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Research Progress on the Application of Semiconductor Nanomaterials in the Field of Renewable Energy

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Abstract: Due to the unique physical and chemical properties, semiconductor nanomaterials are widely used materials in the realm of renewable energy and have gained popularity as a research topic in recent years. With the increasing global energy demand and the worsening environmental issues, the development of renewable energy has become a significant issue in current society. Renewable energy plays an important role in environmental protection, economic development, energy security and other fields. Because of their tremendous application value in numerous renewable domains, including solar energy, hydrogen energy and energy storage, semiconductor nanomaterials have gained widespread societal appreciation in this social context. This paper mainly discusses the definition, characteristics and the significance of renewable energy. It also highlights the application of semiconductor nanomaterials in the field of renewable energy, and outlines the prospects of future application in biomedicine, electronic devices, light-emitting displays and other fields. The study shows that semiconductor nanomaterials have shown great potential in the field of renewable energy due to their distinct physical and chemical properties. Future research should focus on resolving the current challenges to promote their sustainable application in a wider range of fields.

Keywords: Semiconductor nanomaterials, Renewable energy, Solar cell, Hydrogen energy, Quantum dots

1. Introduction

Renewable energy refers to the energy that can be naturally supplemented in nature for a relatively short period of time, usually from natural phenomena, and are energy sources other than non-renewable energy sources such as oil, coal, natural gas [1]. Common renewable energy sources include hydrogen, wind, solar, and biomass. The world has entered the era of large-scale production since the Industrial Revolution, but environmental protection has been neglected for centuries, causing the continuous deterioration of the global environment. As a result, problems like air pollution, the greenhouse effect and global sea level rise must be solved urgently. China is expected to peak carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060 while striving to provide cleaner, more environmentally friendly, low-carbon, safer, and more reliable energy sources and build a more effective and stable renewable energy system [2].

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In the field of renewable energy, semiconductor nanomaterials have extremely high application value. Silicon, gallium nitride, gallium arsenide and other semiconductor materials are used to create semiconductor nanomaterials, which have unique properties and a wide range of applications in photothermal conversion, photocatalysis, sensors, molecular devices, and other fields [3]. By developing and refining the composition and structure of materials, their performance in the fields of photoelectric conversion, light absorption, and catalysis can be significantly improved. In addition, its function in the field of renewable energy can be further enhanced by compounding, for example, using several kinds of semiconductor nanoparticles. Therefore, this paper focuses on the latest advancements in the application of semiconductor nanomaterials in the field of renewable energy, and analyzes their mechanisms and potentials in solar energy, hydrogen energy and catalytic energy storage. It can provide scientific basis and technical support for improving energy conversion efficiency, promoting technological innovation and achieving sustainable development goals.

2. Basic properties of semiconductor nanomaterials

2.1. Quantum size effect

When the semiconductor nanomaterials are reduced to a certain critical size, the movement of the carriers becomes confined due to strong quantum confinement effects. This confinement leads to an increase in energy levels, causing the band structure to transition from a continuous state to splitting energy level, resulting in a widening of the energy gap. Consequently, the optical absorption spectrum and emission spectrum will move towards shorter wavelengths, showing a blue shift phenomenon, which is the quantum size effect in semiconductor nanomaterials. At this time, the optical properties of the nanomaterial differ significantly from those of the original material, such as edge absorption, photoluminescence, cathodoluminescence [4].

2.2. Small size effect

If the scale of the nanoparticles approaches of falls below the wavelengths of light and the de Broglie wavelength of the substance, the periodic boundary conditions of the nanolattice are destroyed and the atomic density of the surface is reduced. This results in a variety of special properties. In addition, the light-absorbing and microwave absorption capacities of nanoparticles have also been improved. Taking advantage of these properties, semiconductor nanomaterials can be used as ideal materials for photothermal and photoelectric conversion.

