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Current Research on Quantum Dots for Solar Energy Conversion to Improve Photovoltaic Stability

Ngai Lau

Northeastern University of China, Shenyang, Liaoning, 110000, China

ABSTRACT
Quantum dots exhibit excellent optical properties, providing a highly promising pathway to reduce the environmental dependence of photovoltaic power generation. This article reviews the latest research progress on the integration of quantum dot materials with photovoltaic technology, with emphasis on quantum dot photoanode materials such as perovskites, cadmium sulfide, and lead sulfide. Multiple studies have demonstrated that integrating appropriate quantum dot materials into semiconductor matrices can promote efficient electron excitation and extend the absorption spectrum of photoanodes to include visible and infrared wavelengths. Notably, this expansion broadens the applicability of photovoltaic power generation under low light intensity conditions and reduces its concentration dependence . This review covers the integration of quantum dots with photovoltaics, emphasizing light absorption by photoanodes, thereby paving the way toward more efficient and widespread energy development.

KEYWORDS
Photovoltaic power generation; Quantum dot materials; Stability; Concentration dependence; Broadening solar spectrum

1 Introduction

1.1 Research Significance and Background

With technological advancement, evolving times, and population growth, increasing global energy consumption has accelerated the depletion of fossil fuels. As early as 2020, British Petroleum indicated that at current global consumption rates, proven oil reserves could be exhausted by 2050, recommending a reduction in fossil energy use. One highly promising energy source has attracted widespread attention due to its environmental friendliness—solar energy. As a novel renewable energy source, solar energy offers numerous advantages, such as abundant reserves and ubiquitous geographical availability[1]. It is also considered a permanent energy source.

The essence of photovoltaic power generation lies in utilizing the photovoltaic effect to convert solar radiation into electricity through a panel composed of interconnected solar cells. Silicon is the most widely used material for manufacturing solar cell technology; crystalline silicon technology is mature and reliable, yet the Shockley-Queisser limit indicates that the maximum conversion efficiency of single-junction solar cells under solar radiation is approximately 31% [2], restricting the development of solar cells. Therefore, scholars worldwide are exploring new semiconductor materials and alternative approaches to enhance photovoltaic conversion efficiency.

A crucial factor limiting solar cell efficiency is that only photons with sufficient energy are absorbed for power generation. Photons with energy higher than the bandgap are absorbed, while those with lower energy pass through the material, resulting in a significant portion of solar radiation remaining unutilized for electricity generation. Furthermore, the energy of electrons excited by above-bandgap photons is not fully utilized; high-energy photons generate high-energy charge carriers, also known as hot carriers, which eventually relax to a stable state. This internal thermal process within solar cells also leads to reduced efficiency[3].

Quantum dots are semiconductor crystals with nanoscale dimensions, exhibiting many excellent optoelectronic properties, such as tunable bandgaps and high molar extinction coefficients. The light absorption characteristics of quantum dots are size-dependent and can be tuned by controlling their dimensions[4]. This indicates that integrating suitable quantum dot materials into semiconductor matrices can promote efficient electron excitation. Provided the quantum dots have appropriate dimensions, the bandgap of the quantum dot layer can match photon energies within a specific range[5], making quantum dots an ideal choice for broadening the solar absorption spectrum. These materials hold promise for solution-processable manufacturing and tunable electronic properties.

Beyond tunable bandgaps, quantum dots can generate multiple excitons upon absorption of a single high-energy photon, a phenomenon known as multiple exciton generation. This effect can effectively prevent the formation of hot carriers during photovoltaic power generation, thereby reducing internal thermal processes and improving photovoltaic efficiency. Due to these characteristics, the theoretical power conversion efficiency of quantum dot solar cells is approximately 66%[6].

1.2 Research Status

Currently, some of the highest-efficiency quantum dot solar cells employ heavy metal compounds such as cadmium selenide (CdSe) and cadmium telluride (CdTe), as well as lead sulfide (PbS) and lead selenide (PbSe), because these materials exhibit excellent optical properties[7]. However, elements such as cadmium and lead are hazardous, posing risks during manufacturing and disposal. For instance, cadmium selenide is a highly carcinogenic substance. These concerns cast doubt on the long-term viability of such materials and subject related technologies to regulatory restrictions and commercial limitations in the future. Consequently, lead- and cadmium-free quantum dot solar cells have emerged, including indium phosphide (InP), zinc selenide (ZnSe), copper indium sulfide ($CuInS_2$), and silver bismuth sulfide ($AgBiS_2$). These materials exhibit lower toxicity and correspondingly reduced environmental harm [8]. However, they face challenges such as insufficient light absorption range and inadequate carrier mobility, issues that must be addressed for broader application.

