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Application of nanomaterials in solar cell

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Abstract. This paper explores the application of nanomaterials in solar cells, emphasizing the urgent need for renewable energy due to fossil fuel depletion and rising energy demands. It categorizes solar cells into three generations: silicon-based, semiconductor compounds, and novel nanomaterials. The third generation, including perovskite, nanowires, dye-sensitized, and quantum dot solar cells, shows significant potential for enhanced efficiency and reduced costs. Perovskite cells achieve high efficiency but face stability and environmental challenges. Nanowire cells offer material reduction and improved absorption but have lower efficiency. Dye-sensitized cells have advanced in stability and are promising for portable applications. Quantum dot cells benefit from core/shell structures and innovative materials. The paper concludes that the future of nanomaterial solar cells hinges on further improving efficiency, durability, and economic viability. Emphasis is placed on optimizing material structures, enhancing longevity under environmental conditions, innovating manufacturing processes, and expanding applications in diverse markets. The development of environmentally friendly nanomaterials is also crucial for sustainable energy solutions. The broad potential of these advanced solar cells promises significant advancements in renewable energy technologies.

1 Introduction

With the development of society and the advancement of modern industry and technology, the world is facing the situation of gradual depletion of fossil energy sources. And the global demand for energy continues to increase, which leads to the gradual emergence of energy crisis around the world. In order to meet this challenge, the development of renewable energy sources has become crucial, including hydro, wind, solar energy and so on. Among these renewable energy sources, solar energy stands out due to its low cost, low carbon emission, accessibility, and abundance of resources. Therefore, it is predicted to be the major renewable energy source in the future [1].

With in-depth research, many types of solar cells have been invented, which can be generally categorized into three generations on the basic of its materials. The first generation is silicon crystalline solar cells, whose main materials are monocrystalline silicon and polycrystalline silicon. Currently, the technology has been very mature and widely used, but there are disadvantages such as high raw material requirements, high price and complex

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process. The second generation is semiconductor compound solar cells. Its synthetic elements mainly include III-V compounds such as gallium arsenide, selenium phosphide and so on. These materials are mostly toxic and harmful, so its safety and environmental protection is difficult to promise. The third generation is made of new nanomaterials, including perovskite solar cells (PSCs), nanowire solar cells (NWSCs), dye-sensitized solar cells (DSSCs) and quantum dot solar cells (QDSCs). Its development time is shorter than others, but its excellent photoelectric conversion efficiency (PCE) has been initially shown.

When the size of the particles is reduced to the nanometer scale (1-100 nm), it will lead to new features in the acoustic, optical, electrical, magnetic, and thermal properties.And because of this characteristic, nanomaterials have gained wide attention and applications in various fields.Currently the technology of silicon crystal solar cells as well as thin film solar cells have already developed mature. In order to make a breakthrough in this direction, it is necessary to introduce nano-materials with new characteristics, such as perovskite, quantum dots and others.

2 Solar cells with nanomaterials

2.1 Perovskite solar cell

Perovskite materials are one of the hot research topics in the field of photovoltaics nowadays because of its superb characteristics, such as high optical absorption coefficient, narrow bandgap, defect-resistant, long minority carrier lifetime and diffusion length, balanced charge carrier transport and low exciton binding energy. Since the development of perovskite solar cell was proposed in 2009, the PCE of single junction PSCs has reached 25.7%, while the PCE of solar cell with perovskite and silicon crystals in tandem has reached 29.8% [2]. Its performance is already comparable to that of commercial silicon crystalline solar cells, with lower cost and broader development potential.

Usually the main structure of PSCs consists of hole transport layer, photosensitive layer, electron transport layer, and two contact, as shown in Fig 1a. The photosensitive layers made of perovskite is the heart of the cell and is used to absorb sunlight.The structure of perovskite materials is generally ABX_3-type cubic structure, which A is cation, B is metal ion, and X is halogen, as shown in Fig 1b.