2.3. Surface effects

The surface effect occurs when the size of a material is reduced to the nanometer level, the specific surface area increases and its surface atom count is much greater than its internal atom count. Therefore, the binding forces of these surface atoms are relatively low, making them more likely to detach due to increasing temperatures, which can lead to a decrease in the melting point of the material. Surface effects also significantly affect other properties of the material, resulting in higher chemical reactivity in nanomaterial, such as an increase of the surface energy and surface tension, and the possibility of changing the configuration, so the surface effects of semiconductor nanomaterials have a significant impact on their overall properties [5].

2.4. Quantum confinement and tunneling effects

When the scale of semiconductor materials is reduced to the nanoscale, the continuous energy levels of electrons will split into discrete energy levels near the Fermi level, which is known as the quantum confinement effect. Because of quantum mechanical interactions, this effect affects the electrical and optical properties. The band gap widens as the size decreases, which may trigger fluorescence at particular wavelengths. In addition, the quantum confinement effect improves the efficiency of photoelectron conversion, making the materials more sensitive to light absorption and changing their luminescence properties.

Quantum tunneling effect refers to the ability of microscopic particles to penetrate the barrier at the nanoscale, even when the barrier height exceeds the particle energy. This concept is a fundamental aspect of quantum mechanics and has significant implications for electronic devices, information storage, photoelectric effects. It also has a crucial impact on the electronic properties of materials, the characteristics of devices and the development of new quantum technologies.

2.5. Commonly used materials and synthesis methods

Semiconductor nanomaterials are classified into four types according to dimensions: zero-dimensional (such as nanoparticles and quantum dots), one-dimensional (such as nanotubes and nanowires), two-dimensional (such as graphene and ultrathin films), and three-dimensional (such as nanoceramics and nanoglass) [6]. The two primary types of its synthesis methods are top-down and bottom-up. Physical methods like cutting and physical vapor deposition are examples of top-down processing, which turns macroscopic materials into nanoscale materials. Bottom-up processing creates nanostructures by self-assembly and chemical synthesis [7]. Different synthesis methods will affect the morphology and properties of semiconductor nanomaterials. Therefore, when preparing them, the synthesis method should be carefully selected based on the intended use.

3. Application of semiconductor nanomaterials in the field of renewable energy

3.1. Application in solar energy

As traditional energy sources decline due to environmental concerns, solar energy has emerged as a widely adopted renewable energy option. The development of solar energy began in the 1950s with the birth of crystalline silicon solar cells, marking the first generation of photovoltaic cells [8]. Although their performance has improved, the high production costs remain a challenge. Therefore, researchers have developed second-generation thin-film solar cells based on vapor deposition, primarily using cadmium telluride or copper indium gallium selenide [9]. However, these cells have complex ,manufacturing processes and environmental impacts, so the third-generation solar cells with relatively simple workmanship technology came into being. Such batteries are mainly prepared by using organic semiconductors, hybrid composites and inorganic semiconductors. Notably, an organic-inorganic hybrid perovskite solar cells (PSCs) is derived.

Perovskite compounds possess a special crystal structure, named after calcium titanate, which conforms to the ABX_3 structure. Many materials fit this crystal configuration and have different properties. One type of the perovskite materials used in PSCs is a perovskite ABX_3 structure formed by the crystallization of organic halides and metal halide salts. These materials have special properties, such as adjustable band gap and high absorption coefficients, leading to excellent photovoltaic performance [10]. Another material used to make perovskite solar cells is perovskite quantum dots (PQDs), which has more unique quantum effects and stronger stability. In solar cells, PQDs can be used as light-absorbing materials or as additives to improve cell performance [11-12]. In addition, they can be used as a light-absorption and emitting material for the study of fluorescence in solar cells [13].

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3.2. Application in hydrogen energy

Hydrogen energy is also a classic renewable clean energy, which can effectively convert electrical energy into chemical energy for storage. It is regarded as a key trend of renewable energy in the future due to its non-polluting and high energy density. The application of semiconductor nanomaterials in the field of hydrogen energy mainly focuses on the preparation, storage and utilization of hydrogen.