Beyond material selection, quantum dot applications in photovoltaic power generation generally fall into three categories. First, quantum dots can directly serve as the core light-absorbing layer—the most central and widely applied approach in photovoltaics—primarily used in quantum dot solar cells (QDSCs). Leveraging their broad-spectral absorption characteristics, which cover the visible to near-infrared region, quantum dots can fully utilize the solar spectrum, compensating for the insufficient near-infrared absorption of traditional crystalline silicon cells and reducing spectral losses[8]; simultaneously, their quantum confinement effect enables flexible band structure tuning through size regulation, achieving energy level alignment with electron transport layers and hole transport layers to facilitate carrier separation and transport[9]. Second, quantum dots can serve as buffer layers to modify the surfaces or interfaces of conventional photovoltaic devices (crystalline silicon, bulk perovskite cells), addressing issues such as abundant interface defects, severe carrier recombination, and insufficient stability. Quantum dots can be deposited at device interfaces via vapor deposition, spin-coating, and other techniques to fill interface defects, passivate trap states, reduce carrier recombination, and enhance photoelectric conversion efficiency[10]. Third, quantum dots can be used as auxiliary layers in tandem cells. Combining the spectral absorption advantages of quantum dots with materials such as crystalline silicon and perovskites, quantum dot layers serve as auxiliary absorbing layers for bottom or top cells in tandem photovoltaic batteries, absorbing near-infrared or ultraviolet light that traditional photovoltaic materials cannot utilize, thereby further broadening the spectral absorption range and improving overall photoelectric conversion efficiency[11].

2 Theoretical Foundation of Physical Properties of Quantum Dots

2.1 Structure and Properties of Lead Chalcogenide Quantum Dots

2.1.1 Structure of Lead Chalcogenide Quantum Dots

Lead chalcogenide quantum dots belong to IV-VI group semiconductors, exhibiting a rock salt crystal structure with the Fm3m space group (face-centered cubic). Their crystal structure can be regarded as the NaCl type, wherein Pb^{2+} and S^{2-} (or Se^{2-}, Te^{2-}) ions alternately occupy face-centered cubic lattice sites, forming an octahedral coordination environment.

PbS quantum dots represent the most mainstream and widely applied quantum dots among lead chalcogenides. The lattice constant of PbS quantum dots is 5.94 Å; this relatively large lattice constant makes it difficult to find shell materials with identical crystal structures and minimal lattice mismatch. The exciton Bohr radius of PbS is approximately 18 nm, and even at relatively large sizes, PbS quantum dots remain strongly quantum-confined, with a tunable bandgap covering the near-infrared region from 800 to 2500 nm[12].

PbSe quantum dots possess an even larger exciton Bohr radius of 46 nm, with a room-temperature bandgap of merely 0.27 eV. PbTe similarly exhibits an exciton Bohr radius of approximately 46 nm and a narrow bandgap of 0.32 eV.

2.1.2 Properties of Lead Chalcogenide Quantum Dots

Lead chalcogenide quantum dots possess high dielectric constants, resulting in strong dielectric screening effects and weak Coulomb forces between electrons and holes. This characteristic facilitates the generation of free carriers upon excitation, benefiting charge extraction in photovoltaic applications.

In terms of band structure, lead chalcogenide quantum dots exhibit narrow direct bandgaps, providing favorable conditions for multiple exciton generation[13].

2.2 Structure and Properties of Perovskite Quantum Dots

2.2.1 Structure of Perovskite Quantum Dots

Perovskite quantum dots are a class of crystalline compounds with the general formula ABX_3, where the A site

accommodates larger metal or organic cations, the B site accommodates smaller cations including various divalent or multivalent metal cations, and the X site is occupied by halide anions. Different crystal phases exert significant influences on the band structure[14].

The cubic phase is stable under high-temperature and high-pressure conditions, featuring the simplest and most stable unit cell structure with excellent dielectric properties. The B site is in octahedral coordination, the A site occupies interstitial positions, and the X site is in tetrahedral coordination; common examples include $BaTiO_3$.

The orthorhombic phase possesses lower symmetry than the cubic phase, with a slightly higher density, and can transform into other more stable phases under the influence of temperature and pressure. It represents the primary phase during actual device operation; $SrTiO_3$ is a typical orthorhombic example.

The trigonal phase features ion arrangements generally consistent with those in the orthorhombic phase, but the unit cell assumes a hexahedral shape with an elongated rod-like morphology. $LaMnO_3$ is an example of the trigonal phase.

2.2.2 Properties of Perovskite Quantum Dots

The unique characteristic of perovskite quantum dots lies in their defect tolerance. Unlike conventional semiconductors, intrinsic defects in perovskite quantum dots do not readily form deep-level traps; instead, they reside near the conduction band minimum or valence band maximum, resulting in low non-radiative recombination probabilities and excellent photoluminescence quantum yields.

