quantum dot surfaces contain numerous defects and uncoordinated atoms, which can act as recombination centers for electron-hole pairs, significantly reducing the efficiency of solar cells.

4.1.1. Surface modification techniques for quantum dots

To reduce surface defects and enhance the optoelectronic performance of quantum dots, researchers have developed various surface modification techniques. Traditional methods employ organic ligands to passivate the quantum dot surface, thereby mitigating the negative effects of surface defects on electron transport. In recent years, surface passivation and ligand exchange techniques have become major research focuses, significantly improving carrier mobility and reducing recombination losses. For example, modifying quantum dots with long-chain organic molecules such as octadecylphosphonic acid (ODPA) has been shown to effectively enhance their optoelectronic properties. In addition, inorganic passivation materials can be used to further improve the stability and carrier mobility of quantum dots.

4.1.2. Multiple Exciton Generation (MEG) in quantum dot materials

Multiple exciton generation (MEG) enables one photon to generate multiple excitons, offering a path to exceed conventional solar cell efficiency limits. This boosts energy conversion in quantum dot solar cells.

Materials like PbS, CdSe, and PbTe have shown MEG behavior, with PbS performing especially well in the near-infrared range [5]. However, challenges such as carrier recombination and energy loss still hinder practical MEG utilization. Enhancing MEG efficiency and reducing losses remain key research priorities.

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4.2. Performance enhancement of quantum dot solar cells

Advances in material synthesis have greatly enhanced the optoelectronic performance of quantum dot solar cells, with key improvements in several areas: (1) Power Conversion Efficiency (PCE): PCE has risen from below 4% to over 18%, thanks to better quantum dot materials, optimized device structures, and improved surface treatments [6]. (2) Carrier Lifetime and Mobility: Enhanced by surface passivation and multilayer designs, which reduce recombination and defects, leading to more efficient charge transport. (3) Wider Absorption Spectrum: Quantum dots' tunable sizes enable absorption across a broader range, especially in the near-infrared. Multijunction designs further boost spectral response and efficiency.

5. Challenges faced by quantum dot solar cells

As a novel photovoltaic technology, quantum dot solar cells (CQD-SCs) show tremendous application potential. However, they still face multiple challenges in practical implementation and large-scale production. These challenges are particularly pronounced in areas such as material stability, efficiency improvement, scalability of production, and environmental concerns.

5.1. Material stability issues

The stability of quantum dot materials is one of the major challenges facing CQD solar cells. Due to the high surface-to-volume ratio of quantum dots, they are more susceptible to environmental factors, such as humidity and temperature, which can lead to performance degradation. Lead-based quantum dots (e.g., PbS, PbSe) are especially prone to oxidation in the presence of moisture and oxygen, which undermines the long-term stability of the devices. To improve stability, researchers have employed surface passivation techniques to reduce defects, but achieving durable long-term performance remains an unresolved issue.

Tin-based (SnQDs) and zinc-based (ZnQDs) quantum dots are emerging as alternative materials due to their environmental friendliness and inherent stability. Although they have not yet surpassed lead-based quantum dots in terms of optoelectronic performance, technological advancements hold promise for closing this gap.

5.2. Scalability of synthesis and fabrication

Although various synthesis methods for quantum dot solar cells exist, large-scale production remains a significant challenge. Current quantum dot synthesis techniques often require high temperatures and precise reaction conditions, and the production process is typically energy-intensive, limiting their viability for industrial-scale applications. To achieve low-cost and large-scale manufacturing, researchers are exploring more accessible fabrication methods such as low-temperature solution processing, spray coating, and roll-to-roll (R2R) techniques. However, achieving consistent control over quantum dot size and maintaining stable optoelectronic performance continue to be critical barriers to scalable production.

5.3. Efficiency bottlenecks

Quantum dot solar cells achieve high efficiency in labs but face challenges in real-world use. The size of quantum dots affects both light absorption and recombination: smaller sizes enhance absorption range but can worsen carrier loss. Thus, precise size control is vital to balance absorption

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and transport. Surface defects remain a major obstacle, as they reduce charge collection efficiency by facilitating recombination. Techniques like surface passivation and multijunction structures offer some relief but are not yet sufficient to fully resolve this issue. Additionally, while multiple exciton generation (MEG) could improve efficiency, its practical application remains limited. Continued efforts to reduce surface defects and recombination losses are crucial to improving real-world performance.