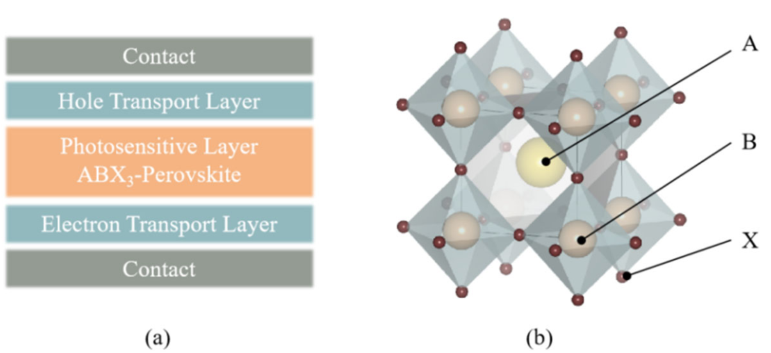

Fig. 1. (a) Structure of PSCs. (b) ABX_3 crystal structure. (Photo/Picture credit: Original)

Due to the energy band properties of its structure, the perovskite material can be modified and optimized by replacing different atoms. For example, it is possible to change the solar spectral range absorbed by the material.This flexibility allows the perovskite material to be used in combination with another absorber material with a different bandgap, enhancing the cell's PCE. In 2023, the PCE of perovskite and Si tandem materials further improves to 28.6%, which far exceeds the average PCE of 22%-24% of mainstream SiC solar cells [3].

The major challenges obstructing commercialization of perovskite solar cells are cycling stability and environmental protection. Kymakis [4] claims that the Stability of PSCs for long-term operation under real work environment is primarily affected by heat and moisture. Perovskite materials become easily degraded by long-term light exposure due to the existence of ultraviolet radiation, water, thermal stresses, and electrochemical reactions on the surface. Degradation can be reduced to enhance stability through interfacial engineering and compositional modification strategies, such as site substitution in the perovskite lattice, doping in the charge transport layer, and a variety of passivation methods using polymers and small molecules materials.

2.2 Nanowire solar cell

Semiconductor nanowire is a kind of high-aspect-ratio structure material with two-dimensional lengths ranging from a few nanometers to a few hundred nanometers, which are promising for applications in numerous fields. The best property of semiconductor nanowire materials compared to conventional flat or thin film solar cells is their light absorption properties dependent on the binding structure, which gives them light interaction properties. Nanowire materials can reduce its production cost and material usage on the one hand, and on the other hand, they also have the potential advantage of reducing the lifetime of minority carriers and lowering the optical reflectivity. However, currently the biggest problem limiting nanowire solar cells is its low PCE, which can be improved from the optimization of single nanowire and nanowire array.

There are two main methods of nanowire synthesis: 'top-down' and 'bottom-up', and two types of configurations: axial and radial, as shown in Fig 2. It can be optimized by means of photon management of single nanowires, such as anti-reflective coatings, configuration of diffraction gratings, and plasma dielectric compartments. Emanuele Bochicchio and his colleagues conducted a research on a specific type of microlens that has the ability to concentrate light on a small portion of the nanowires in an arrayed InP nanowire solar cell. This ultimately increases the short-circuit current of the relatively short nanowires, thereby reducing the amount of expensive semiconductor material used.

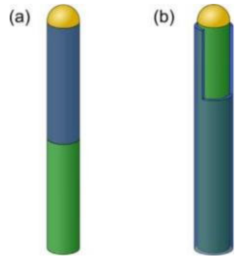

Fig. 2. Schematic structure of nanowire heterojunction [6].

Nanowire solar cells mainly utilize vertically oriented arrays of nanowires to absorb solar light. This structure enhances light absorption, especially for direct bandgap materials such as group III-V materials, which achieve efficient close bandgap light absorption at low material dosages. Nanowire's morphology, diameter, length, array spacing, and symmetry can be adjusted to optimize the light absorption properties. Xin Yan et al. [7] used non-uniformly distributed GaAs nanowire array to make solar cells in their studies and finally obtained an ideal efficiency of 34.3%, which is 1.1% higher than cells of the uniformly distributed GaAs nanowire array.

2.3 Dye-sensitized Solar Cells

Basic architecture for dye-sensitized solar cells (DSSCs) includes transparent conductives oxide glass electrode, a titanium dioxide photoanode loaded with dye, a counter electrode coated with catalyst, and a redox mediator-containing electrolyte (Figure 3). The working principle is that dye molecules absorb photons to excite electrons, which are injected into the titanium dioxide conduction band, move through an outer circuit to the opposing electrode, produce current, and the redox agent in the electrolyte restores the dye molecules to complete the charge cycle.

