Proceedings of the 5th International Conference on Materials Chemistry and Environmental Engineering
DOI: 10.54254/2755-2721/2025.23744

Research Progress of Two-Dimensional Semiconductor Materials in Photocatalysis

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Abstract: With the rapid development of the economy, there is no doubt that photocatalytic technology is becoming increasingly important in the preparation of green and clean energy as well as in environmental protection fields. Traditional photocatalysts have disadvantages such as rapid electron-hole recombination and low light utilization rates, which limit their application in the field of photocatalysis. Two-dimensional (2D) semiconductor materials, due to their unique structures and properties, can suppress electron-hole recombination and shorten the bandgap to improve light utilization by constructing appropriate heterojunctions and designing defect structures, showing great potential in this field. Therefore, this article focuses on 2D semiconductor materials, comprehensively introducing recent research progress in the principles, structures, material classification, preparation, and applications of 2D materials from multiple aspects, aiming to provide basic theoretical guidance for subsequent research. Lastly, this paper finds that the unique properties of 2D semiconductors offer promising avenues for advancing photocatalytic efficiency and expanding their practical applications in sustainable energy and environmental purification.

Keywords: Two-dimensional semiconductor materials, photocatalysis, heterojunction

1. Introduction

As science and technology have advanced along with humanity, the overconsumption of fossil fuels has become a significant issue in many ways, leading to increasingly severe environmental pollution. Therefore, seeking renewable and sustainable energy sources and formulating green, environmentally friendly energy strategies are crucial for the development of future technologies [1-2]. One of them, semiconductor photocatalytic materials, is now one of the most promising technologies for converting copious solar energy into solar fuels (like H_2) [3].

Semiconductor materials have a unique band structure, including the valence band (VB) and the conduction band (CB), with a certain energy difference between them, known as the bandgap width (Eg). Electrons in the valence band absorb photon energy and are stimulated to move into the conduction band when semiconductor materials are exposed to light with energy greater than or equal to their bandgap width. After the formation of photogenerated electrons (e^-) and holes (h^+), Under the influence of an electric field or via diffusion, they move to the semiconductor material's surface, where they react with materials adsorbed there to undergo reduction and oxidation. Due to their high catalytic activity and stability, semiconductor photocatalysts have gathered more interest [4-5]. However, they also exhibit some drawbacks, such as poor absorption of visible light and fast charge recombination, which significantly reduce their practical application potential [6].

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By constructing heterojunctions with different two-dimensional (2D) semiconductor materials or other materials, 2D semiconductor materials can effectively regulate photogenerated electron-hole carrier separation and transfer, therefore enhancing catalytic efficiency. Additionally, a large proportion of surface atoms are present because of their small size effect, which provides a larger specific surface area. This offers a multitude of active sites for substrates to capture pollutant molecules and facilitates photocatalytic reactions, ensuring a faster electron transfer rate [7]. Compared to conventional semiconductor materials, strong absorption capabilities in the visible and near-infrared spectrum are demonstrated by 2D semiconductor materials, enabling more efficient utilization of solar energy. This is vital for improving the efficiency of photocatalytic reactions. This paper focuses on the current research progress on two-dimensional semiconductor photocatalytic materials, covering aspects such as structure, principles, material preparation and modification, potential applications, and future challenges, thereby laying a foundation for subsequent research.

2. Semiconductor photocatalysis principles

2.1. The basic band structure of semiconductors

In solid-state physics, when a large number of atoms combine together to form a solid, the outer electron orbitals of the atoms overlap with each other. According to quantum mechanics, these overlapping orbitals can no longer be described by the orbitals of a single atom. In solids, the energy of electrons is not continuous but quantized, forming a series of energy levels. These energy levels can be divided into different energy bands, which determine the electrical conductivity of the material. The highest energy band of a semiconductor entirely composed of electrons is called the valence band. In an insulator, there is a large bandgap between the conduction band (CB) and the valence band (VB). The conduction band is the lowest unfilled energy band in a semiconductor, where electrons can move freely and thus participate in conduction. The energy difference between the top of the valence band and the bottom of the conduction band is known as the bandgap, as illustrated in Figure 1. Since semiconductors have a narrow bandgap, they can transmit electricity by excitation of electrons from the valence band to the conduction band through thermal excitation or other methods. The energy level at which there is a 50% chance of electron occupation in a semiconductor is known as the Fermi level. It is situated in the center of the bandgap at absolute zero temperature, and as the temperature increases, it shifts toward the conduction band.

