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Research Progress on Semiconductor Nanomaterials in Photocatalysis

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Abstract: With the development of modern industry, industrial pollution has become increasingly severe, posing significant challenges to environmental protection and human health. In this context, semiconductor nanomaterials have garnered considerable attention due to their unique photocatalytic properties. This paper provides an overview of research advancements in composite, metal, and non-metal semiconductor nanomaterials within the field of photocatalysis, summarizing their applications in environmental purification, energy conversion, and production optimization. Composite semiconductor nanomaterials offer new directions for environmental purification through methods such as constructing heterostructures. Metal and non-metal semiconductor nanomaterials exhibit excellent catalytic activity and stability, providing new solutions for optoelectronic sensing and pollutant degradation. By comparing the advantages of these materials in the field of photocatalysis, the paper finds that semiconductor nanomaterials play a pivotal role in promoting environmental protection. Despite their benefits, including efficient light energy conversion and good stability, challenges remian concerning their cost, preparation, and recycling. The paper anticipates that overcoming these limitations to promote broader application in environmental protection and sustainable development.

Keywords: Photocatalytic technology, semiconductor nanomaterials, environmental purification, energy conversion

1. Introduction

Since the 21st century, rapid industrialization has led to the widespread discharge of untreated or inadequately treated industrial wastewater and exhaust gases, significantly impacting both the natural environment and human health. This has resulted in frequent energy crises and environmental issues, creating a critical situation requiring immediate attention [1]. In recent years, nanophotocatalytic technology has developed rapidly, characterized by low energy consumption and high processing rates, enabling many reactions that are difficult under normal conditions to occur under milder settings. This technology demonstrates considerable potential in mitigating current energy crises and addressing environmental pollution. The photoelectric magnetic properties of semiconductor nanomaterials have been further explored for broader applications in photocatalysis [2].

Since the 1980s, China has intiated researching nanomaterials, primarily applied in ceramics, catalysis, and biotechnology [1]. As the field of nanomaterials has evolved and their application in photocatalysis has expanded, these materials have moved beyond their early uses in environmental protection to include modern applications in hydrocarbon fuels, metal catalysis, and non-metal optoelectrochemical sensing. Research on composite semiconductor nanomaterials and metal and non-metal materials in photocatalysis has significantly advanced environmental protection and optimized lifestyles. As photocatalytic technology continues to progress, the unique properties of nanomaterials, such as electrical and magnetic characteristics, are gradually being discovered, contributing new impetus to sustainable development [2].

This paper reviews the research advancements of semiconductor nanomaterials in the field of photocatalysis and discusses composite semiconductor nanomaterials, metal, as well as non-metal semiconductor nanomaterials, further uncovering new strategies to address environmental issues and promote sustainable development.

2. Overview of Semiconductor Nanomaterials

This section provides a detailed examination of advancements in composite semiconductor nanomaterials and metal-nonmetal semiconductor nanomaterials, offering a comprehensive understanding of their contributions to photocatalysis.

2.1. Composite Semiconductor Nanomaterials

Composite semiconductor nanomaterials have garnered significant attention in the field of photocatalysis due to their unique electronic structures and excellent photocatalytic properties. Typically composed of two or more different semiconductors, these materials allow for the optimization of light absorption, charge separation, and transport processes through adjustments in composition, structure, and morphology, thereby enhancing photocatalytic efficiency. In recent years, various researchers have developed various types of composite semiconductor nanomaterials through different methods, such as heterojunctions, core-shell structures, and multilayer structures [3-5]. These designs aim to promote effective separation of photo-generated electrons and holes, reduce recombination rates, and broaden the light absorption range, thus improving solar energy utilization efficiency.

In the realm of environmental purification, composite semiconductor nanomaterials exhibit outstanding photocatalytic degradation performance. For example, TiO_2-based composite semiconductor materials are widely used for degrading organic pollutants and removing heavy metal ions. By combining with other semiconductors like CdS, ZnO, and SnO_2, the photocatalytic activity of TiO_2 can be significantly enhanced, reducing the recombination rate of photo-generated electrons and holes, and thus increasing the degradation capacity of pollutants [6].

