Proceedings of the 4th International Conference on Computing Innovation and Applied Physics
DOI: 10.54254/2753-8818/79/2025.20107

Research on the Improvement of Solar Cell Performance by Low-Dimensional Semiconductor Nanomaterials

Zijian Xu[1,a,*]

[1]*South China University of Technology, Guangzhou, 510000, China*
a. 19905241515@163.com
**corresponding author*

Abstract: With the depletion of non-renewable resources, renewable energy sources like solar energy and hydrogen will play an important role in the future. Efficient and stable utilization of these energy sources has become a primary focus of research. Low-dimensional semiconductor nanomaterials, including quantum dots, nanowires, and thin films, exhibit unique properties due to their size being close to or smaller than certain characteristic lengths of the material. As the dimensionality decreases, quantum effects become more pronounced, leading to significant changes in the material's electronic, optical, and thermal properties. This paper focuses on the improvement of the performance of various types of solar cells through the unique properties of low-dimensional semiconductor nanomaterials while discussing the challenges in their application. This study shows that low-dimensional nanostructured semiconductor materials can enhance the performance of solar cells in energy conversion efficiency, stability and lifespan, providing new directions and methods for future solar technology development.

Keywords: Low-dimensional semiconductor nanomaterials, power conversion efficiency, stability, solar cells

1. Introduction

An intense research on renewable energy and storage technologies is driven by the growing need for conversion and storage, caused by environmental concerns about global warming and fossil fuel depletion [1]. The lithium-ion batteries widely used in daily life are still limited by raw material shortages and high costs. They also have limitations such as poor high-temperature performance, long charging times, and limited cycle life. Although future batteries, such as solar cells, hydrogen fuel cells, and sodium-ion batteries, currently have drawbacks like low energy conversion efficiency, low energy density, poor stability, and safety concerns, their abundant raw materials and environmentally friendly characteristics give them unlimited potential for future energy storage technologies.

Low-dimensional semiconductor nanomaterials, which are divided into zero-dimensional (quantum dots), one-dimensional (nanotubes, nanowires and nanofibers), and two-dimensional (nanofilms) materials. They have strong prospects in future energy storage due to their low processing costs, offering a wide range of attractive quantum mechanical properties, particularly in optoelectronic performance, which significantly outperform bulk materials [2]. Recent breakthroughs have been made in solar cell power conversion efficiency, battery stability under radiation and high temperatures, long-life charge generation through photocatalytic hydrogen production, and

© 2025 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2753-8818/79/2025.20107

fabrication of highly efficient catalytic electrodes and films [3, 4]. This review focuses on summarizing and comparing the applications of low-dimensional nanosemiconductor materials in various types of solar cells, as well as the strategies employed for enhancing performance in these materials. It also analyzes the issues currently encountered in the application of low-dimensional nanosemiconductor materials, summarizes existing solutions, and proposes future directions. This study offers researchers deeper insights into new thoughts and improvement strategies in the limited field.

2. Solar Cells

Currently, over 90% of the global photovoltaic market relies on crystalline silicon solar cells, with a Power Conversion Efficiency (PCE) of 26.7% [5]. Through the evolution of device structures, the efficiency continues to improve [6]. However, the high melting point of silicon makes its manufacturing challenging, and finding alternatives has been a key area of research. Notable alternatives include perovskite solar cells, organic solar cells and dye-sensitized solar cells. The use of low-dimensional nanomaterial semiconductors offers methods to enhance their PCE and improve their stability under harsh conditions such as solar radiation and high temperatures.

2.1. Improvement of Power Conversion Efficiency

Many studies aimed at improving PCE of solar cells make use of zero-dimensional quantum dots. These quantum dots, with sizes smaller than or comparable to their Bohr radius, exhibit quantum confinement effects, which result in tunable band gaps and confined charge carrier behavior based on particle size [7]. One way to enhance PCE using these quantum confinement effects is by improving the material's absorption of solar radiation at higher wavelengths. For organic materials, which are narrow bandgap materials, incorporating quantum dots of different sizes (with varying band gaps) can further broaden the absorption range of the solar spectrum, thus enhancing the PCE [8].

