


 Cite this: *RSC Adv.*, 2022, 12, 32480

In situ fabrication of a novel CdS/ZnIn₂S₄/g-C₃N₄ ternary heterojunction with enhanced visible-light photocatalytic performance†

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In this study, a novel g-C₃N₄-based ternary heterojunction was rationally designed and constructed by the *in situ* growth of ZnIn₂S₄ nanosheets and CdS nanoparticles onto the g-C₃N₄ nanosheets using a facile two-step oil-bath method. Through optimizing the proportion of ZnIn₂S₄ and CdS component, g-C₃N₄ nanosheets coupled with ZnIn₂S₄ nanosheets and CdS nanoparticles (denoted as CdS/ZnIn₂S₄/g-C₃N₄) exhibited obviously higher photocatalytic properties for RhB removal than the single-component and dual-component systems. Among the as-obtained ternary photocatalysts, it was found that the ternary CdS/ZnIn₂S₄/g-C₃N₄-0.2 photocatalyst displayed the optimum photocatalytic property (96%) within a short time (30 min), which was almost 27.42 and 1.17 times higher than that of pure g-C₃N₄ and binary ZnIn₂S₄/g-C₃N₄-0.7 composite. The excellent activity of the ternary CdS/ZnIn₂S₄/g-C₃N₄ heterostructure is assigned to the synergetic effects of CdS nanoparticles, ZnIn₂S₄ nanosheets and g-C₃N₄ nanosheets, which not only broaden the visible-light absorption range, but also improve the charge mobility and separation rate, thus boosting the visible-light-driven photocatalytic property of g-C₃N₄.

 Received 8th October 2022
 Accepted 8th November 2022

DOI: 10.1039/d2ra06328j

rsc.li/rsc-advances

1. Introduction

With the rapid development of modern industrialization, environmental pollution, especially water pollution, has become a deadly threat to human health and environmental security due to its long-term harm to human beings and aquatic organisms.^{1–3} Traditional techniques such as physical,⁴ chemical⁵ and biological methods⁶ for eliminating residual organic contaminants from water suffer from inefficiency and secondary pollution. Nowadays, photocatalysis, as a green technology, has been widely accepted as a potential alternative method for energy conversion and environmental governance due to its high efficiency and environmentally friendliness.^{7–9} Unfortunately, insufficient utilization of visible light restricts

the practical application of conventional photocatalysts such as TiO₂ and ZnO.^{10,11} Thus, the development of efficient visible-light-responsive photocatalysts is still greatly desired.

In recent years, the use of two-dimensional (2D) metal-free graphite carbon nitride (g-C₃N₄) in the field of visible-light photocatalysis for hydrogen production,^{12,13} CO₂ reduction^{14,15} and organic pollutants degradation^{16,17} has attracted extensive attention owing to its excellent stability and environment friendly preparation process. Nonetheless, the pristine g-C₃N₄ still suffers from poor separation of the photo-induced charge carriers and insufficient absorption of visible light, which severely restrict its actual application.^{18,19} Various strategies, such as construction of heterojunctions,^{20,21} elements doping,^{22,23} and morphologies regulation,^{24,25} have been proposed to control and modify g-C₃N₄. Of which, construction of heterojunctions with other narrow-band-gap semiconductors is designated as an effective strategy to overcome the above-mentioned shortcomings of unitary g-C₃N₄.^{26,27} Indium zinc sulfide (ZnIn₂S₄), as a ternary chalcogenide, has been widely used in the field of photocatalysis owing to wide visible-light response range, excellent photoelectric properties, and remarkable chemical stability.^{28,29} More importantly, ZnIn₂S₄ possesses an appropriate bandgap structure, which can match well with g-C₃N₄.³⁰ Actually, the construction of ZnIn₂S₄/g-C₃N₄ heterojunction has been proved to be an effective measure to achieve high separation and migration efficiency of photo-generated carriers.³¹ Additionally, cadmium sulphide (CdS) is also an attractive candidate to couple with g-C₃N₄ for constructing the heterojunction photocatalyst owing to its excellent

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† Electronic supplementary information (ESI) available: The XRD patterns of ZnIn₂S₄/g-C₃N₄ composites, XPS survey spectrum and EDS element mappings of CdS/ZnIn₂S₄/g-C₃N₄-0.2, XRD spectra and SEM image of CdS/ZnIn₂S₄/g-C₃N₄-0.2 during a four-cycle experiment. See DOI: <https://doi.org/10.1039/d2ra06328j>



electronic and structural properties.^{32,33} Recently, CdS is widely used as a promoter decorating the main catalyst to further enhance the photocatalytic properties of the ternary heterostructures such as CdS/ZnIn₂S₄/TiO₂,³⁴ CdS-g-C₃N₄-GA³⁵ and CdS/Bi₂₀TiO₃₂/Bi₄Ti₃O₁₂.³⁶ Thus, we expect the introduction of CdS nanoparticles to the binary ZnIn₂S₄/g-C₃N₄ heterojunction will further enhance the photocatalytic property of g-C₃N₄.