5.4. Environmental and safety concerns

Although lead-based quantum dots exhibit excellent optoelectronic performance, their toxicity and environmental pollution issues significantly hinder their commercial application. Consequently, researchers have begun exploring lead-free quantum dot materials such as tin-based and zinc-based quantum dots, which reduce toxicity while still maintaining favorable optoelectronic properties. In addition, the synthesis of quantum dots often involves the use of organic solvents that may pose environmental risks. As a result, the development of green synthesis methods and recycling technologies will be a major focus of future research.

6. Future development directions of quantum dot solar cells

As a new photovoltaic technology with breakthrough optoelectronic performance, quantum dot solar cells (CQD-SCs) have achieved remarkable laboratory progress, but still face many challenges in commercial application. Future research will focus on several aspects—materials, device structure, and fabrication processes—with the goal of overcoming current bottlenecks and enabling high efficiency, large-scale production, and long-term stable operation of CQD solar cells. This section outlines the future prospects of CQD-SCs in terms of new material development, device structure optimization, and system integration.

6.1. Development of new quantum dot materials

Optimizing quantum dot materials is key to enhancing CQD solar cell performance. While PbS, CdSe, and PbTe offer excellent optoelectronic properties, their instability and lead toxicity highlight the need for environmentally friendly alternatives.

Tin-based quantum dots (SnQDs) have attracted interest for their good light absorption and low toxicity, and recent advances in synthesis and surface passivation have improved their prospects. Zinc-based quantum dots (ZnQDs) also offer decent efficiency and stability but face synthesis challenges. Meanwhile, carbon quantum dots (CQDs) stand out for their low toxicity and eco-friendliness, though their optoelectronic performance remains limited.

Future research should prioritize lead-free quantum dots with improved performance and stability to reduce environmental impact and advance CQD solar cell applications.

6.2. Structural optimization of quantum dot solar cells

The efficiency of quantum dot solar cells depends not only on the materials' optoelectronic properties but also on device architecture. Recent research emphasizes optimizing multijunction structures and interface engineering to surpass the efficiency limits of single-junction cells. By stacking quantum dots with different bandgaps, multijunction cells absorb a broader range of the solar spectrum, improving power conversion efficiency. For example, combining near-infrared-absorbing PbS with visible-absorbing CdSe broadens absorption and enhances energy utilization.

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Interface engineering further improves performance by reducing charge recombination and enhancing carrier mobility through better contact between quantum dots and transport layers (ETL/HTL) [7]. Minimizing interfacial defects and optimizing layer thickness and stacking also help reduce recombination losses and boost efficiency.

6.3. Integrated applications of quantum dot solar cells

As research advances, quantum dot solar cells are finding growing applications in fields like wearable electronics and building-integrated photovoltaics (BIPV). Their high efficiency, low-cost fabrication, and excellent flexibility make them well-suited for flexible substrates and wearable power solutions. In BIPV, they offer energy generation while integrating seamlessly into modern architecture.

CQD solar cells can also pair with photothermal technologies to create integrated optoelectronic systems, improving solar energy utilization. These systems show strong potential in areas such as commercial buildings and agricultural greenhouses.

7. Conclusion

As a novel photovoltaic technology, quantum dot solar cells (CQD-SCs) demonstrate great application potential owing to their unique optoelectronic properties, low-cost fabrication, and broad spectral absorption capability. Compared with traditional silicon-based solar cells, CQD-SCs can effectively absorb the near-infrared region of the solar spectrum, thereby improving power conversion efficiency while offering advantages in cost and flexibility.

At present, CQD-SCs still face various challenges in terms of power conversion efficiency and material optimization. Chief among these is the stability of quantum dot materials—especially maintaining performance under environmental fluctuations and long-term operation—which remains a major obstacle to wide-scale application. Although surface passivation and the development of novel lead-free materials have alleviated some issues, further improvements in material durability and long-term stability are still required.

Future developments in CQD-SCs will center on environmentally friendly materials, enhanced efficiency, and large-scale deployment. The creation of lead-free, non-toxic, high-performance quantum dot materials is key to driving sustainable development. In parallel, designing multijunction architectures and optimizing interface engineering to reduce carrier recombination and improve power conversion efficiency will remain primary research goals. On the manufacturing side, the realization of low-temperature, energy-efficient, and environmentally conscious processes is essential for reducing costs and enabling industrial-scale production.

Moreover, CQD-SCs show tremendous promise in fields, such as flexible electronics, wearable devices, and building-integrated photovoltaics (BIPV). Their flexibility and thin form factor present new possibilities for energy integration. Although current limitations in efficiency, stability, and scalability remain unresolved, continued technological advancement suggests that CQD-SCs may achieve commercial viability in the near future. These breakthroughs could not only accelerate the adoption of photovoltaic technologies but also offer novel solutions for global energy transition and climate change mitigation.

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