Metal halide perovskite quantum dots not only exhibit the traditional quantum confinement effects of quantum dots, but also benefit from the long exciton lifetimes and defect tolerance inherent in perovskite materials. Under ideal conditions, the power conversion efficiency (PCE) of a single-junction semiconductor solar cell is limited by the theoretical Shockley-Queisser limit. To overcome this limit, multi-junction solar cell structures have been widely studied. Similar to using quantum dots of different sizes, multi-junction structures stack multiple sub-cells with different band gaps. This allows for the absorption of a broader range of solar radiation wavelengths, particularly the infrared portion of the solar spectrum, while reducing thermal losses associated with the absorption of high-energy photons. By utilizing III-V compound semiconductor materials in tandem configurations, the PCE has reached 47.6%, significantly surpassing the single-junction limit of 37% [9, 10]. This represents a promising new approach to improving the PCE of solar cells.

Stacking multiple layers of materials can significantly improve PCE, but it imposes higher standards on the fabrication due to precision and compatibility requirements. The inevitable surface defects of each material may lead to voltage losses, which could limit the efficiency of the solar cells. Whether this will establish a new upper limit for PCE remains an area for further research.

Some two-dimensional semiconductor nanomaterials, such as transition metal dichalcogenides, carbides, nitrides, and black phosphorus, can effectively tune their electronic structures by adjusting the number of layers and dimensions, thereby altering their bandgap width and energy level alignment. Similar to the different bandgap materials in tandem solar cells, these materials offer excellent compatibility, which could reduce the impact of fabrication precision and interlayer material matching, potentially leading to a breakthrough in further enhancing the PCE of solar cells.

DOI: 10.54254/2753-8818/79/2025.20107

The working principle of dye-sensitized solar cells (DSSCs) differs from other third-generation solar cells. In DSSCs, the semiconductor primarily serves as a charge transport medium, while photons are provided by the photosensitive dye. Electrons are injected into the conduction band of nanoporous materials and then reach the counter electrode, completing the circuit. In DSSCs, the focus of low-dimensional nanomaterials differs. For example, semiconductor nanoparticles enhance dye adsorption, improving long-term power generation. However, due to the presence of grain boundaries, zero-dimensional nanoparticles cause higher recombination losses during electron transport. To mitigate this, one-dimensional nanorods are often added to reduce recombination and compensate for the limitations of single low-dimensional semiconductor nanomaterials. Similarly, the power conversion efficiency (PCE) can be improved by incorporating quantum dots to increase solar light absorption, a strategy similar to those used in perovskite and organic solar cells [11].

2.2. Improvement of Stability of Solar Cell

Despite significant improvements in the power conversion efficiency (PCE) of solar cells in recent years, their thermal and chemical instability when exposed to solar radiation, moisture, and oxygen has become another major limitation to their application. This instability is partly due to the degradation of organic materials in perovskite solar cells, organic solar cells, and dye-sensitized solar cells, which can lead to irreversible performance loss [10, 12].

To address this exposure-induced degradation, several strategies have been proposed. One approach is to design protective mechanisms, such as coatings, to cover the surface of the solar cells. Additionally, low-dimensional nanomaterials, can take advantage of favorable surface energy properties. Some semiconductor materials can control the shape and size of one-dimensional nanowires and two-dimensional nanofilms by adjusting surface energy, controlling the growth environment, and selecting appropriate catalysts. At the same time, these methods ensure the thickness and uniformity of the synthesized low-dimensional nanosemiconductor materials, making them well-suited for adhesion to the surface of solar cells and providing a certain degree of protection against moisture and oxygen. Moreover, by selecting semiconductors with a wide band gap, these materials can absorb all Ultraviolet (UV) radiation and prevent it from reaching the organic material layer. Wide bandgap semiconductor materials generally have good reflective properties, so they not only absorb UV light but also reduce reflection losses. Experiments have shown that the reduction in reflection losses increases photon absorption in the organic layer, leading to a certain improvement in PCE [8].

Internally, degradation of perovskite solar cells is primarily manifested in the impact on the interface between the donor and acceptor (D/A) interface. Under the influence of adverse environmental factors, the morphology of the donor and acceptor layers in perovskite solar cells is affected, leading to microscopic separation. This separation causes the interface scale to exceed the exciton diffusion length, preventing some excitons from diffusing efficiently, which reduces the operational stability of the cell. At the same time, defects at the D/A interface cause carrier recombination, further compromising cell stability.