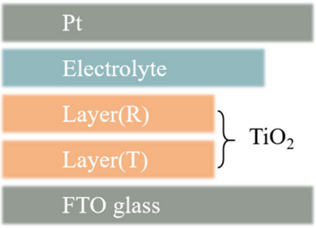

Fig. 3. Structure of DSSC. (Photo/Picture credit: Original)

In recent years, DSSC has made significant progress in many aspects, including the development of new cobalt and copper-based redox mediators, which have shown higher photoelectric conversion efficiency and better chemical stability. For example, with an electrolyte using cobalt complexes, DSSC achieved over 14% photoelectric conversion efficiency under full illumination. In addition, to address the problem of liquid electrolyte leakage, researchers have developed solid-state hole conductors, such as copper-based redox pairs, which further improve the stability and efficiency of DSSCs [8].

In terms of photoanode materials, researchers have improved electron transport efficiency and reduced electrolyte diffusion resistance by adjusting the size and morphology of TiO_2 nanoparticles. Using TiO_2 nanoparticles of different sizes and optimizing their porosity, higher short-circuit current density was achieved in cobalt redox electrolytes.

For example, the research team EPFL (Swiss Federal Institute of Technology) optimized TiO_2 nanoparticle porosity for various sizes, thereby achieving higher short-circuit current density in cobalt redox electrolytes. Through this method, they successfully improved the overall performance of DSSCs [9].

In addition, using inkjet printing technology to quickly dye-sensitize TiO_2 photoanodes not only accelerates the dye adsorption process but also precisely controls the dye distribution, generating colorful patterns and improving the aesthetics and application potential of DSSCs.

For example, the DSSCs prepared by the EPFL team using inkjet printing technology achieved a combination of artistry and functionality in design, making them not only efficient in power generation but also applicable as decorative materials for building windows and facades. Such applications not only expand the market for DSSCs but also demonstrate their broad potential in modern architecture [10].

2.4 Quantum Dot Solar Cells

Quantum dot solar cell (QDSC) use semiconductor nanocrystals, exhibit distinctive optical and electronic properties because of quantum confinement effects. The typical structure of QDSCs includes a porous structure sensitized with quantum dots wide-bandgap semiconductor photoanode, a redox couple-containing electrolyte, and counter electrodes. When quantum dots absorb photons, electrons in the valence band are elevated to the conduction band. The energized electrons are introduced into TiO_2's conduction band and move through an external circuit, generating photocurrent. Oxidized quantum dots are restored by the redox couple within the electrolyte, completing the charge cycle [11].

Recent studies have achieved substantial advancements in improving the performance and stability of QDSCs. To address surface defects of high density in quantum dots, researchers have developed core/shell quantum dots. This structure passivates the surface by coating the core quantum dots with shells of different materials, reducing surface defects and enhancing optical and electronic properties. Core/shell quantum dots have been shown to improve carrier separation, accelerate carrier transfer, and reduce exciton recombination losses [12].

Researchers have also improved QDSC efficiency by developing new material combinations and fabrication methods. For example, redox mediators containing cobalt and copper have shown high photoelectric conversion efficiency and chemical stability. At the same time, using inkjet printing technology to quickly sensitize TiO_2 photoanodes not only accelerates the dye adsorption process but also allows precise control of dye distribution, generating colorful patterns and improving the aesthetics and application potential of the cells [13].

To optimize electron and hole transport efficiency, researchers introduced alloy layers at the core/shell interface. This method can reduce lattice mismatch, enhance charge injection rates, and reduce non-radiative recombination. These improvements have significantly enhanced the performance and stability of QDSCs.