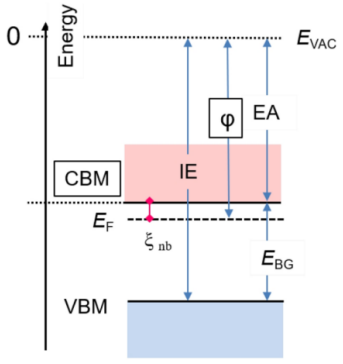


Figure 1: Energy level scheme for n-doped semiconductors and the corresponding derived quantities [8]

As is shown in Figure 1, conduction band minimum and valence band maximum are denoted as CBM and VBM, respectively. The Fermi level is located at EF. IE is the ionization energy, EA is electron affinity, $\emptyset$ is work function, and E_{BG} is the band gap. The reference energy of an electron in vacuum at rest is known as E_{VAC}.

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2.2. The basic process of photocatalytic reactions

Figure 2 shows that the photocatalytic process mainly includes four steps. First, the semiconductor materials capture and collect light energy. Secondly, the photogenerated charge carriers are generated. Electrons in the valence band (VB) absorb the energy of photons and move to the conduction band (CB) when semiconductor materials are exposed to photons with energy larger than or equal to the bandgap width (E_g), thereby creating photogenerated electrons and holes (e^- and e^--h^+). For example, the common semiconductor photocatalyst titanium dioxide (TiO_2) has an Eg of about 3.2 eV, and it generates photogenerated electrons and holes when exposed to ultraviolet light with a wavelength of about 387 nm or less.

Thirdly, the migration of photogenerated charge carriers, which can be divided into bulk migration and surface migration. Bulk migration is the movement of Photogenerated holes and electrons within the semiconductor material. Due to the opposite charges of electrons and holes, there is a Coulomb force interaction between them, and the electric field within the semiconductor material also affects their migration. During this process, some photogenerated charge carriers may recombine within the semiconductor, releasing the absorbed light energy in the form of heat, which is also one of the reasons for reducing the photocatalytic efficiency of semiconductor materials. Surface migration refers to photogenerated charge carriers migrating towards the surface of the semiconductor material. Since there are numerous defects and dangling bonds on the surface of the semiconductor material, these surface states can act as trapping centers for photogenerated charge carriers, promoting their migration to the surface.

Fourth, photogenerated holes (e^--h^+) arriving at the surface of the semiconductor have strong oxidizing power and oxidize substances adsorbed on the material's surface, while photogenerated electrons have strong reducing properties. Under the combined action of the two, various redox reactions occur, such as the production of H_2, O_2, CO_2 , N_2 and other substances.

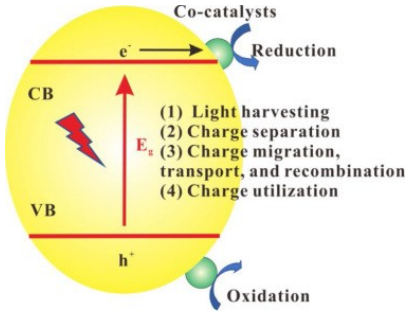


Figure 2: The four main steps in photocatalysis process [2]

2.3. The influence of semiconductor bulk and surface defects

Bulk and surface defects in semiconductors can greatly influence the photocatalytic reaction activity to a certain extent. New energy levels may be introduced into the semiconductor material's bandgap via bulk imperfections, allowing it to absorb photons with lower energy and expanding the range of light absorption wavelengths. This improves the utilization rate of light sources such as solar energy, thereby enhancing the photocatalytic reaction activity. Additionally, bulk defects can act as charge carrier traps, temporarily capturing photogenerated electrons or holes, which extends the lifetime of charge carriers and the availability of thus providing more active charge carriers for photocatalytic reactions. Surface defects can cause unsaturated atomic coordination on the semiconductor surface, leading to numerous dangling bonds. These bonds and unsaturated sites can serve as active sites for photocatalytic reactions, adsorbing reactant molecules, reducing the activation energy, and increasing the reaction rate. For example, oxygen vacancies on the semiconductor surface can adsorb oxygen

DOI: 10.54254/2755-2721/2025.23744

molecules, forming reactive oxygen species that participate in photocatalytic reactions. Surface defects can also induce the formation of local electric fields, spurring the separation and transfer of photogenerated charge carriers on the semiconductor surface, facilitating charge separation efficiency, and therefore enhancing photocatalytic reaction activity. However, if there are too many bulk defects in the semiconductor or if the type of defects is inappropriate may become recombination centers for charge carriers, leading to rapid recombination of photogenerated electrons and holes and thus reducing the efficiency of photocatalytic reactions. Severe bulk defects can also disrupt the crystal lattice structure of the semiconductor, reducing the material's stability and shortening its lifespan.

One common method of photocatalyst modification, defect engineering, has been successful in enhancing the catalytic activity of semiconductor photocatalysts. It improves light absorption capabilities and achieves efficient charge carrier separation and transport characteristics through controlling the surface/interface configuration and the electronic structure of photocatalysts. Moreover, the synergistic impact of many defects can accomplish the multifunctionality of photocatalysts, and defect engineering can improve the interfacial interactions between various components. Defect engineering-based photocatalytic technology therefore has a wide range of potential applications in the energy and environmental domains [9]. Common techniques for defect engineering include metallic ion doping, nonmetal ion doping, multiple-ion co-doping, thermal annealing, and ion irradiation.