Effectively regulating the D/A interface internally and constructing a stabilized regulation mechanism such as modifying the D/A interface with low-dimensional semiconductor nanomaterials that have excellent charge carrier mobility and high thermal stability can improve interface stability, thereby enhancing the overall stability of the cell [13]. In addition to the environmental factors that cause internal thermal expansion, light, and chemical decomposition in the battery, the perovskite thin film itself exhibits lattice distortion, grain boundary defects, and the incomplete pairing or absence of metal halide ions and halogen atoms during the synthesis process, all of which reduce the stability of the battery during charge transport and cause ion migration. Its instability also makes it prone to erosion by organic hole transport materials and metal electrodes. Doping the perovskite thin

DOI: 10.54254/2753-8818/79/2025.20107

film with two-dimensional semiconductor nanomaterials can enable fast exciton dissociation and charge carrier transfer [14]. At the same time, artificially introducing defects into the two-dimensional semiconductor nanomaterials to create new vacancies enhances charge extraction ability and expands the range of improved stability.

3. The Defects and the Prospects

Although low-dimensional nanosemiconductor materials have broad applications in batteries due to their unique optoelectronic properties, they also suffer from structural defects. One of the most critical drawbacks affecting the efficiency and stability of batteries is charge recombination. Charge recombination can generally be divided into radiative recombination and non-radiative recombination. The unique properties and applications of low-dimensional nanosemiconductor materials exacerbate these recombination issues. For example, the large surface area and abundance of surface atoms in low-dimensional nanosemiconductors make their surfaces ideal sites for charge recombination. In addition, for multilayer and heterostructured low-dimensional nanosemiconductor materials, the mismatched energy bands at the interfaces can further accelerate electron-hole recombination. Moreover, low-dimensional nanosemiconductor materials used in high-power batteries can cause fast recombination of electrons and holes, transferring energy to another electron-hole pair, which then annihilates. These recombination processes often result in energy loss, preventing it from being converted in the desired direction.

Some solutions have already been proposed to address the energy loss caused by charge recombination. These include introducing an insulating barrier layer at the D/A interface to separate charge carriers,constructing a ternary structure to improve exciton dissociation efficiency and reduce recombination losses , selecting appropriate n-type and p-type electron transport layers to enhance charge carrier extraction and minimize recombination, or developing efficient interconnection layers to to suppress charge recombination [15, 16, 17, 18]. Additionally, directly modifying the surface of the material to reduce the exciton binding energy to mitigate the impact of charge recombination on efficiency in low-dimensional semiconductor nanomaterials [2].

Although these methods have been proven effective in suppressing charge recombination, most of them still rely on introducing new materials or replacing the transport layers with higher-performance ones, which may be limited by processing and material availability. The key to solving charge recombination is to increase the volume occupied by photo-induced charges. Non-layered, two-dimensional structures provide a direction for spatial separation of multiple charges. Recent research on two-dimensional quantum shells has reported the longest optical gain lifetimes. In the future, new two-dimensional models, or new model constructions combining the advantages of multiple dimensions, may be the key to overcoming structural defects in low-dimensional semiconductor nanomaterials.

4. Conclusion

This article reviews the application of low-dimensional semiconductor nanomaterials in solar cells, highlighting how their unique quantum effects enhance the photovoltaic performance, conversion efficiency, and overall stability of solar cells. By adjusting their size, the band structure can be tuned to absorb a wider range of solar wavelengths. Additionally, the modulation of the band structure allows for better energy level matching with adjacent interfaces, which improves charge extraction and transfer while reducing energy losses due to charge recombination. When used alone, semiconductor materials with a wide band gap can form one-dimensional and two-dimensional nanostructures that effectively cover the surface of organic films and perovskite thin films in solar cells. These materials not only absorb strong ultraviolet light but also prevent ion migration between

DOI: 10.54254/2753-8818/79/2025.20107

layers, significantly enhancing the stability of the solar cells. The high electron mobility of low-dimensional semiconductor nanomaterials also makes them suitable as interface modifiers to compensate for defects at the interfaces, facilitating the rapid dissociation of excitons and the transfer of charge carriers.

Although this paper mainly summarizes and compares the applications of low-dimensional nanosemiconductor materials in different types of solar cells, it does not analyze the specific properties of materials, such as organic, inorganic, or organic-inorganic composite materials, in terms of their respective characteristics and focus when enhancing solar cell performance.

Looking ahead, the properties of a low-dimensional nanomaterial semiconductor are limited, making it unsuitable for complex solar cell applications. To overcome these challenges, future research is needed to break through the limitations of layered structures, further explore spatial dimensions to achieve a balance between exciton separation and good quantum effects, and use nanosemiconductor materials of multiple dimensions to complement each other's performance. This approach could provide a path forward for low-dimensional semiconductor nanomaterials.