In the context of energy conversion, composite semiconductor nanomaterials also show great potential. For instance, in water splitting for hydrogen production, constructing suitable heterojunction structures can achieve effective spatial separation of photo-generated electrons and holes, thereby improving hydrogen production efficiency [7]. Additionally, composite semiconductor nanomaterials are used in solar cells and photoelectrochemical cells, optimizing the photovoltaic conversion process to enhance energy conversion efficiency.

2.2. Metal and Non-Metal Semiconductor Nanomaterials

Metal and non-metal semiconductor nanomaterials have unique advantages in photocatalysis. On one hand, metal nanoparticles exhibit excellent electrical conductivity and catalytic activity, accelerating the transfer and conversion of photo-generated electrons. On the other hand, by adjusting the size, shape, and distribution of metal nanoparticles, both light absorption and charge separation processes can be optimized.

Common metal semiconductor nanomaterials include noble metals (such as Au, Ag, Pt) and non-noble metals (such as Zn, Cu, Ni, Co) based composites. These materials have demonstrated

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good performance in photocatalytic degradation of pollutants, water splitting for hydrogen production, and CO_2 reduction [8-10]. For example, the $Ni(OH)_2/Pt/TiO_2$ composite material is used for water splitting to produce hydrogen, where the introduction of Pt nanoparticles significantly enhances the photocatalytic activity of TiO_2 and reduces the cost of hydrogen production [11].

Non-metal semiconductor nanomaterials also have wide applications in photocatalysis. Compared to metal semiconductors, non-metal semiconductor materials offer lower costs and better stability while exhibiting unique optoelectronic properties. Common non-metal semiconductor nanomaterials include graphene, carbon nanotubes, and C_3N_4. These materials demonstrate excellent performance in photocatalytic degradation of pollutants and photocatalytic reduction of CO_2. For instance, the graphene/TiO_2 composite material, through the introduction of graphene, significantly improves the light absorption ability and charge separation efficiency of TiO_2, thereby enhancing its photocatalytic degradation performance [12].

In summary, composite semiconductor nanomaterials and metal and non-metal semiconductor nanomaterials each hold an irreplaceable important position in the research of photocatalysis. The following sections will provide a more detailed and rigorous discussion on specific application scenarios and performance characteristics of these two types of materials.

3. Applications of Semiconductor Nanomaterials in Photocatalysis

3.1. Composite Semiconductor Nanomaterials

3.1.1. Heterostructured Photocatalytic Materials

Heterogeneous structured photocatalytic materials are a key category of composite semiconductor nanomaterials. By combining semiconductors with different band structures, heterojunction structures can be formed, effectively separating photo-generated electrons and holes in space. This design significantly enhances photocatalytic efficiency and broadens the range of light absorption.

For example, in the TiO_2/CdS heterojunction, TiO_2 is a wide-bandgap semiconductor material known for its excellent photostability and chemical stability, while CdS is a narrow-bandgap semiconductor material with superior light absorption capabilities. When TiO_2 and CdS are combined into a heterojunction, photo-generated electrons transfer from CdS to TiO_2, while holes remain in CdS, achieving effective separation of electrons and holes. This structure not only improves photocatalytic efficiency but also expands the range of light absorption, enabling the material to exhibit good photocatalytic performance under visible light [13].

3.1.2. Photocatalytic Water Splitting for Hydrogen Production

Photocatalytic water splitting for hydrogen production is one of the significant applications of composite semiconductor nanomaterials in energy conversion. By constructing suitable heterojunction structures or incoperating co-catalysts, the efficiency of photocatalytic water splitting can be significantly improved.

For example, in the case of the ternary composite material Pt/TiO_2/CdS, the introduction of Pt nanoparticles as co-catalysts accelerates the transfer and transformation of photogenerated electrons. Additionally, when TiO_2 and CdS form a heterojunction, it effectively separates photogenerated electrons and holes. This structural design not only enhances photocatalytic efficiency but also reduces hydrogen production costs. Experimental results show that this ternary composite material exhibits excellent photocatalytic water splitting performance under visible light, with a significantly increased hydrogen production rate [14].