In this work, we designed and prepared a novel ternary-component CdS/ZnIn₂S₄/g-C₃N₄ heterojunction *via* thermal polymerization followed by a two-step *in situ* deposition method. The photocatalytic property of the as-obtained ternary samples was investigated *via* degrading contaminant Rhodamine B (RhB) under visible light irradiation. Owing to the rational construction of ternary composite, CdS/ZnIn₂S₄/g-C₃N₄ revealed a faster transfer and separation rate of photo-induced charge carriers as well as a wider visible-light response range compared to that of g-C₃N₄ and ZnIn₂S₄/g-C₃N₄-0.7, and thus obtaining obvious higher photocatalytic activity. Finally, the underlying mechanism of CdS/ZnIn₂S₄/g-C₃N₄ is elucidated in detail to explain the improvement of the photocatalytic property.

2. Materials and methods

2.1. Materials

All the chemicals were of analytical grade and used without pretreatment. Ethylenediamine tetraacetic acid disodium (EDTA-2Na) and zinc chloride (ZnCl₂) were commercially available from Xilong Science Co., Ltd (Guangdong, China). RhB was bought from Aladdin Biochemical Technology Co., Ltd (Shanghai, China). *p*-Benzoquinone (BQ) and tertiary butyl alcohol (*t*-BuOH) were purchased from Shanghai Zhanyun Chemical Co., Ltd (Shanghai, China). Absolute ethanol (EtOH) and hydrochloric acid (HCl) were acquired from Kermel Chemical Reagent Co., Ltd (Tianjin, China). Cadmium chloride hemi (pentahydrate) (CdCl₂·2.5H₂O) and indium chloride (InCl₃) were supplied by Macklin Biochemical Co., Ltd (Shanghai, China). Dicyandiamine (DICY), ammonium chloride (NH₄Cl), and thioacetamide (TAA) were originated from Sino-pharm Chemical Reagent Co., Ltd (Shanghai, China). Deionized water was used during the experiments.

2.2. Preparation of g-C₃N₄ nanosheets

The g-C₃N₄ nanosheets were obtained *via* a polymerization process according to the literature.³⁷ In detail, 3 g of DICY and 15 g of NH₄Cl were transferred into a 100 mL round flask containing 50 mL of deionized water, and then the mixture was heated at 80 °C until completely evaporated. The obtained white powder underwent calcination at 550 °C for 4 h in a muffle furnace under air. Finally, light yellow powder of g-C₃N₄ nanosheets was obtained.

2.3. Synthesis of ZnIn₂S₄/g-C₃N₄ binary heterojunctions

The ZnIn₂S₄/g-C₃N₄ composites were *in situ* constructed *via* oil-bath heating. Typically, 0.2 g of g-C₃N₄ was dispersed in 50 mL of deionized water (pH = 2.5) by ultrasonic. Then calculated quantity of ZnCl₂, InCl₃, and TAA were dissolved in the above

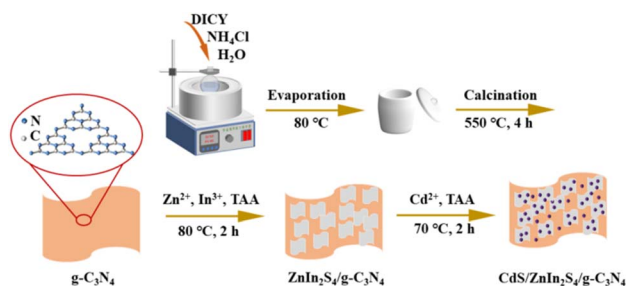
solution *via* magnetic stirring. After that, the mixture was heated at 80 °C for 2 h. After washed by water and ethanol three times as well as dried at 60 °C overnight, the target product was obtained and labelled as ZnIn₂S₄/g-C₃N₄-X (X presents the weight percent of ZnIn₂S₄ and g-C₃N₄). For reference, ZnIn₂S₄ was also prepared by same procedure but in the absence of g-C₃N₄.

2.4. Synthesis of CdS/ZnIn₂S₄/g-C₃N₄ ternary heterojunctions

The synthesis of ternary CdS/ZnIn₂S₄/g-C₃N₄ heterojunctions was performed by another oil-bath heating process. Briefly, 0.015 g of as-obtained ZnIn₂S₄/g-C₃N₄-0.7 was first dispersed in 50 mL of deionized water by magnetic stirring, while 0.05 g CdCl₂·2.5H₂O and 0.02 g of TAA were dispersed into the above solution. Afterward, the mixture was heated at 70 °C for 2 h. After centrifugation, washing and drying, the target product was collected and labeled as CdS/ZnIn₂S₄/g-C₃N₄-Y (Y presents the weight percent of CdS and ZnIn₂S₄/g-C₃N₄). For comparison, CdS, CdS/ZnIn₂S₄-0.2, and CdS/g-C₃N₄-0.2 were also prepared by same procedure in the absence of ZnIn₂S₄/g-C₃N₄-0.7 and using ZnIn₂S₄ or g-C₃N₄ instead of ZnIn₂S₄/g-C₃N₄-0.7, respectively. The detailed process utilized to prepare the CdS/ZnIn₂S₄/g-C₃N₄ composites is depicted in Scheme 1.

