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Applications of Semiconductor Nanomaterials in Renewable Energy

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Abstract. With the rapid advancement of nanotechnology and material preparation techniques, semiconductor nanomaterials have garnered increasing attention across various fields due to their distinctive optical and catalytic properties. These materials hold significant potential for applications in renewable energy, particularly in solar energy utilization, owing to their high energy conversion efficiency and other superior physical characteristics. This article not only summarizes the definition and classification of semiconductor nanomaterials but also delves into their underlying mechanisms. Additionally, it examines their applications and advantages in the realm of renewable energy in light of current technological progress and offers insights into future prospects and challenges. Given the broad application potential and innovative nature of semiconductor nanomaterials, they are poised to significantly enhance the utilization of renewable energy. The research findings indicate that the strategic application of these nanomaterials can lead to substantial improvements in energy conversion efficiency and overall system performance, thereby contributing to a more sustainable and efficient energy future.

Keywords: Semiconductor nanomaterials, renewable energy, solar cells, photocatalytic CO_2 fixation, wind power generation

1. Introduction

The development of semiconductor nanomaterials can be traced back to the rise of quantum mechanics. Einstein's proposal of the photoelectric effect and Planck's theory of energy quantization provided a crucial theoretical foundation for the unique electronic behavior of semiconductor materials. These foundational theories have paved the way for the exploration and application of semiconductor nanomaterials in various scientific and technological domains. Over the years, researchers have made significant strides in understanding and harnessing the properties of these materials, leading to their widespread use in electronics, optoelectronics, and renewable energy systems.

Despite the broad application prospects of semiconductor nanomaterials, the field still faces numerous challenges. For instance, the high manufacturing costs associated with materials like gallium arsenide (GaAs) pose a significant barrier to their widespread adoption. Additionally, the large-scale synthesis of nanomaterials remains a complex and often costly process, which limits

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their commercial viability. These challenges highlight the need for continued research and innovation to overcome the obstacles and fully realize the potential of semiconductor nanomaterials.

This article reviews the characteristics of common semiconductor nanomaterials and their applications in renewable energy through a method of resource organization. It also summarizes existing achievements, aiming to promote the development of renewable energy technology and encourage further exploration into the vast potential of semiconductor nanomaterials.

2. Definition and types of semiconductor nanomaterials

Semiconductor material is a kind of materials with conductivity between the dielectric and conductor materials. In general, semiconductor conductivity is considered in the range between 10^-8 and 10^3 (Ω-cm)^-1. Nanomaterials are materials with at least one of the three dimensions between 1 and 100 nanometers. Thus, semiconductor nanomaterials are supposed to inherit the physical properties and advantages common to these materials.

Semiconductor nanomaterials are categorized by dimensionality and composition. Dimensionally, they range from zero-dimensional quantum dots to one-dimensional nanowires, two-dimensional graphene, and three-dimensional SiC particles. Compositionally, they include inorganic materials (e.g., silicon, germanium quantum dots, ZnO nanoparticles), organic-inorganic hybrids (e.g., chalcogenides), and carbon-based materials (e.g., carbon nanotubes, graphene quantum dots). Semiconductor nanomaterials are currently used in renewable energy for solar cells, fuel cells, photocatalysis, and CO_2 fixation. With advancing technology, their applications could expand into energy storage and biological carbon fixation cycles.

3. Semiconductor nanomaterials for renewable energy applications

Due to the following unique properties of semiconductor nanomaterials, they have become the key to break through the bottleneck of traditional energy technologies, thus demonstrating transformative potential in a wide range of fields.

3.1. Applications in solar cells

Solar energy is a renewable energy source and is the basis for human survival. In order to efficiently utilize solar energy, people use the photovoltaic effect to make solar cells.

In recent years, halogenated chalcogenide nanocrystals with strong light absorption, high fluorescence quantum yield, high carrier mobility and tunable bandgap have shown broad prospects in the field of solar cells [1]. In 2009, Tsutomu Miyasaka's team at the University of Tokyo first applied MAPbI3NCs and MAPbBr3NCs (both are halogenated chalcogenide nanocrystals; NCs stands for nanocrystals) as sensitizers to solar cells, and the cells based on MAPbI3NCs achieved the power conversion efficiency (PCE) of 3.8%, and the photovoltaic voltage of the cells based on MAPbBr3NCs could reach 0.96V. Since then, chalcogenide solar cells have entered a phase of rapid development. In addition, the current PCE of chalcogenide solar cells has been improved to 26.81%, which is comparable to the efficiency level of silicon cells, showing broad application prospects, such as embodied in the promotion of the application of stacked-layer technology.