3 Conclusion

To address the global energy crisis, renewable energy sources have received much attention, and solar energy stands out among them due to its excellent characteristics of low cost, low carbon emissions, easy accessibility, and abundant resources. This article introduces several new types of nanomaterial-based solar cells, among which perovskite solar cells have achieved high energy conversion efficiency, but issues with material stability and cell cycle need to be overcome. Nanowire solar cells can improve efficiency while reducing material usage and significantly lowering costs. The development of dye-sensitized photovoltaic technology shows broad application prospects in portable electronic devices, IoT devices, and indoor photovoltaic applications. Quantum dot solar cells have made significant progress by developing core/shell structures to reduce surface defects, introducing new materials and manufacturing methods to improve efficiency, optimizing interface engineering for charge transfer, and using new catalysts to enhance stability and performance.

New nanomaterial-based cells have great potential in the future, with key areas including:

(1) Further improving photoelectric conversion efficiency by optimizing the structure and composition of nanomaterials, such as developing multilayer core/shell structures and heterojunction nanomaterials for more efficient carrier separation and transport.

(2) Researching more durable nanomaterials to cope with long-term illumination and environmental changes, thereby improving the lifespan of the cells.

(3) Innovating manufacturing processes and material alternatives, such as using Affordable, high-efficiency catalysts made from non-precious metals, to reduce the costs and make new nanomaterial-based cells more economically competitive.

(4) Expanding the application of new nanomaterial-based cells in portable electronic devices, IoT devices, and wearable devices, leveraging their high efficiency, lightweight, and flexibility to meet diverse market demands.

(5) Developing environmentally friendly nanomaterials to reduce the use of toxic elements and improve material recyclability, promoting the development of green energy.

Overall, the future development of new nanomaterial-based cells holds broad prospects, continually making breakthroughs in energy conversion efficiency, stability, cost, and application diversity, driving the advancement and popularization of renewable energy technologies.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

References

1. D. Feldman, K. Dummit, J. Zuboy, and R. Margolis, Spring 2023 Solar Industry Update.
2. Perovskite Solar Cells (2024, May 31). Energy.Gov. https://www.energy.gov/eere/solar/perovskite-solar-cells
3. Oxford PV sets new solar cell world record (2 July 2024). https://www.oxfordpv.com/news/oxford-pv-sets-new-solar-cell-world-record
4. E. Kymakis, Interfacial Engineering of Perovskite Solar Cells for Improved Performance and Stability. Advanced Materials Interfaces. **5**(22), 1801595 (2018).
5. M. C. Beard, J. M. Luther and A. J. Nozik, The promise and challenge of nanostructured solar cells. Nature Nanotechnology. **9**(12), 951–954 (2014).
6. G. Otnes and M. T. Borgström, Towards high efficiency nanowire solar cells. Nano Today **12**, 31 (2017).
7. X. Yan, Y. Liu, T. Fu, Y. Li, X. Zhang, and X. Ren, Inverse design of GaAs nanowire array solar cell structures with nonuniform diameters. Optics Communications. **536**, 129374 (2023).
8. F. Bella, S. Galliano, C. Gerbaldi, and G. Viscardi, Cobalt-Based Electrolytes for Dye-Sensitized Solar Cells: Recent Advances towards Stable Devices. Energies. **9**(5), 384 (2016).
9. V. A. González-Verjan, B. Trujillo-Navarrete, R. M. Félix-Navarro, J. N. D. de León, J. M. Romo-Herrera, J. C. Calva-Yáñez, J. M. Hernández-Lizalde, and E. A. Reynoso-Soto, Effect of TiO2 particle and pore size on DSSC efficiency. Mater Renew Sustain Energy. **9**, 13 (2020).
10. N. Papageorgiou, A new dye shakes up solar cells. (2021). https://actu.epfl.ch/news/a-new-dye-shakes-up-solar-cells/
11. J. Chen, D. Jia, E. M. J. Johansson, A. Hagfeldt, and X. Zhang, Emerging perovskite quantum dot solar cells: feasible approaches to boost performance. Energy Environ. Sci. **14**, 224 (2021).
12. G. S. Selopal, H. Zhao, Z. M. Wang, and F. Rosei, Quantum Dots Solar Cells: Core/Shell Quantum Dots Solar Cells (Adv. Funct. Mater. 13/2020). Adv Funct Materials. **30**, 2070086 (2020).
13. D. Yan, M. Liu, Z. Li, and B. Hou, Colloidal quantum dots and metal halide perovskite hybridization for solar cell stability and performance enhancement. J. Mater. Chem. A. **9**, 15522 (2021).