2.5. Characterization

The microstructure and morphologies were investigated by X-ray diffraction (XRD, XRD-6100), X-ray photoelectron spectroscopy (XPS, ESCALAB 250Xi), scanning electron microscopy (SEM, Zeiss Sigma) and transmission electron microscope (TEM, Tecnai G220 S-TWIN). Light absorption property was evaluated by UV-vis diffuse reflectance spectroscopy (UV-vis DRS, UV-2550). Photoluminescence (PL) spectra (excitation at 320 nm) were implemented on a spectrophotometer (ZolixLSP-X500A). The surface specific areas of the samples were measured by N₂ isothermal adsorption-desorption spectroscopy (Autosorb-Iq2, Quantachrome). Photoelectrochemical tests were performed on an electrochemical station (CHI660E) three-electrode cell system using 500 W Xe lamp as light source. The total organic carbon (TOC) measures were performed on a TOC analyser (TOC-2000, Metash). Electron spin resonance (ESR) spectra were acquired using an EMXnano spectrometer (Bruker).



Scheme 1 The formation procedure of CdS/ZnIn₂S₄/g-C₃N₄ ternary photocatalysts.



2.6. Evaluation of the photocatalytic activity

The photodegradation properties were evaluated by using RhB as simulated organic pollutants under the visible light irradiation provided by a 500 W Xe lamp with a cutoff filter ($\lambda \geq 420$ nm). Shortly, photocatalysts (20 mg) were dispersed in fresh RhB aqueous solution (50 mL, 50 mg L⁻¹) and stirred for 60 min in a dark environment to realize the saturation adsorption prior to the light irradiation. After given intervals, aliquots (~3 mL) were taken out, filtered by 0.22 μ m filter membrane, and traced absorbance change at 554 nm on a UV-vis spectrophotometer (Lambda 35, PerkinElmer). Furthermore, the reusability of CdS/ZnIn₂S₄/g-C₃N₄-0.2 was also investigated by recycled photocatalytic experiments.

3. Results and discussion

The purity and crystalline nature of the specimen series were firstly analyzed by XRD. As displayed in Fig. 1 and S1,[†] the characteristic pattern of the pure g-C₃N₄ are assigned to the graphite-like hexagonal phase, which ascribes well to JCPDS card no. 87-1526.³⁸ The observed diffraction peaks of pristine ZnIn₂S₄ were attributed to hexagonal crystal structure (JCPDS no. 72-0773).³⁹ The diffraction peaks of bare CdS matched well with reported value by JCPDS no. 77-2306.⁴⁰ For the binary ZnIn₂S₄/g-C₃N₄, CdS/ZnIn₂S₄ or CdS/g-C₃N₄ photocatalysts, the XRD spectra can well indexed to g-C₃N₄ and ZnIn₂S₄ or CdS, which reflects the coexistence of two phases. After CdS was further incorporated into ZnIn₂S₄/g-C₃N₄-0.7 composite, several typical peaks of CdS appear, revealing that CdS was successfully presented in CdS/ZnIn₂S₄/g-C₃N₄ composite. With the increase of ZnIn₂S₄ content in the binary ZnIn₂S₄/g-C₃N₄ composites (Fig. S1[†]) and CdS content in the ternary CdS/ZnIn₂S₄/g-C₃N₄ composites (Fig. 1), the peak intensity of ZnIn₂S₄ and CdS gradually increased, respectively. Simultaneously, it can be seen that the diffraction peak of g-C₃N₄ (002) is appearing at almost same position of the diffraction peaks of ZnIn₂S₄ (102), CdS (002), and CdS (101), so as to the peak belonging to g-C₃N₄ is

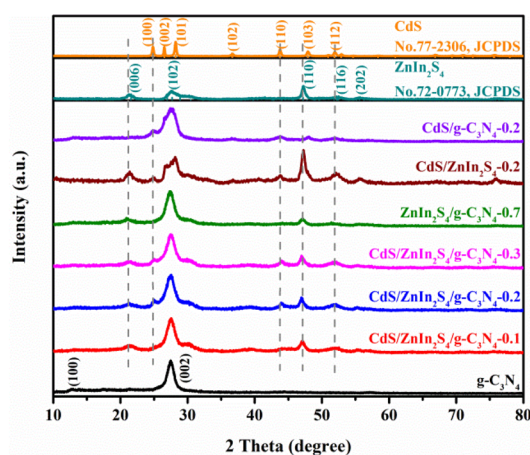


Fig. 1 The XRD patterns of g-C₃N₄, ZnIn₂S₄, CdS, CdS/g-C₃N₄-0.2, CdS/ZnIn₂S₄-0.2, ZnIn₂S₄/g-C₃N₄-0.7 and CdS/ZnIn₂S₄/g-C₃N₄-Y (Y = 0.1, 0.2 and 0.3).

possibly overlapping of the ZnIn₂S₄ (102), CdS (002), and CdS (101) peaks, and thus possessing a distinguishable diffraction widening. Besides, no other peaks could be detected in the XRD spectra of single-component, binary-component, and ternary-component photocatalysts, indicating that there are no impurities produced during the synthesis.