As the top light-absorbing material (more than 10 times that of crystalline silicon), calcite is able to form a stacked cell with crystalline silicon cells. Some of China's enterprises have already realized the efficiency of stacked batteries exceeding 33%, and it is expected to reach more than 43% in the future, which will reduce the energy loss and improve the performance of batteries to a

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greater extent. Baimalakelab has applied the theoretical technology of all-calcite double-junction stacked cells to the development of stacked cells to promote the industrialization of solar cells [2-4].

3.2. Applications in photocatalysis

For photocatalytic reactions, the band gap width and the positions of the conduction and valence bands of the selected semiconductor photocatalyst must match the redox potential of water decomposition. ZnO is a common semiconductor material that has been extensively researched in the field of water treatment. It has the benefits of strong photocatalytic activity, cheap manufacturing costs, and ease of preparation and synthesis [5]. The solid energy band theory serves as the foundation for the principle of semiconductor photocatalysis, which is the most popular and extensively studied type of photocatalyst in the photocatalytic research process. However, the wide band gap of ZnO leads to its low utilization of sunlight and cannot correspond well to visible light, which limits its further application in photocatalysis [6]. Therefore, the modification of ZnO by noble metal deposition, doping, and heterostructure buildingwas investigated. Photocatalytic degradation experiments show that these methods significantly enhance the photocatalytic performance of semiconductor materials. The derivative 15MQ@ZnO@20%CuO was created by Wuwu Mu from Lanzhou University of Science and Technology from ZnO, and the nano semiconductor material replicated how sunlight breaks down organic materials. The findings revealed that the 15MQ@ZnO@20%CuO composite photocatalyst has excellent photocatalytic performance, and its photocatalytic mechanism is shown in Fig. 1.

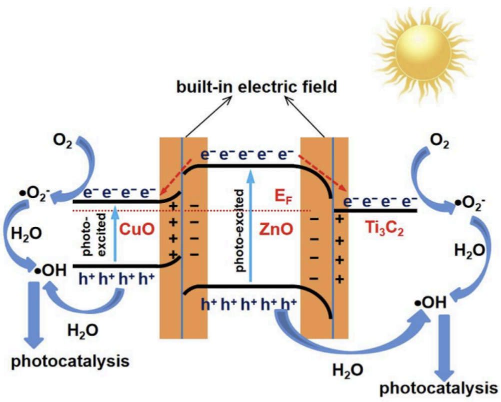

Figure 1: Photocatalytic mechanism of 15MQ@ZnO@20%CuO [6]

Semiconductor materials also have their specialty in photocatalytic hydrogen production.Since Honda and Fujishima's 1972 discovery of photocatalytic water splitting using titanium dioxide electrodes under UV light, research has evolved from elucidating the reaction mechanism to developing common photocatalysts like ZnO and TiO_2. Despite pure TiO_2's low hydrogen production efficiency, using co-catalysts or modified TiO_2 composites remains a viable strategy [7].

3.3. Applications in CO_2 fixation

The band structure of semiconductor materials is composed of three main components: the conduction band, the valence band, and the forbidden band (Ig). When the energy of incident light exceeds or equals the width of the forbidden band, electrons in the valence band are excited and migrate to the conduction band. This process results in the formation of highly reactive, reducing

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conduction band electrons and the creation of positively charged, oxidizing holes in the valence band. Therefore, in order to construct a semiconductor-non-photosynthetic microorganism system, semiconductor materials with suitable light absorption properties and good biocompatibility should be selected. Semiconductor-non-photosynthetic microorganisms are a composite system that has been widely used in fields such as environmental pollution remediation and energy development (Fig. 2). The system consists of two parts: semiconductor materials and whole-cell microbial catalysts. Cadmium sulfide (CdS) serves as a quintessential example [8]. In 2016, Yang Peidong's group found for the first time that the CdS inorganic semiconductor material bound to the outer surface of M. thermoacetica could significantly promote CO_2 fixation by bacteria to produce acetic acid under light conditions [9]. Since then, studies have been carried out to combine micro CdS semiconductor materials on the surface of different microorganisms and used them to enhance the microorganisms' own functions. However, in contrast, organic semiconductor materials such as conjugated polymer nanoparticles and organic dyes (methyl blue, etc.), which exhibit lower biotoxicity and higher electron transfer efficiency, are also an important photosensitizing material for the construction of the aforementioned system [10-11].