References

[1] *Sikiru, S., Oladosu, T. L., et al. (2023). Advance and Prospect of Carbon Quantum Dots Synthesis for Energy Conversion and Storage Application: A Comprehensive Review. Journal of Energy Storage, 60, 106556.*

[2] *Cassidy, J., Harankahage, D., Porotnikov, D., Malko, A. V., Zamkov, M. (2022). Colloidal Quantum Shells: An Emerging 2D Semiconductor for Energy Applications. ACS Energy Letters. 7 (3), 1202–1213.*

[3] *Kosco, J., Gonzalez-Carrero, S., et al. (2022). Generation of Long-Lived Charges in Organic Semiconductor Heterojunction Nanoparticles for Efficient Photocatalytic Hydrogen Evolution. Nat Energy, 7 (4), 340–351.*

[4] *Shah, M. A. K. Y., Lu, Y., et al. (2023). Semiconductor-Membrane Fuel Cell (SMFC) for Renewable Energy Technology. Renewable and Sustainable Energy Reviews, 185, 113639.*

[5] *Janjua, M. R. S. A., Shafiq, Z., et al. (2024). Recent Developments and Future Challenges for Perovskite Solar Cells: Physical Insights to Improve PCE. Brazilian Journal of Physics, 54 (4), 134.*

[6] *Baoquan, S., Zhuoying, C., Xinbo, Y. (2021). Hybrid Photovoltaics and Semiconductors. physica status solidi (RRL)-Rapid Research Letters, 15 (12), 2100393.*

[7] *Mengmeng, H., Shanshan, D., et al. (2024). Perovskite Quantum Dot Solar Cells: Current Status and Future Outlook: Focus Review. ACS Energy Letters, 9 (1), 308–322.*

[8] *Ram, K. S., Singh, J. (2019). Highly Efficient and Stable Solar Cells with Hybrid of Nanostructures and Bulk Heterojunction Organic Semiconductors. Advcd Theory and Sims, 2 (6), 1900030.*

[9] *Juncheng, Z., Kunyuan, L. (2024). Tandem Solar Cells Based on Quantum Dots. Mater. Chem. Front, 8 (7), 1792–1807.*

[10] *Jiang, X., Shucheng, Q., et al. (2024). Isomeric Diammonium Passivation for Perovskite–Organic Tandem Solar Cells. Nature, 635 (8040), 860–866.*

[11] *Rao, A. A., Joseph, A. P., Balachandran, M. (2024). An Outlook on Zero-Dimensional Nanocarbons as Components of DSSC. Biomass Conv. Bioref, 14 (8), 9023–9045.*

[12] *Lana, G. M., Bello, I. T., et al. (2024). One-Dimensional TiO_2 Nanocomposite-Based Photoanode for Dye-Sensitized Solar Cells: A Review. Solar Energy, 279, 112850.*

[13] *Feng, G., Weihua, H., Ziying, Z., et al. (2023). The Construction of a Three-Dimensional Donor/Acceptor Interface Based on a Bilayered Titanium Dioxide Nanorod Array-Flower for Perovskite Solar Cells. Nanoscale, 15 (2), 490–496.*

[14] *Qingwei, Z., Jialong, D., Yanyan, D., Qunwei, T. (2022). Review on Engineering Two-Dimensional Nanomaterials for Promoting Efficiency and Stability of Perovskite Solar Cells. Journal of Energy Chemistry, 68, 154–175.*

[15] *Tao, Z., Holmes, R. J. (2018). Overcoming the Trade-off between Exciton Dissociation and Charge Recombination in Organic Photovoltaic Cells. Applied Physics Letters, 113 (14), 143302.*

[16] *Cui, X., Ran, G., et al. (2024). Enabling Low Nonradiative Recombination Losses in Organic Solar Cells by Efficient Exciton Dissociation. Advanced Functional Materials, 34 (28), 2400219.*

[17] *Ling, Q., Dai, Q., et al. (2023). Influence of the Charge Transport Layers on Charge Extraction and Interface Recombination in Quasi-Two-Dimensional Perovskite Solar Cells. Journal of Physics: Condensed Matter, 35 (36), 365001.*

DOI: 10.54254/2753-8818/79/2025.20107

[18] Xuning, Z., Shiqing, B., et al. (2017). Temperature-Dependent Charge Transport in Solution-Processed Perovskite Solar Cells with Tunable Trap Concentration and Charge Recombination. Journal of Materials Chemistry C, 5 (36), 9376–9382.