The surface chemical composition and valence state of CdS/ZnIn₂S₄/g-C₃N₄-0.2 were further evaluated by XPS. As depicted in Fig. S2,[†] the survey XPS spectrum declared the co-occurrence of Cd, S, Zn, In, S, C and N elements in the ternary sample. In the C 1s spectrum (Fig. 2a), the peaks centered at 288.1 and 284.8 eV could be ascribed to graphitic carbon (C=C) and sp²-hybridized carbon (N-C=N), respectively.⁴¹ For N 1s (Fig. 2b), the binding energies of peaks at 398.4, 399.5, and 400.7 eV are derived from sp²-hybridized nitrogen (C-N=C), tertiary nitrogen N-(C)₃ groups and amino functions carrying hydrogen (C-N-H), separately.⁴² The S 2p XPS regions could be deconvoluted into two peaks at 161.6 eV (S 2p_{3/2}) and 162.9 eV (S 2p_{1/2}) seen in Fig. 2c, which implies the existence of S²⁻ ions in the ternary composite.⁴³ The high-resolution XPS spectrum of Zn 2p (Fig. 2d) displayed two significant peaks located at 1044.7 eV (Zn 2p_{1/2}) and 1021.6 eV (Zn 2p_{3/2}), which corresponded to the Zn²⁺ state.⁴⁴ The In 3d XPS spectrum shows two characteristic peaks at 444.7 and 452.3 eV, corresponding to In 3d_{5/2} and In 3d_{3/2} of In³⁺ in ZnIn₂S₄ (Fig. 2e).⁴⁵ The Cd 3d XPS spectrum reveals two strong peaks at 406.0 (Cd 3d_{5/2}) and 412.5 eV (Cd 3d_{3/2}), which are ascribed to the state of Cd²⁺ (Fig. 2f).⁴⁶

The morphology and microstructures of as-obtained photocatalysts were systematically characterized *via* SEM and TEM, and the results are depicted in Fig. 3. Fig. 3a shows the morphology of as-constructed g-C₃N₄ with irregular nanosheets. In Fig. 3b, the pure ZnIn₂S₄ with hierarchical flowerlike architecture consisted of thin nanosheets is also successfully constructed *via* a simple oil-bath method. As for ZnIn₂S₄/g-C₃N₄-0.7 (Fig. 3c), ZnIn₂S₄ nanosheets uniformly disperse on the surface of g-C₃N₄, meaning that a typical 2D/2D heterojunction forms between ZnIn₂S₄ and g-C₃N₄. The SEM image (Fig. 3d) of CdS/ZnIn₂S₄/g-C₃N₄-0.2 clearly shows a laminated structure consisting of ZnIn₂S₄ nanosheets and g-C₃N₄ nanosheets. Nevertheless, CdS nanoparticles cannot be clearly distinguished, which may be ascribed to the small particle size of CdS, the

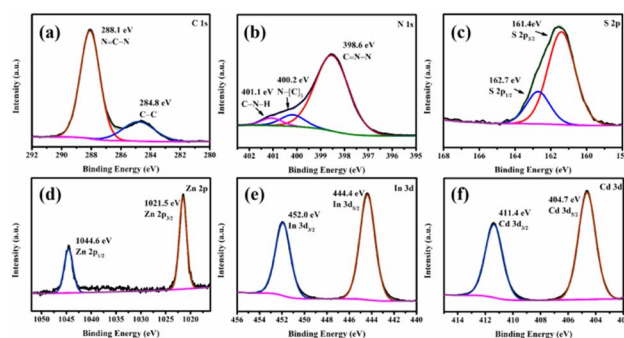


Fig. 2 The XPS spectra of CdS/ZnIn₂S₄/g-C₃N₄-0.2: C 1s (a), N 1s (b), S 2p (c), Zn 2p (d), In 3d (e), and Cd 3d (f).



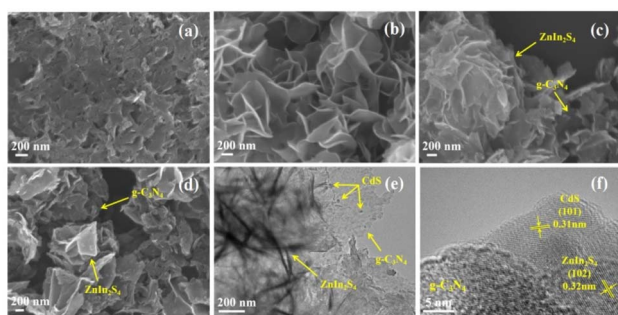


Fig. 3 SEM images of g-C₃N₄ (a), ZnIn₂S₄ (b), ZnIn₂S₄/g-C₃N₄-0.7 (c), and CdS/ZnIn₂S₄/g-C₃N₄-0.2 (d); TEM (e) and HR-TEM (f) images of CdS/ZnIn₂S₄/g-C₃N₄-0.2.