3.1.3. Enhancement of Hydrocarbon Fuels

Composite semiconductor nanomaterials also show great potential in enhancing hydrocarbon fuel combustion. By integrating these nanomaterials as catalysts or co-catalysts, the combustion process of hydrocarbon fuels can be accelerated, improving combustion efficiency while reducing harmful emissions and lowering environmental pollution.

For example, TiO_2-based composite materials, when incorporated with nanoparticles as catalysts, can accelerate the combustion process. Additionally, TiO_2, as a semiconductor material, absorbs light energy to generate photoelectrons and holes, further promoting the combustion reaction. Experimental results indicate that this composite material exhibits excellent performance in catalyzing hydrocarbon fuel combustion, significantly increasing combustion efficiency and reducing harmful emissions [15].

3.2. Metal and Non-Metal Semiconductor Nanomaterials

3.2.1. Applications of Metal Semiconductor Nanomaterials in Optoelectronic Sensing

Metal-semiconductor nanomaterials have extensive applications in optoelectronic sensing. By adjusting parameters such as the size, shape, and distribution of metal nanoparticles, it is possible to optimize light absorption and charge separation processes. Additionally, these metal nanoparticles exhibit excellent conductivity and catalytic activity, which can accelerate the transport and conversion of photogenerated electrons. These characteristics make metal-semiconductor nanomaterials advantageous in the field of optoelectronic sensing.

For example, in the case of GO (graphene oxide)/Ag_2S/ZnO composite materials, the introduction of Ag_2S nanoparticles and the rapid transfer of photogenerated electrons via GO significantly enhances the ZnO's light absorption capacity and charge separation efficiency. This structural design results in superior performance of the GO/Ag_2S/ZnO composite material in optoelectronic sensing. Experimental results show that the sensitivity of this composite material is significantly improved, with reduced response time, as well as good stability and repeatability [16].

3.2.2. Degradation Performance of Non-metallic Semiconductor Nanomaterials

Non-metallic semiconductor nanomaterials have demonstrated excellent performance in photocatalytic degradation of pollutants. Compared to metal semiconductors, non-metallic semiconductor materials offer lower costs and better stability. Additionally, by adjusting parameters such as the structure and morphology of non-metallic semiconductor materials, optimization of light absorption and charge separation processes can be achieved.

For example, C_3N_4, as a novel non-metallic semiconductor material, exhibits outstanding light absorption capability and charge separation efficiency. Its unique electronic structure and chemical stability also contribute to its excellent performance in photocatalytic pollutant degradation. Experimental results indicate that C_3N_4 effectively degrades various organic pollutants. Furthermore, its photocatalytic degradation performance can be further enhanced by combining it with other semiconductor materials to form heterostructures or by introducing co-catalysts [17].

4. Challenges and Prospects

4.1. Potential Challenges

The application of semiconductor nanomaterials in photocatalysis shows great potential but faces multiple challenges. Firstly, the preparation process for composite semiconductor nanomaterials is relatively complex, requiring precise control over the proportions and structures of each component

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to achieve optimal photocatalytic performance. Achieving optimal photocatalytic performance requires precise control over the proportions and structures of each component, which increases production costs and may hinder large-scale applications. Additionally, some composite semiconductor nanomaterials may experience stability issues during long-term use, leading to a decline in photocatalytic performance, which further affects their reliability in practical applications.

Metal and non-metal semiconductor nanomaterials, while offering lower costs and better stability, also face certain challenges. Metal semiconductor nanomaterials may produce toxic byproducts during the photocatalytic process, necessitating careful handling to avoid environmental and health hazards. On the other hand, optimizing the performance of non-metal semiconductor nanomaterials presents its own difficulties, requiring continuous research and innovation to overcome existing technological limitations.

Additionally, both composite semiconductor nanomaterials and metal and non-metal semiconductor nanomaterials may cause environmental pollution during their preparation processes. Thus, reducing environmental pollution while maintaining material performance is a critical area of focus for future research.