3. Two-dimensional semiconductor photocatalytic materials

3.1. The classification and characteristics

Table 1 shows the five major classifications and charateristics of two-dimensional semiconductor materials.

Table 1: The classification of two-dimensional semiconductor materials

Material category	Material Composition	Features
Graphene-like	Composed of carbon atoms arranged in sp^2 hybridized orbitals, can be single-layer or multi-layer	High strength, high toughness, ultra-high electron mobility, high thermal conductivity, and excellent light absorption ability within a certain wavelength range
Transition Metal Dichalcogenides (TMDs)	Commonly structured with transition metal M and chalcogen element X forming MX_2	For example, MoS_2 has excellent electron and hole mobility, with a bandgap of about 1.2-1.9 eV
Black Phosphorus-like	The crystal structure is composed of phosphorus atoms forming a hexagonal structure, with atoms in a single layer not lying in the same plane, and the arrangement is directional	High carrier mobility, and the bandgap can be tuned with the number of layers
Hexagonal Boron Nitride (h-BN)	Composed of boron and nitrogen elements, with a structure similar to layered graphene	Wide bandgap, a good insulator, and can be used as a substrate for two-dimensional semiconductor materials
MXenes-like	Composed of several atomic layers of transition metal carbides, nitrides, or carbonitrides	Rich in surface chemical modification properties, allowing for various chemical modifications and functionalizations

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3.2. Typical materials

Typical two-dimensional semiconductor photocatalytic materials include metal oxides, metal chalcogenides, metal oxynitrides, and non-metal photocatalysts. Among them, titanium dioxide (TiO_2) is the most famous and widely studied [10].

Titanium dioxide has strong oxidizing properties after forming electron-hole pairs, and it also has the advantages of stability, non-toxicity, and relatively low cost. It is widely used in environmental purification such as air purification, water treatment, and antibacterial disinfection. In recent years, metal nitrides (MXenes) have drawn increasing attention from researchers. They possess a large surface area and abundant surface defects, and the numerous functional groups on the surface can also effectively bind more metal nanostructures. As shown in Figure 3, these characteristics make MXene metal composite materials widely applicable in various fields [11]. In the field of photocatalysis, MXene can be utilized for various applications such as photocatalytic CO_2 reduction, photocatalytic water splitting, photocatalytic pollution degradation, and photocatalytic N_2 fixation. To promote the activity of photocatalytic reactions, it is beneficial to promote the separation of photogenerated charge carriers.As a robust supporting material, MXene can restrict the size of photocatalysts and improve the absorption rate of the reaction.

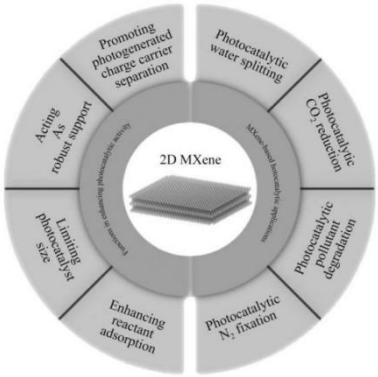


Figure 3: Application of 2D MXene in photocatalysis [11]

4. Preparation methods of two-dimensional semiconductor materials

Table 2: Bottom-up and Top-down method

Bottom-up method	Top-down method
Chemical Vapor Deposition (CVD)	Mechanical Exfoliation
Molecular Beam Epitaxy (MBE)	Physical Vapor Deposition (PVD)
Electrochemical Exfoliation	Ion Implantation
Liquid Phase Exfoliation	

The preparation methods for two-dimensional semiconductors are divided into top-down and bottom-up approaches, with some common methods as shown in Table 2. By using a top-down technique, the structure's size is down to the nanoscale. However, as seen in Figure 4, the bottom-up method creates a huge nanostructure from smaller atoms and molecules [12]. Different preparation methods for two-dimensional semiconductor materials have their own characteristics and advantages, and the performance of the prepared materials depends on a variety of factors and specific application requirements [13]. For example, in the bottom-up method, Chemical Vapor Deposition (CVD) has the advantage of being able to precisely control the thickness, composition, and large-area uniformity of the thin film. Figure 5 shows a schematic diagram of the procedure. The prepared two-dimensional

DOI: 10.54254/2755-2721/2025.23744

semiconductor materials have high crystalline quality, fewer defects, and thus good electrical performance and light absorption characteristics. However, its disadvantages are also apparent, as it requires a high temperature and high vacuum environment, with complex equipment and high costs. The preparation conditions have a significant impact on material performance and require strict control. In the top-down method, mechanical exfoliation is particularly advantageous because it is simple to operate and can produce high-quality two-dimensional semiconductor materials while retaining their intrinsic properties of the materials. However, the yield is low. Additionally, it is hard to control the shape and size of the materials obtained. The introduction of impurities and defects may also affect the consistency of material performance. Therefore, it is not suitable for large-scale production.