corresponding energy-dispersive system (EDS) element mappings (Fig. S3[†]) indicate the simultaneous existence and even distribution of g-C₃N₄, ZnIn₂S₄, and CdS. Fig. 3e shows the TEM image of CdS/ZnIn₂S₄/g-C₃N₄-0.2 heterojunction, which consists of g-C₃N₄ nanosheets, ZnIn₂S₄ nanosheets, and CdS nanoparticles. High resolution TEM (HR-TEM) image (Fig. 3f) displays the lattice fringes space of 0.32 and 0.31 nm corresponded to the (102) plane of ZnIn₂S₄ and (101) plane of CdS, separately.^{47,48} These results further confirm the successful construction of target product.

Commonly, large specific surface areas may provide abundant surface active sites for the absorption of reactant molecules, and thus boosting the photocatalytic property.⁴⁹ Thereby, the specific surface area and pore volume distribution of g-C₃N₄, ZnIn₂S₄/g-C₃N₄-0.7, and CdS/ZnIn₂S₄/g-C₃N₄-0.2 were investigated by N₂ adsorption method. As displayed in Fig. 4a, all three samples show the classical type IV isotherms with the type H₃ hysteresis loops, indicating the existence of mesoporous structure.⁵⁰ The specific surface area (Fig. 4a, inset) of pristine g-C₃N₄ is 25.186 m² g⁻¹. After successively coupling with ZnIn₂S₄ and CdS, the specific surface area of g-C₃N₄ increases from 25.186 m² g⁻¹ to 40.944 and 49.175 m² g⁻¹, which suggests that ZnIn₂S₄ and CdS can obviously improve the BET surface area of g-C₃N₄ providing more active sites for photocatalysis. Moreover, the pore size distributions are displayed in Fig. 4b, the results show that the pore sizes (Fig. 4b, inset) of all three samples distribute at 2–10 nm, which further confirm the presence of mesopores, the mesoporous characteristics are beneficial for producing high surface areas.

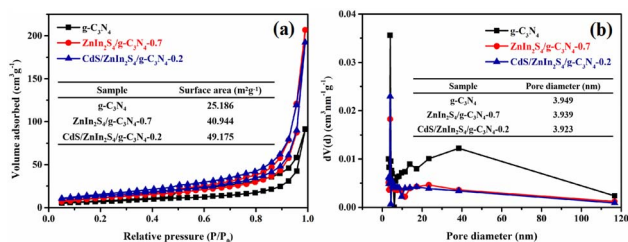


Fig. 4 N₂ adsorption–desorption isotherms (a) and the corresponding pore size distribution plots (b) of g-C₃N₄, ZnIn₂S₄/g-C₃N₄-0.7 and CdS/ZnIn₂S₄/g-C₃N₄-0.2.

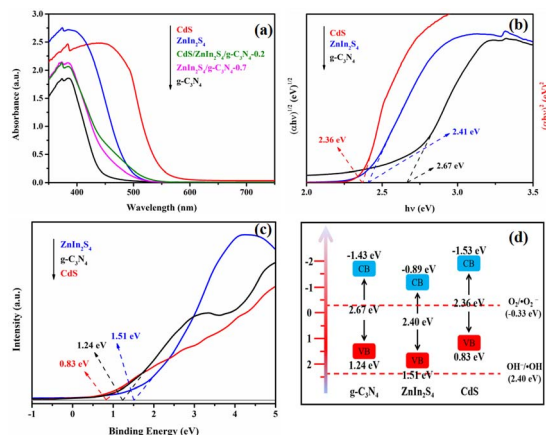


Fig. 5 UV-vis DRS of g-C₃N₄, ZnIn₂S₄, CdS, ZnIn₂S₄/g-C₃N₄-0.7 and CdS/ZnIn₂S₄/g-C₃N₄-0.2 (a); the band gap (b), VB-XPS (c), and energy band structure (d) of g-C₃N₄, ZnIn₂S₄, CdS.