4.2. Future Outlook

Despite numerous challenges, the application prospects of semiconductor nanomaterials in photocatalysis remain promising. Future research could focus on several key areas for breakthroughs:

Improvement of Preparation Processes and Optimization of Material Structures: addressing the complexity and stability issues of composite semiconductor nanomaterials by improving preparation processes and optimizing material structures. For instance, introducing new preparation methods and co-catalysts can simplify the process and enhance photocatalytic efficiency; meanwhile, adjusting parameters such as morphology and size can optimize stability performance.

Exploration of New Applications and Performance Optimization Strategies: To overcome the limitations of metal and non-metal semiconductor nanomaterials, exploring new application fields and performance optimization strategies can expand their usage range. For example, combining with other materials or introducing new functional groups can improve catalytic activity and selectivity; adjusting electronic structure and band structure can optimize light absorption and charge separation processes.

Environmental Safety and Sustainability Assessments: Future studies should also strengthen environmental safety and sustainability assessments of semiconductor nanomaterials in practical applications. This includes comprehensive evaluations of their environmental impact during preparation, use, and disposal, along with developing corresponding environmental protection measures and recycling strategies to minimize negative effects.

Interdisciplinary Collaboration and Integrated Innovation: Interdisciplinary collaboration and integrated innovation can further advance the development of semiconductor nanomaterials in photocatalysis. Combining knowledge and technologies from chemistry, physics, materials science, and environmental science can address current challenges; enhancing international cooperation and exchange can promote global technological innovation and knowledge sharing.

In summary, while the application prospects of semiconductor nanomaterials in photocatalysis are broad, many challenges still need to be overcome. Future research must continuously explore new preparation methods and performance optimization strategies, and strengthen interdisciplinary collaboration and integrated innovation to promote their widespread application in environmental protection and sustainable development.

5. Conclusion

This paper reviews the research progress of semiconductor nanomaterials in photocatalysis, covering aspects such as the preparation, performance optimization, and applications of composite semiconductor nanomaterials and metal-nonmetal semiconductor nanomaterials. Through case analysis, it explores the application prospects and challenges of these materials in environmental purification, energy conversion, optoelectronic sensing, and pollutant degradation. In terms of composite semiconductor nanomaterials, effective separation and transfer of photo-generated electrons and holes have been achieved through methods like constructing heterostructures and introducing co-catalysts, thereby enhancing photocatalytic efficiency. These advancements provide new solutions for environmental purification and energy conversion. Meanwhile, metal-nonmetal semiconductor nanomaterials also exhibit unique advantages and potential, showing excellent performance in optoelectronic sensing and pollutant degradation.

However, these materials still face challenges and limitations in practical applications, such as complex preparation processes, stability issues, cost increases, and environmental pollution. Future research needs to further explore their preparation methods and performance optimization strategies to achieve more efficient and stable photocatalytic performance. Additionally, attention should be paid to the environmental safety and sustainability of these materials in practical applications. Although this paper summarizes the research progress of composite and metal-nonmetal semiconductor nanomaterials in photocatalysis, it does not cover all the latest achievements and insufficiently considers industrial applications. Future research should strengthen the integration with practical applications, taking into account multiple factors to promote the widespread use of semiconductor nanomaterials. Looking ahead, with the continuous advancement of photocatalytic technology and the ongoing development of nanomaterial science, the application prospects of semiconductor nanomaterials in photocatalysis will further expand. By continuously optimizing material performance and exploring new application areas, new vitality and possibilities can be injected into environmental protection and sustainable development.