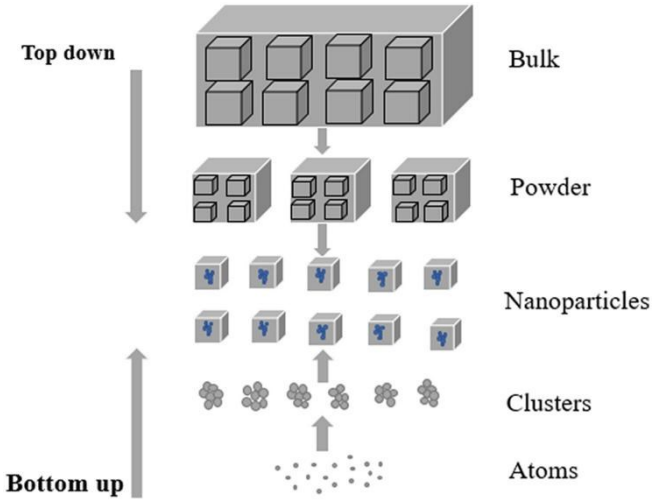


Figure 4: The top-down approach and the bottom-up approach [13]

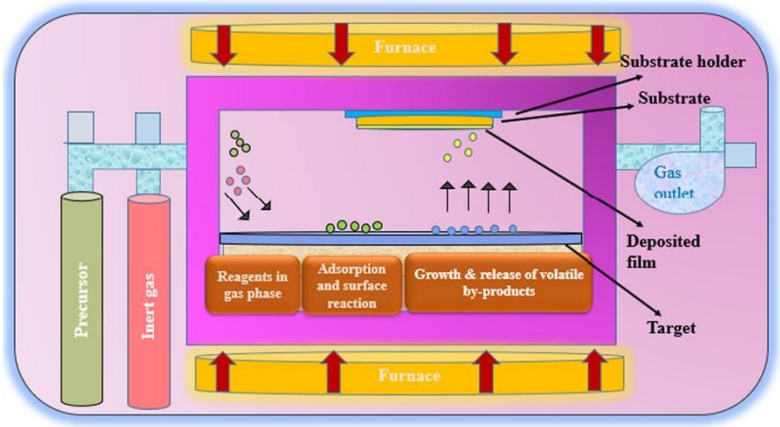


Figure 5: Schematic diagram of CVD technique [13]

5. Applications and challenges of two-dimensional semiconductor photocatalytic materials

5.1. Applications

Two-dimensional semiconductor materials can directly use low-density sunlight to generate electron-hole pairs (e^--h^+) to drive chemical reactions. Nowadays, they are widely used in various fields such as wastewater treatment, removal of harmful gases, degradation of organic pollutants,

DOI: 10.54254/2755-2721/2025.23744

production of clean energy, and energy-saving and emission reduction of carbon dioxide reduction [14-15].

5.1.1. Environmental remediation

Two-dimensional materials, due to their smaller kinetic barriers and higher surface area, are highly suitable for the photodegradation reaction of oxidizing fuels. Zhang and colleagues used a hydrothermal method to create highly crystalline BiOCl single-crystalline nanosheets [16]. BiOCl-001 and BiOCl-010 had direct semiconductor degradation efficiencies of 99% and 59%, respectively, whereas Figure 6a shows photoexcitation degradation in BiOCl nanomaterials [17]. In addition to degrading fuels, two-dimensional photocatalytic materials also have important applications in the elimination of phenolic compounds from medicine, printing and dyeing, agriculture, and other heavy industries. For instance, Liu and co-workers found that a hetero-junctioned photocatalysts based on g-C_3N_4/Bi_2WO_6/rGO (incorporated with 3 wt% of rGO) displayed a 86% and 98% reduction in ibuprofen by photocatalytic degradation under optical light and solar light irradiation, respectively [18]. Indirect semiconductors generally exhibit lower photocatalytic activity, compared to direct semiconductors. In the case of BiOCl nanomaterials, their photoexcitation performance is significantly higher under UV light than under visible light. Furthermore, BiOCl and BiOCl-OH photocatalysts were created by Yang et al. to effectively photocatalyze and degrade Rhodamine B dye in wastewater when exposed to UV light at a wavelength of 365 nm, as depicted in Figure 6b and 6c.