The light absorption capacity of the g-C₃N₄, ZnIn₂S₄, CdS, ZnIn₂S₄/g-C₃N₄-0.7 and CdS/ZnIn₂S₄/g-C₃N₄-0.2 photocatalysts was investigated by UV-vis DRS, and the related results are depicted in Fig. 5. Based on the results displayed in Fig. 5a, the light absorption thresholds of g-C₃N₄, ZnIn₂S₄, and CdS are approximately 446 and 500, 562 nm, separately, which are basically in accord with the previous reports.^{51,52} After *in situ* growing ZnIn₂S₄ and CdS on g-C₃N₄, the light absorption threshold of the ZnIn₂S₄/g-C₃N₄-0.7 and CdS/ZnIn₂S₄/g-C₃N₄-0.2 heterojunctions have significant red shifts, indicating that the combination of ZnIn₂S₄ and CdS can effectively widen the light absorption range of g-C₃N₄. The wider the light absorption range, the more conducive it is to utilize visible light, which is more beneficial to enhance the photocatalytic performance. Fig. 5b shows the bandgap energies (E_g) of g-C₃N₄, ZnIn₂S₄, and CdS estimated by Tauc plot method,⁵³ which are 2.67, 2.40 and 2.36 eV, separately. To further obtain the band edges of g-C₃N₄, ZnIn₂S₄, and CdS, their valence band XPS spectra (VB-XPS) were further measured. According to the VB-XPS results depicted in Fig. 5c, the valence band (VB) potentials of g-C₃N₄, ZnIn₂S₄, and CdS are 1.24, 1.51, and 0.83 eV, separately. E_g and edge potentials of VB and conduction band (CB) possess the relationship: $E_g = E_{VB} - E_{CB}$. As a result, the CB potentials of g-C₃N₄, ZnIn₂S₄, and CdS can be determined as -1.43, -0.89, and -1.53 eV, separately. Accordingly, the overall band structure positions of g-C₃N₄, ZnIn₂S₄, and CdS can be obtained and the results are shown in Fig. 5d.

The internal electron transfer behaviors of photo-induced charge carrier were firstly analyzed by PL technique. As we all know, a lower PL signal represents a higher separation efficiency of photo-generated charge carrier.⁵⁴ As illustrated in Fig. 6a, intense emission peak near 450 nm can be observed for the pristine g-C₃N₄, indicating an inherent nature of a low separation rate. In contrast, the PL intensity of the ZnIn₂S₄/g-C₃N₄-0.7 and heterojunction obviously quenched. After further coupling with CdS, the obtained CdS/ZnIn₂S₄/g-C₃N₄-0.2 ternary heterojunction displays a lower PL signal, indicating that the charge

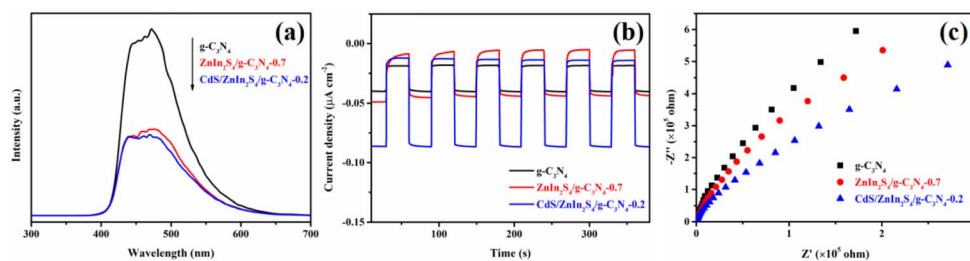


Fig. 6 PL spectra (a), transient photocurrent responses (b), and Nyquist plots (c) of $g\text{-C}_3\text{N}_4$, $\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4\text{-}0.7$ and $\text{CdS}/\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4\text{-}0.2$.

carriers' separation efficiency of $g\text{-C}_3\text{N}_4$ can be accelerated by forming ternary heterojunction with ZnIn_2S_4 and CdS . To verify this result, photoelectrochemical measurements were performed to support the improved separation and transfer efficiency. Generally, higher photocurrent intensity or smaller semicircle radius means higher separation and transfer efficiency of photo-generated charge carriers.⁵⁵ As displayed in Fig. 6b, the photocurrent intensity of $\text{CdS}/\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4\text{-}0.2$ composite is obviously higher than that of $\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4\text{-}0.7$ and $g\text{-C}_3\text{N}_4$. The results of electrochemical impedance spectroscopy (EIS) (Fig. 6c) show $\text{CdS}/\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4\text{-}0.2$ possesses the lowest charge transfer impedance due to its smaller semicircle radius than the two other samples. The photoelectrochemical results forcefully verify that the constructing of $\text{CdS}/\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4\text{-}0.2$ ternary composite significantly promotes the charge carrier transfer and separation, and thus delivering boosting photocatalytic property.