There are three main ways to prepare hydrogen. The first method involves using fossil fuels as raw materials while the other is prepared from coal fuels [14]. Both methods produce carbon dioxide and require fossil fuels. The third method, which produces hydrogen by electrolysis of water, generates energy from water and stores it in the form of chemical bonds, with no carbon dioxide emissions throughout process. Therefore, efficient catalysis of water electrolysis is crucial, and transition metal sulfides (TMS) have efficient catalytic activity [15].

Transition metal dichalcogenides are typical two-dimensional nanomaterials exhibit diverse crystal structures, excellent stability in chemical reactions and high-temperature environments, and outstanding catalytic performance. In addition, semiconductor nanomaterials are widely used in photocatalytic water splitting to produce hydrogen. Materials such as titanium dioxide (TiO_2), gallium phosphide (GaP) can efficiently catalyze the decomposition of water under light to produce hydrogen.

In terms of hydrogen storage, semiconductor nanomaterials can be used as effective adsorption media for hydrogen molecules due to their high specific surface area [16]. Graphene nanosheets are typical hydrogen storage materials. However, pure graphene is difficult to hydrogenate, making it difficult to meet the requirements of hydrogen storage. Modifying graphene, such as heteroatom doping, modification, and the introduction of defects, can improve its hydrogen storage performance. Thus, graphene nanosheets with excellent hydrogen storage performance can be prepared [17].

3.3. Application in photothermal conversion

Photothermal conversion refers to the process of converting light energy into heat energy, in which photothermal conversion materials act as absorbers of light energy [18]. Semiconductor nanomaterials can also be used for photothermal conversion, as their optical properties are related to the energy of the band gap. Local heating induced by free carrier-induced plasma can control the light absorption of nanosemiconductor materials [19]. For example, nanorods, nanosheets, and quantum dots have excellent light absorption characteristics due to their high surface area. TiO_2 nanomaterials also have good photothermal conversion performance under light conditions. Semiconductor nanomaterials can also be used in photocatalytic reactions to improve the conductivity through composites, thereby improving the photothermal conversion capacity.

4. Future prospects for other applications of semiconductor nanomaterials

Semiconductor nanomaterials have important application prospects in various fields. For example, in biological applications, researchers have developed a photoelectrochemical aptamer sensor based on the fullerene/cadmium telluride quantum dot sensitization structure, which incorporates signal quenching porphyrin manganese. This sensor can accurately detect markers and ions of various organisms. Additionally, semiconductor nanomaterials can serve as a drug delivery system to accurately transport drugs to damaged cells [20]. These materials also have important applications in optoelectronic devices. For example, some nanoscale light-emitting diode (LED) materials outperform ordinary LED materials, and some have been used in some electronic devices. Furthermore, lasers, night vision devices and other products are also inseparable from the contribution of semiconductor nanomaterials. It can be said that semiconductor nanomaterials will be applied to all aspects of life in the future.

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5. Conclusion

This paper discusses the basic properties of semiconductor nanomaterials and their application in renewable energy, highlighting the importance of renewable energy in today's society and predicting the future development trend of semiconductor nanomaterials in other fields. Semiconductor nanomaterials have a wide range of applications in renewable energy, such as photovoltaic power generation, hydrogen preparation and storage, etc. However, despite their promising potential, these materials still face many challenges. For example, issues like maintaining the long-term stability and activity, achieving large-scale preparation and cost control, and assessing environmental impacts in practical applications still need urgent solutions. In addition, although this paper provides a comprehensive overview of the application of semiconductor nanomaterials, practical factors such as cost and processing in their implementation are not fully explored. Therefore, future research should pay more attention to the sustainable development of materials, and explore ways to make production and application greener. In summary, semiconductor nanomaterials play an important role in advancing renewable energy and achieving global sustainable development goals.

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