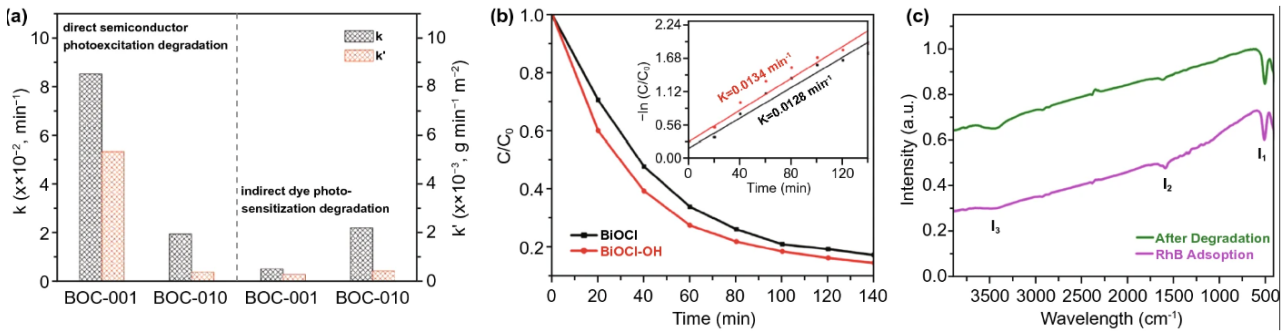


Figure 6: (a) Direct semiconductor photoexcitation pollutant degradation in single-crystalline BiOCl nanosheets under UV light [16]. (b), (c) BiOCl and BiOCl-OH photocatalyst for UV light driven photocatalytic dye degradation [19]

5.1.2. Energy conversion

Energy crisis and environmental pollution increase the demand for hydrogen energy development in various countries.The hydrogen evolution reaction (HER) is the cathodic reaction which can be depicted as $2H^+ + 2e^- \rightarrow H_2$, known as the half part of water splitting [20]. Numerous studies have revealed that two-dimensional photocatalytic materials have the potential to be used as efficient catalysts for HER. For example, using bulk black phosphorous, Ma and colleagues created ice-assisted exfoliated BP/g-C_3N_4 nanosheets that demonstrated great lateral dimensions, low density of anomalous structural flaws, and good product quality [21]. Figure 7a inllustrates the absorption spectra of BP, g-C_3N_4, and BP/g-C_3N_4 nanosheets indicate that BP nanosheets exhibit a broad absorption range spanning the ultraviolet, visible and near-infrared regions. In contrast, g-C_3N_4 and BP/g-C_3N_4 nanosheets' absorption edges are observed at approximately 466 nm and 474 nm. Figure 7b, 7c and 7d show that BP/g-C_3N_4 nanosheets are better than other components in total amount of hydrogen generation product and hydrogen generation rate.

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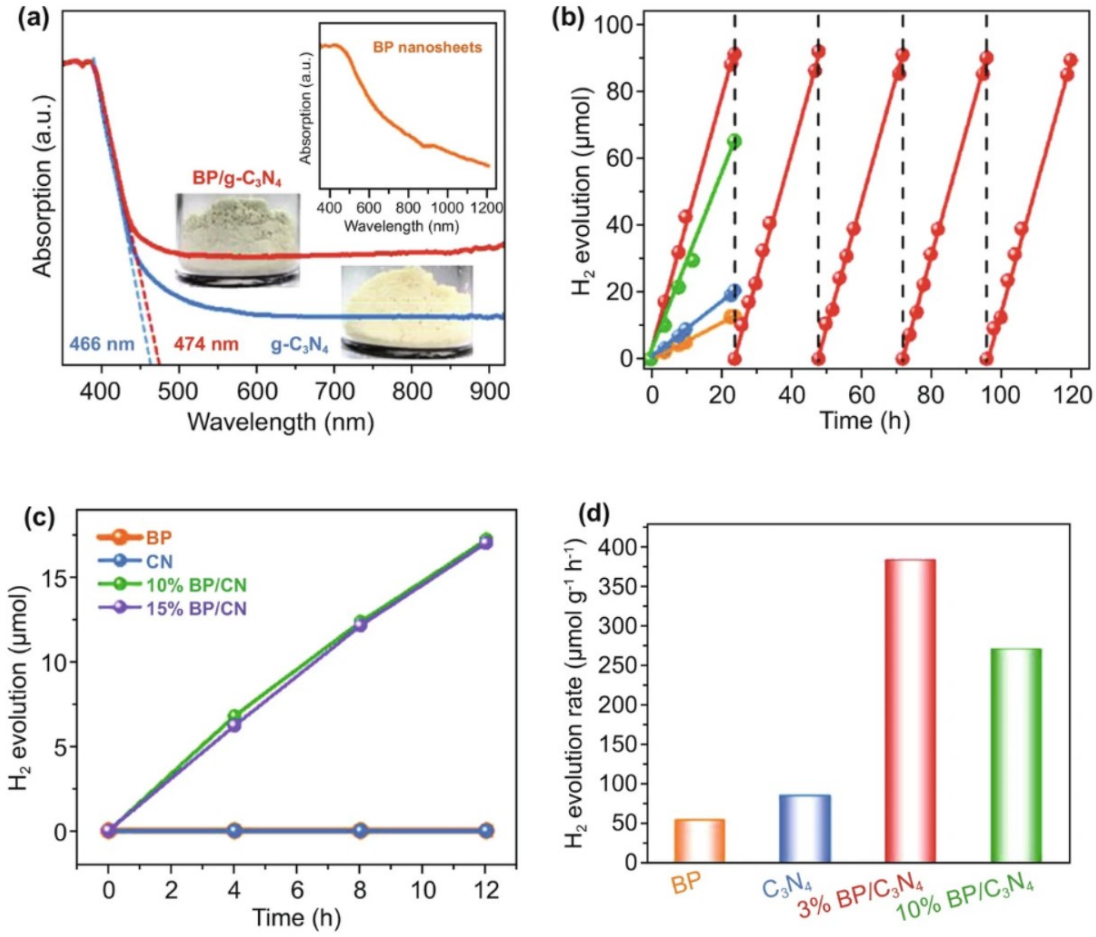