The visible-light photocatalytic activities of the pristine $g\text{-C}_3\text{N}_4$, ZnIn_2S_4 , CdS , $\text{CdS}/g\text{-C}_3\text{N}_4\text{-}0.2$, $\text{CdS}/\text{ZnIn}_2\text{S}_4\text{-}0.2$, and a series of $\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4$ and $\text{CdS}/\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4$ composites were evaluated by the degradation of RhB. As depicted in Fig. 7a, the degradation efficiency of ZnIn_2S_4 and CdS is obviously higher than that of $g\text{-C}_3\text{N}_4$ due to their wider visible-light response range. The photocatalytic properties of $g\text{-C}_3\text{N}_4$ and ZnIn_2S_4 are obviously improved after coupling with ZnIn_2S_4 or CdS . Among of the $\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4$ composites, $\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4\text{-}0.2$ exhibited the highest degradation efficiency of 82% within 30 min. When $\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4\text{-}0.2$ further coupled with CdS , the photocatalytic activities could be obviously improved. Among the ternary photocatalysts, $\text{CdS}/\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4\text{-}0.7$ exhibited the highest degradation efficiency, in which 96% of RhB could be degraded within 30 min. Moreover, the photocatalytic kinetics of RhB degradation were evaluated using the pseudo-first-order model (Fig. 7b). The $\text{CdS}/\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4\text{-}0.2$ showed the highest apparent rate constant, approximately 0.10868 min^{-1} , which is far greater than that of the pristine $g\text{-C}_3\text{N}_4$ (0.00043 min^{-1}), $\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4\text{-}0.7$ (0.05475 min^{-1}) and $\text{CdS}/g\text{-C}_3\text{N}_4\text{-}0.2$ (0.02580 min^{-1}) under the same conditions, separately. Furthermore, the TOC measurements were also carried out to investigate the mineralization abilities of photocatalysts under 30 min of visible light irradiation. As illustrated in Fig. 7c, the TOC removal efficiency of $\text{CdS}/\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4\text{-}0.2$ (84.65%) is obviously higher than that of $g\text{-C}_3\text{N}_4$ (0.40%) and $\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4\text{-}0.7$ (73.97%), which is coincident with the trend of photodegradation performance. This result fully confirms

the high mineralization ability of $\text{CdS}/\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4\text{-}0.2$ for RhB. The stability is a crucial factor affecting the actual application of the photocatalyst,⁵⁶ and thus sequential cycling experiments were performed to detect the stability of the $\text{CdS}/\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4\text{-}0.2$ ternary photocatalyst. As displayed in Fig. 7d, the photocatalytic efficiency had no obvious change after four reused tests. Besides, the structure and morphology can also be preserved after undergoing four runs of photo-degradation reaction as no noticeable change can be observed in the XRD pattern (Fig. S4†) and SEM image (Fig. S5†). The results prove that the as-prepared ternary catalysts can meet the practical application requirements.

To expound the photocatalytic mechanism of the photocatalytic activity improvement of $\text{CdS}/\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4$ photocatalysts, the predominant active species formed during the photocatalytic process were distinguished *via* a series of trapping experiments over $\text{CdS}/\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4\text{-}0.2$. In the experiments, EDTA-2Na, BQ, and *t*-BuOH were chosen as the scavengers of hydroxyl radicals ($\cdot\text{OH}$), radical superoxide ($\cdot\text{O}_2^-$), and hole (h^+), separately. Fig. 8a exhibits the addition of BQ has a significant effect on the degradation activity, which mean that $\cdot\text{O}_2^-$ was the primary active substance during the photocatalytic process. However, after adding EDTA-2Na and *t*-BuOH, the

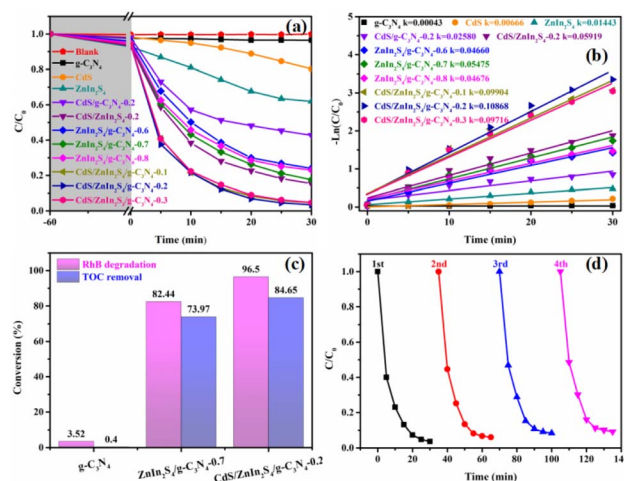


Fig. 7 Visible-light photodegradation of RhB over as-obtained samples (a) and the corresponding kinetics (b); removal rate of TOC by $g\text{-C}_3\text{N}_4$, $\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4\text{-}0.7$, and $\text{CdS}/\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4\text{-}0.2$ for RhB degradation (c); four cycling tests of photocatalytic degradation RhB for $\text{CdS}/\text{ZnIn}_2\text{S}_4/g\text{-C}_3\text{N}_4\text{-}0.2$ (d).



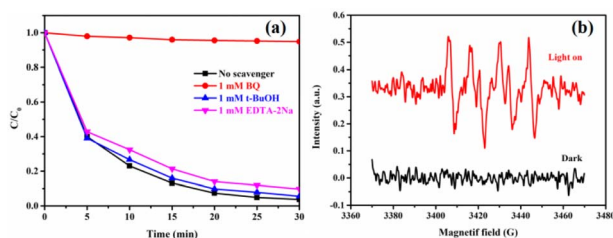
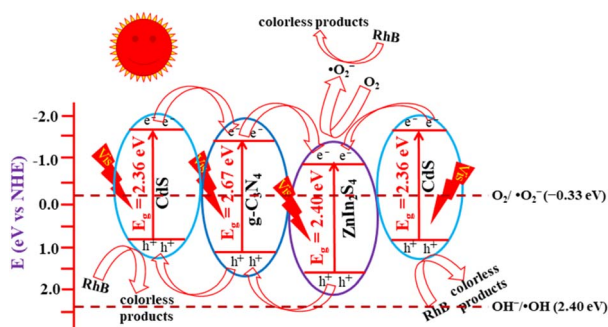