The bandgap tunability of perovskite quantum dots is achieved through halide composition regulation. By altering their chemical composition, the bandgap can be precisely and continuously tuned, enabling targeted optimization of solar cell efficiency[15].

2.3 Structure and Properties of Heavy-Metal-Free Quantum Dots

Heavy-metal-free quantum dots are numerous; the most common and widely applied are InP quantum dots.

2.3.1 Structure of Indium Phosphide Quantum Dots

InP quantum dots belong to typical III-V group semiconductors, exhibiting a zinc blende crystal structure with the F-43m space group. Their crystal structure can be regarded as two interpenetrating face-centered cubic sublattices.

The lattice constant of InP is 5.87 Å, with a relatively narrow bandgap of 1.35 eV and a large exciton Bohr radius of approximately 9.6 nm. The quantum confinement effect of InP is comparable to that of cadmium-containing quantum dots, though its size tunability is relatively limited, covering the visible to near-infrared region[16].

2.3.2 Properties of Indium Phosphide Quantum Dots

The special crystal structure of InP quantum dots endows them with extraordinary properties. Their exciton fine structure is determined by the combined effects of electron-hole exchange, crystal field splitting, and shape anisotropy. For zinc blende quantum dots, the exciton fine structure comprises five energy levels; the lowest state is the dark state with total angular momentum projection $F = \pm 2$, which is optically forbidden for electric dipole transitions; the next higher state is the bright state with $F = \pm 1$, allowing electric dipole transitions. The energy difference between the dark and bright states increases with decreasing size[17].

3 Research Status

Stability is enhanced through strategies such as surface ligand engineering, interface passivation, and device encapsulation.

For lead chalcogenide quantum dots, surface oxidation and moisture/oxygen erosion constitute the primary degradation mechanisms. Albaladejo-Siguan et al. adopted a novel passivation approach using a triple-cation perovskite ($Cs^+/MA^+/FA^+$) layer as a multifunctional passivation layer, which not only minimizes interface trap states but also improves energy level alignment between the quantum dot layer and the electron transport layer, enabling devices to maintain over 90% of their initial performance after 1000 hours under ambient conditions[18]. Ding et al. achieved 15.45% efficiency and enhanced stability through synergistic optimization of the three primary interfaces—quantum dot/quantum dot, quantum dot/electron transport layer, and quantum dot/hole transport layer—employing strategies including internal passivation with ultrathin perovskite shells, combined with a PMMA-graphene oxide buffer layer and a PMMA-PCBM layer for balanced electron transport[19].

Research on perovskite quantum dot stability is more extensive. Zhang et al. achieved efficiencies exceeding 19%

through consecutive surface matrix engineering[20]. Lin et al. utilized a multifunctional polymer buffer layer with magnetic endohedral metallofullerene (Nd@C_{32}) dispersed in a PMMA polymer matrix, effectively suppressing ion migration; unencapsulated devices maintained 82% of initial efficiency after continuous operation at 65°C for 2500 hours[21]. Artuk et al. employed a thin AlO_x interlayer between the perovskite absorber layer and the electron transport layer, increasing the device T_{80} lifetime from 80 hours to 530 hours, effectively blocking ion species migration and retarding the ingress of external moisture and oxygen[22].

Among heavy-metal-free quantum dots, InP and $CuInS_2$ have attracted considerable attention due to their low toxicity, yet they suffer from poor photo-oxidation stability. Surface SiO_2@TiO_2 composite passivation layers and Ga doping combined with ZnS shell encapsulation represent the primary strategies, capable of improving the photoluminescence[23].

4 Summary and Outlook

Finally, this article summarizes how several mainstream quantum dots applied in photovoltaic power generation improve photovoltaic stability and the methods employed to achieve such improvements. Quantum dots hold tremendous potential not only in the photovoltaic field but also in other domains. The incorporation of quantum dots enables humanity to better utilize solar energy, amplify the contribution of solar radiation to human society, improve the conversion rate of solar energy into electricity, and promote human development.

References

[1] Sunil Kumar, Niranjan Patra, Ismail Hossain, Abhinay Thakur, T. Jaseetharan, Navinchandra Gopal Shimpi. Exponential developments of quantum dots ecosystem for solar energy conversion and photocatalytic reactions: From photoanode design to renewable energy applications [J]. Materials Research Bulletin, 2025, 184: 1.

[2] M. Green, Y. Hishikawa, E. Dunlop, D. Levi, J. Hohl-Ebinger, M. Yoshita and A. Ho-Baillie, "Solar cell efficiency tables (version 53)", Prog. Photovolt. Res. Appl., vol. 27, pp. 3-12, November 2018.

[3] Omar López-Rojas, Jesús García Guzmán. A review on quantum dot solar cells: properties, materials, synthesis and devices [J]. 2019 IEEE International Conference on Engineering Veracruz (ICEV).