Figure 7: (a) BP/g-C_3N_4 nanosheets light absorption spectrum.(b), (c)Total amount of hydrogen generation product. (d) Hydrogen generation rate [21]

5.1.3. Biomedical science

Since the 21st century, cancer has been one of the greatest threats to human society. Du's group illustrated cancer therapy by employing 2D nanomaterials based on rare-earth metals [22-23]. Dai et al. synthesized two-dimensional O-BiOCl-PVP nanosheets with oxygen vacancies by hydrothermal method, and constructed oxygen vacancies on the surface of the material by irradiating ultraviolet light. This material, combined with its unique physicochemical properties and photocatalytic effects, successfully achieved efficient ablation of tumors, as illustrated in Figure 8a and 8b.

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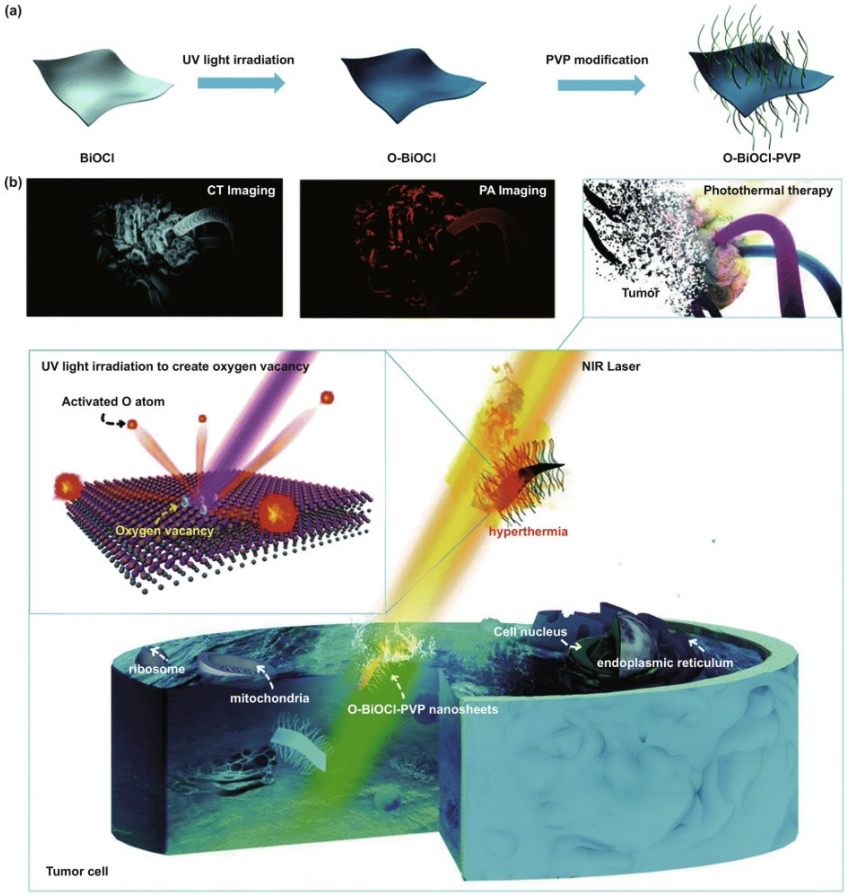


Figure 8: (a) Preparation of O-BiOCl-PVP nanosheets. (b) O-BiOCI-PVP nanosheets for tumor imaging and therapy [24]

5.2. Challenges

With the continuous advancement of research, an increasing number of high-performance two-dimensional semiconductor materials have been developed, showcasing remarkable properties. However, they still face significant challenges in practical applications.