References

[1] *Zhang Wei, Huang Ying, Shao Jie, et al. Research Progress on Semiconductor Nanomaterials in Photocatalysis [J]. Material Development and Application, 2012, 27(03): 92-96. DOI: 10.19515/j.cnki.1003-1545.2012.03.021.*

[2] *Zhang Haoyu, Zhang Xia, Peng Liman, et al. Research Progress on the Application of Composite Semiconductor Nanomaterials in Photocatalysis [J]. Modern Chemical Industry, 2023, 43(S2): 36-41+47. DOI: 10.16606/j.cnki.issn0253-4320.2023.S2.008.*

[3] *Ma Qinghua. Study on the Performance of $BiVO_4$-Based Composite Semiconductor Heterojunction Materials for Photocatalytic Water Oxidation [D]. Lanzhou Jiaotong University, 2024.*

[4] *Yang Junfeng. Design, Preparation, and High-Efficiency Photocatalytic Hydrogen Production of Semiconductor Heterojunction Composite Materials [D]. Jilin University, 2022. DOI: 10.27162/d.cnki.gjlin.2022.000525.*

[5] *Chen Tianming. Synthesis, Characterization, and Photocatalytic Studies of Plasmonic Metal-Semiconductor Core-Shell Nano-Materials [D]. Xiamen University, 2020. DOI: 10.27424/d.cnki.gxmdu.2020.003429.*

[6] *Dong Hanqiu. Study on the Photoelectric and Photocatalytic Properties of TiO_2 and Its Composite Semiconductor Materials [D]. Yangzhou University, 2022. DOI: 10.27441/d.cnki.gyzdu.2022.001744.*

[7] *Zhu Wenjing. Design of Composite Semiconductor Photocatalytic Materials and Their Applications in Water Splitting for Hydrogen Production [D]. Northeast Normal University, 2016.*

[8] *Jiang Xiaoqing. Preparation and Photocatalytic Performance of ZnO-Based Nano-Semiconductor Composite Materials [D]. Sichuan University, 2021. DOI: 10.27342/d.cnki.gscdu.2021.006203.*

[9] *Zhang Weina, Song Jinbo, Ye Xin, et al. Research Progress on ZnO Semiconductor Photocatalytic Nano-Decomposition Materials [J]. Contemporary Chemical Industry, 2022, 51(07): 1672-1678. DOI: 10.13840/j.cnki.cn21-1457/tq.2022.07.030.*

[10] *Xue Jinbo. Construction of Nano-Metal Enhanced Semiconductor Photocatalytic Materials and Their Application in Reducing CO_2 to Hydrocarbon Fuels [D]. Shanxi Province, Taiyuan University of Technology, 2023-07-05.*

DOI: 10.54254/2755-2721/142/2025.KL22306

[11] Xiaochen Ren. Study on the Preparation of NiO/Ni/TiO_2 and $Ni(OH)_2$/Pt/TiO_2 Nanocomposites and Their Photocatalytic Hydrogen Production Performance [D]. Harbin Engineering University, 2019.

[12] Fang Liu, Fengtao Fan, Yucui Lu, et al. Research Progress on Graphene/TiO_2 Composite Materials for Photocatalytic Degradation of Organic Pollutants [J]. Journal of Chemical Industry, 2016, 67(05): 1635-1643.

[13] Xinlin Liu. Preparation and Photocatalytic Properties of Cadmium/Titanium-Based Nano-Composite Semiconductor Materials [D]. Jiangsu University, 2014.

[14] Shaoqin Peng, Xiaoyan Liu, Min Ding, et al. Preparation of Composite Photocatalyst CdS-Pt/TiO_2 and Its Visible Light Photocatalytic Water Splitting Performance [J]. Journal of Molecular Catalysis, 2013, 27(05): 459-466. DOI: 10.16084/j.cnki.issn1001-3555.2013.05.008.

[15] Wenguang Tu. Structural Regulation of Titanium Dioxide Nanocomposites and Their Photocatalytic Reduction of CO_2 into Renewable Hydrocarbon Fuels [D]. Nanjing University, 2015.

[16] Wei Liu. Preparation and Photoelectrochemical Sensing Properties of ZnO Nanostructured Composites [D]. Wuhan University of Science and Technology, 2019.

[17] Yanyan Zhao, Zhuangzhuang Tian. Preparation and Visible Light Degradation Performance of g-C_3N_4 Suppo rted Nano-Ag Composite Material [J/OL]. Inorganic Salt Industry, 1-13 [2025-02-14]. https://doi.org/10.199 64/j.issn.1006-4990.2024-0399.