[4] Sunil Kumar, Niranjan Patra, Ismail Hossain, Abhinay Thakur, T. Jaseetharan, Navinchandra Gopal Shimpi. Exponential developments of quantum dots ecosystem for solar energy conversion and photocatalytic reactions: From photoanode design to renewable energy applications [J]. Materials Research Bulletin, 2025, 184: 2.

[5] Omar López-Rojas, Jesús García Guzmán. A review on quantum dot solar cells: properties, materials, synthesis and devices [J]. 2019 IEEE International Conference on Engineering Veracruz (ICEV).

[6] Omar López-Rojas, Jesús García Guzmán. A review on quantum dot solar cells: properties, materials, synthesis and devices [J]. 2019 IEEE International Conference on Engineering Veracruz (ICEV).

[7] Quantum Dots and Next-Gen Solar Cells Evaluating the Physics and Sustainability Potential of Emerging Photovoltaics. (n.d.).

[8] Sunil Kumar, Niranjan Patra, Ismail Hossain, Abhinay Thakur, T. Jaseetharan, Navinchandra Gopal Shimpi. Exponential developments of quantum dots ecosystem for solar energy conversion and photocatalytic reactions: From photoanode design to renewable energy applications [J]. Materials Research Bulletin, 2025, 184: 4.

[9] Chia-Hao Marcus Chuang(2016). Toward Efficient and Stable Quantum Dot Solar Cells: Design and Characterization. MASSACHUSETTS INSTITUTE OF TECHNOLOGY. http://hdl.handle.net/1721.1/104105.

[10] André F. V. Fonseca, Guilherme M. Germano, Lucas Scalon, Charles A. N. de Almeida, Alvaro C. C. Barra, Douglas S. Ribeiro, Zeno C. Brandão, Francisco C. Marques, Iván Mora-Seró, Ana F. Nogueira. CdS quantum dot interlayer engineering for enhanced SnO_2/perovskite interfaces in solar cells [J]. Materials Today Chemistry, 2025, 50: 2.

[11] André F. V. Fonseca, Guilherme M. Germano, Lucas Scalon, Charles A. N. de Almeida, Alvaro C. C. Barra, Douglas S. Ribeiro, Zeno C. Brandão, Francisco C. Marques, Iván Mora-Seró, Ana F. Nogueira. CdS quantum dot interlayer engineering for enhanced SnO_2/perovskite interfaces in solar cells [J]. Materials Today Chemistry, 2025, 50: 2.

[12] Machut, P., Antonini, A. K., Rivaux, C., Gromova, M., Kaur, H., Ling, W. L., ... Reiss, P. (2024). Continuous flow synthesis of PbS/CdS quantum dots using substituted thioureas. Nano Research, 17(12), 10677–10684.

[13] Liu Chang-Ju, Lu Min, Su Wei-An, Dong Tai-Yuan, & Shen Wen-Zhong. (2018). Recent advance in multiple exciton generation in semiconductor nanocrystals. ACTA PHYSICA SINICA, 67(2), 027302.

[14] Xu, L., Yuan, S., Zeng, H., & Song, J. (2019). A comprehensive review of doping in perovskite nanocrystals/quantum dots: evolution of structure, electronics, optics, and light-emitting diodes. Materials Today Nano, 6, 100036.

[15] Lei, H., Singh, U., Ji, F., Lin, T., Kobera, L., Shang, Y., ... Abbrent, S. (2024). Palladium-Doped $Cs_2AgBiBr_6$ with 1300 nm Near-Infrared Photoresponse. Small, 20(49).

[16] Peixian Chen. (2023). Study on the optical properties of indium phosphide quantum dots. (Doctoral dissertation, Hubei University).

[17] Brodu, A., Ballottin, M. V., Buhot, J., van Harten, E. J., Dupont, D., La Porta, A., ... Zwiller, V. (2018). Exciton Fine Structure and Lattice Dynamics in InP/ZnSe Core/Shell Quantum Dots. ACS Photonics, 5(8), 3353–3362.

[18] Albaladejo-Siguan et al. Triple-cation perovskite passivation for PbS QDSCs. Micromachines, 2026, 17(4): 474.

[19] Ding et al. Interface engineering for 15.45% PbS QDSCs. Micromachines, 2026, 17(4): 474.

[20] Zhang et al. Consecutive surface matrix engineering for >19% PQDSCs. Energy & Environmental Science, 2025, 18: 8964-8976.

[21] Lin et al. Nd@C_{32}-PMMA buffer layer for ion migration suppression. Electronics, 2025, 14(22): 4428.

[22] Artuk et al. AlO_x interlayer for operational stability. Electronics, 2025, 14(22): 4428.

[23] Tang et al. Improvement of photoluminescence efficiency and photoelectricity performances of InP quantum dots through the passivation of surface defects. Functional Materials Letters, 2025, 18.