One of the primary challenges is the recombination of photogenerated charge carriers, significantly limiting the photocatalytic efficiency. While constructing appropriate heterojunctions and introducing defect structures can mitigate this issue, these approaches also increase the complexity of material synthesis and processing. Moreover, while defect engineering can effectively modulate the electronic structure and optical properties of materials, an excessive concentration of defects may act as recombination centers, thereby diminishing the photocatalytic efficiency. Therefore, precise control over defect concentration and distribution is essential. Secondly, although two-dimensional photocatalytic materials can harness low-density sunlight, most of these materials exhibit a wide band gap, primarily absorbing ultraviolet light. This results in limited utilization of visible and infrared light, leading to low overall light energy conversion efficiency. To extend the light absorption range, researchers have explored strategies such as doping, surface modification, and band engineering to tailor the band gap structure. However, these approaches often face challenges related to stability and reproducibility in practical applications. For instance, doping may introduce impurity levels, which can adversely affect charge carrier mobility and separation efficiency.

In addition, the stability of some two-dimensional materials remains a critical issue in practical applications. Certain sulfides and oxides are prone to photocorrosion under prolonged light exposure,

DOI: 10.54254/2755-2721/2025.23744

leading to performance degradation. Enhancing the chemical and photostability of these materials is therefore a key focus for future research. Potential solutions include surface coating, the introduction of protective layers, or the development of novel stable material systems.

Finally, despite the development of numerous high-performance two-dimensional semiconductor photocatalytic materials, their complex synthesis processes, high costs, and low yields hinder large-scale commercialization. For example, methods like mechanical exfoliation and chemical vapor deposition (CVD) while capable of creating superior materials, are limited by low production efficiency and high costs.

Therefore, the development of simple, low-cost, efficient and scalable synthesis methods for two-dimensional semiconductor photocatalytic materials remains a critical research direction for future advancements. By optimizing synthesis techniques, exploring innovative approaches such as liquid-phase exfoliation and self-assembly, and leveraging advanced tools like machine learning for material design, researchers can accelerate the transition of these materials from laboratory research to practical applications.

6. Conclusion

Two-dimensional semiconductor materials, owing to their unique electronic and band structures, as well as their large specific surface area and quantum size effects, have a wide range of applications in the generation of green and clean energy, energy conservation, and emission reduction. The basic band structure of two-dimensional semiconductor materials, the principles of two-dimensional semiconductor photocatalysis, the classification and preparation of two-dimensional materials, and their applications and challenges are the four main topics covered in this paper, which offers a comprehensive introduction to the research progress of two-dimensional semiconductor photocatalytic materials in recent years. It includes a detailed discussion on the principles of photocatalysis and the classification and preparation of materials, offering guidance for future research. However, this paper's shortcomings lie in the lack of experimental data to support the research, which is based solely on existing literature. Subsequent researches can build on this foundation and conduct more rigorous experimental validation.

References

[1] *Palagiri, B., Murid, H., Young-Kwon, P. (2022). Recent advancements on the sustainable biochar-based semi conducting materials for photocatalytic applications: A state-of-the-art review [J]. Journal of Cleaner Produ ction, 330.*

[2] *Guangfu, L., Chunxue, L., Shi-Yong, L., et al. (2022). Z-scheme systems: From fundamental principles to characterization, synthesis, and photocatalytic fuel-conversion applications [J]. Physics Reports, 983, 1-41.*

[3] *Bhavani, P., Kumar, D. P., et al. (2018). Multidirectional-charge-transfer urchintype Mo-doped $W_{18}O_{49}$ nanostructures on CdS nanorods for enhanced photocatalytic hydrogen evolution [J]. Catalysis Science & Technology, 8(7), 1880–1891.*

[4] *B. Yang, X. Li, Q. Zhang, X. Yang, J. Wan, G. Liao, J. Zhao, R. Wang, J. Liu, R.D. Rodriguez, X. Jia. (2022). Ultrathin porous carbon nitride nanosheets with well-tuned band structures via carbon vacancies and oxygen doping for significantly boosting H_2 production, Appl. Catal. B: Environ. 314, 121521.*

[5] *H. Zhu, S. Cai, G. Liao, Z. Gao, X. Min, Y. Huang, S. Jin, F. Xia. (2021). Recent advances in photocatalysis based on bioinspired superwettabilities, ACS Catal. 11, 14751–14771.*

[6] *H. Wang, L. Zhang, Z. Chen, J. Hu, S. Li, Z. Wang, J. Liu, X. Wang. (2014). Semiconductor heterojunction photocatalysts: Design, construction, and photocatalytic performances. Chemical Society Reviews, 43(14), 5234–5244.*