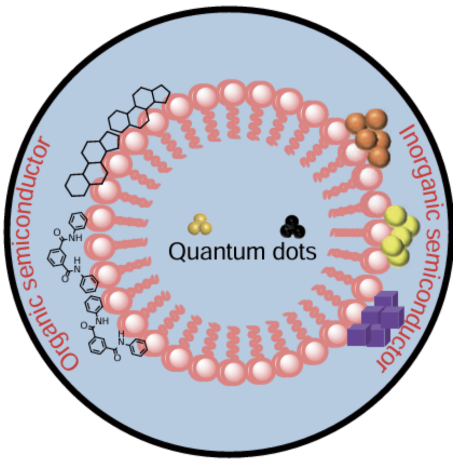

Figure 2: Schematic representation of inorganic and organic semiconductors in combination with microorganisms [12]

Currently, the binding of semiconductor materials to microorganismspredominantly involves attaching these materials to the outer membrane surface of the microorganisms [13]. Some studies have entured into the internalization of semiconductor quantum dots, with sizes under 10 nm, by microorganisms, thereby facilitating binding to intracellular sites [14]. The advantages of the extracellular binding approach are the simplicity of the binding process and the stronger absorption of light energy. However, specific catalytic enzymes and metabolic pathways are often located intracellularly. The transmembrane transport of photoelectrons from the extracellular to the intracellular sites, where these enzymes and pathways reside, is complex and results in energy loss. This complexity also limits the interaction opportunities between the photoelectrons and the intracellular functional enzymes. In contrast, intracellularly bound semiconductor materials have the opportunity to interact with intracellular multifunctional enzymes, however, the current process of intracellular binding (mainly internalization of quantum dots) is complex and microbial selectivity for quantum dots is high. Successful semiconductor quantum dots constructed by intracellular semiconductor-non-photosynthetic microbial composite systems in recent years include carbon quantum dots, Au nanoclusters, and $CuLnS_2/ZnS$ quantum dots [15-17].

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3.4. Applications in wind power generation

Nowadays, China's wind power generation ranks third among all types of power generation, whcih is an important source of energy for the country. Wind turbine blades are the core components for wind energy conversion, which are generally required to have high strength, low weight and better fatigue resistance. Carbon nanotubes (CNTs) are tubular one-dimensional nanomaterials with excellent mechanical, electrical, and thermal properties. By adding a small amount of CNTs to the polymer matrix, the properties of the material can be significantly improved. By introducing carbon nanomaterials into the components (fibers or matrix) of fiber-reinforced composites (FRPs), which are wind turbine blade materials, the properties of the matrix and the interfacial interaction between the fibers and the FRP matrix can be improved, which in turn offers the possibility of improving the overall performance of wind turbine blades [18]. Commonly used materials for wind turbine blades are glass fibers, epoxy carbon fibers, epoxy composites, or hybrid materials of carbon fibers, glass fibers, and epoxy resin. The mechanical characteristics can be significantly enhanced by adding carbon nanotubes as a reinforcing phase to glass fiber or carbon fiber composites to create carbon nanotube reinforced glass fiber or carbon fiber composites [19].

4. Challenges of semiconductor nanomaterials for renewable energy applications

4.1. Potential for future growth

Semiconductor nanomaterials, by virtue of their unique optical properties and band structure, in the manufacture of chalcogenide solar cells and quantum dot solar cells show great potential. At the same time they are also conducive to promoting the development of green energy. The future of non-toxic semiconductors (such as some organic semiconductors, iron-based oxides, etc.) will become a significant alternative to the conventional path of toxic materials with ongoing process improvement and technological advancements. This will help to address the issue of environmental pollution and foster the peaceful coexistence of humans and nature.

4.2. Challenges

Semiconductor nanomaterials also possess significant variations in properties compared to other conventional materials due to the similarity in size and coherence length of electrons. In terms of photocatalysis, semiconductor nanomaterials are currently an innovative photocatalyst. Due to their large surface area, abundant surface states and easy modeling, they are very helpful for the simulation experiments of photocatalysis. However, some semiconductor nanomaterials (e.g., quantum dots) are expensive to develop, and heavy metal-based semiconductors, such as CdS, can cause environmental pollution, so there is still a need to reduce the toxicity of semiconductor materials or explore new non-toxic semiconductor materials. In addition, some semiconductor materials, such as chalcogenide, are less stable, and there is still a need to solve the problem of their degradation under long-term operation.

5. Conclusion

Semiconductor nanomaterials, with their unique optical properties and catalytic properties, show great potential for application in the field of renewable energy. In the field of solar cells, halogenated chalcogenide nanocrystals have significantly improved the energy conversion efficiency due to their efficient light absorption and carrier mobility, and their performance is now close to that of silicon-based cells; in photocatalysis, semiconducting materials such as ZnO and TiO_2 can significantly improve photocatalytic performance through modification, and they perform excellently in catalytic hydrogen production. In addition, semiconductor materials can be combined with non-photosynthetic microorganisms for CO_2 fixation and conversion, which helps to realize carbon neutrality. However, due to the insufficient experimental data in this paper, there are difficulties in fully dissecting and solving the problems of high R&D cost of semiconductor nanomaterials, pollution and insufficient stability of toxic materials. Future research directions include the development of non-toxic materials and the enhancement of long-term stability for a wider range of green energy applications. Through continuous technological breakthroughs, semiconductor nanomaterials in the field of renewable energy are expected to promote the popularization of efficient and clean energy and make significant contributions to the realization of sustainable development.

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