[7] *Haiwei, Y., Huiqi, W., Zhuolin, P., et al. (2023). Research progress on two-dimensional materials/TiO_2 composite materials in photocatalysis [J]. Journal of Materials Heat Treatment, 44(02), 13-29.*

[8] *Kavan, L. (2024). Electrochemistry and band structure of semiconductors (TiO_2, SnO_2, ZnO): Avoiding pitfalls and textbook errors [J]. Journal of Solid State Electrochem, 28(3), 829–845.*

DOI: 10.54254/2755-2721/2025.23744

[9] Guojing, W., Shasha, L., et al. (2024). Advancements in heterojunction, cocatalyst, defect and morphology engineering of semiconductor oxide photocatalysts [J]. Journal of Materiomics, 10(2), 315-338.
[10] Ruohang, X., Dandan, C., Weichang, H. (2023). Research progress of two-dimensional semiconductor photocatalytic materials [J]. Natural Journal, 45(05), 355-362.
[11] Yantao, S., Zhi, Y., Lei, C. (2024). Research progress of MXene and its metal composites in photocatalysis [J]. Journal of Jilin Normal University (Natural Science Edition), 45(01), 98-104.
[12] Christian P, Von Der Kammer F, Baalousha M, Hofmann T. (2008). Nanoparticles: Structure, properties, preparation and behavior in environmental media. Ecotoxicology, 17(5), 326–43. Springer. Jul. 06.
[13] Namra A, Muhammad A K, Sara S, et al. (2022). Synthesis of nanomaterials using various top-down and bottom-up approaches, influencing factors, advantages, and disadvantages: A review [J]. Advances in Colloid and Interface Science, 300102597-102597.
[14] H. Wang, L. Zhang, Z. Chen, J. Hu, S. Li, Z. Wang, J. Liu, X. Wang. (2014). Semiconductor heterojunction photocatalysts: Design, construction, and photocatalytic performances, Chem. Soc. Rev. 43, 5234–5244.
[15] C. Li, X. Liu, G. Ding, P. Huo, Y. Yan, Y. Yan, G. Liao. (2022). Interior and surface synergistic modifications modulate the $SnNbO_6$/Ni-doped $ZnIn_2S_4$ S-scheme heterojunction for efficient photocatalytic H_2 evolution, Inorg. Chem. 61, 4681–4689.
[16] J. Jiang, K. Zhao, X. Xiao, L. Zhang. (2012). Synthesis and facetdependent photoreactivity of biocl single-cr ystalline nanosheets. J. Am. Chem. Soc. 134, 4473–4476.
[17] Weiqi Q., Suwen X., Xiaoming Z., et al. (2021). Differences and Similarities of Photocatalysis and Electrocatalysis in Two-Dimensional Nanomaterials: Strategies, Traps, Applications and Challenges. Nano-micro letters, 13(1), 156.
[18] S.-H. Liu, W.-T. Tang, P.-H. Chou. (2020). Microwave-assisted synthesis of triple 2D g-C_3N_4/Bi_2WO_6/rGO composites for ibuprofen photodegradation: Kinetics, mechanism and toxicity evaluation of degradation products. Chem. Eng. J. 387, 124098.
[19] S. Wu, J. Xiong, J. Sun, Z. D. Hood, W. Zeng, et al. (2017). Hydroxyldependent evolution of oxygen vacancies enables the regeneration of biocl photocatalyst. ACS Appl. Mater. Interfaces 9, 16620–16626.
[20] C. Zhang, Y.M. Shi, Y.F. Yu, Y.H. Du, B. Zhang. (2018). Engineering sulfur defects, atomic thickness, and porous structures into cobalt sulfide nanosheets for efficient electrocatalytic alkaline hydrogen evolution. ACS Catal. 8, 8077–8083。
[21] Q. Zhang, S. Huang, J. Deng, D.T., Gangadharan, F. Yang, et al. (2019). Ice-assisted synthesis of black phosphorus nanosheets as a metal-free photocatalyst: 2D/2D heterostructure for broadband H_2 evolution. Adv. Funct. Mater. 29, 1902486.
[22] M.M. Wu, Y.M. Xue, N. Li, H.Y. Zhao, B. Lei, et al. (2019). Tumormicroenvironment-induced degradation of ultrathin gadolinium oxide nanoscrolls for magnetic-resonance-imagingmonitored, activatable cancer chemot herapy. Angew. Chem. Int. Ed. 58, 6880–6885.
[23] J.L. Xia, Y.M.L. Xue, L.L. Xu, M.Z. Sun, N. Li, et al. (2020). Multimodal channel cancer chemotherapy by 2D functional gadolinium metal-organic framework. Natl. Sci. Rev.
[24] C. Dai, R.Z. Hu, C.M. Wang, Z. Liu, S.J. Zhang et al. (2020). Defect engineering of 2D BiOCl nanosheets for photonic tumor ablation. Nanoscale Horiz. 5, 857–868.