Fig. 8 Photodegradation of RhB over the CdS/ZnIn₂S₄/g-C₃N₄-0.2 photocatalyst in the presence of different radical scavengers (a); ESR detection of $\cdot\text{O}_2^-$ over CdS/ZnIn₂S₄/g-C₃N₄-0.2 (b).

removal efficiency of RhB decreased from 96% to 90% and 94%, separately, which revealed that h^+ had a weak effect on the photocatalytic reaction, while the role of $\cdot\text{OH}$ could be ignored owing to the negligible effect of EDTA-2Na on the RhB removal efficiency. Consequently, it could be inferred that the active species played a different role during the photocatalytic reaction process with a sequence of $\cdot\text{O}_2^- > \text{h}^+ > \cdot\text{OH}$. In addition, the ESR results (Fig. 8b) provided a persuasive proof for the existence of $\cdot\text{O}_2^-$ in the photodegradation reaction. No ESR signals were observed under dark, while the signals of the DMPO- $\cdot\text{O}_2^-$ adducts (intensity ratio of 1 : 1 : 1) could be easily identified after irradiating by visible light, which is fully in accord with the results of radical trapping experiments.

Based on the conclusions above, a plausible photocatalytic charge-transfer mechanism of the CdS/ZnIn₂S₄/g-C₃N₄ composite for photocatalytic degradation of RhB is put forward and displayed in Scheme 2. Under the visible light irradiation, g-C₃N₄, ZnIn₂S₄ and CdS can adsorb photons and generate a great deal of photo-induced electrons (e^-) and h^+ pairs, where the e^- and h^+ gather at CB and VB, separately. According to the calculated band structure and close contact interface, e^- in the CB of CdS can readily migrate to the CB of ZnIn₂S₄ by a one-step process or two-step process. Meanwhile, h^+ in the VB of ZnIn₂S₄ transfers to the VB of CdS under the driving force of potential difference. Then, the accumulated e^- in ZnIn₂S₄ will react with dissolved O_2 to produce $\cdot\text{O}_2^-$ due to its more negative potential than $\text{O}_2/\cdot\text{O}_2^-$ (-0.33 eV *versus* NHE),⁵⁷ while the VB potential of CdS is too low for h^+ to convert -OH into $\cdot\text{OH}$ (+2.4 eV *versus*



Scheme 2 Proposed mechanism for the visible-light photo-degradation of RhB over CdS/ZnIn₂S₄/g-C₃N₄ ternary composite.

NHE).⁵⁸ Finally, the $\cdot\text{O}_2^-$ and h^+ behave as oxidation active site for the degradation of RhB due to their high oxidative capacity.

4 Conclusions

In general, the CdS/ZnIn₂S₄/g-C₃N₄ ternary photocatalyst was prepared by a facile pyrolysis route coupling with simple two-step oil-bath procedure and the photoactivity was evaluated by degrading RhB under visible light irradiation. As expected, CdS/ZnIn₂S₄/g-C₃N₄ ternary composites possess boosted photocatalytic performance, which is not only higher than bare g-C₃N₄, ZnIn₂S₄ and CdS, but also even superior to ZnIn₂S₄/g-C₃N₄ and CdS/g-C₃N₄ binary photocatalysts. Among them, the CdS/ZnIn₂S₄/g-C₃N₄-0.2 photocatalyst achieves the best photocatalytic activity with a degradation rate of 96%. Additionally, the proposed CdS/ZnIn₂S₄/g-C₃N₄-0.2 composite reveals excellent photostability and reusability after four reused tests. The reasonable construction of ternary heterojunction not only facilitates the photogenerated charge carrier separation and migration as well as widens the visible-light response range, but also enhances the specific surface area, all of which are favorable for photocatalytic process. The design and fabrication of the CdS/ZnIn₂S₄/g-C₃N₄ ternary heterojunction photocatalysts represent a promising approach to fabricate high efficient g-C₃N₄-based photocatalysts for environmental remediation.

Author contributions

Jingzhe Li: data curation, investigation, writing – original draft. Yue Chen and Liezhen Zhu: investigation, validation, data curation. Linfa Liao and Xinmao Wang: investigation, validation. Xun Xu and Lingfang Qiu: conceptualization, funding acquisition, supervision. Jiangbo Xi: investigation, methodology. Ping Li: conceptualization, methodology, funding acquisition, writing – review & editing, supervision. Shuwang Duo: conceptualization, funding acquisition, project administration, supervision.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 41763020), the Natural Science Foundation of Jiangxi Province (No. 20212BAB204020, 20202BABL214040, and 20202BABL213014), and the Post-graduate Innovation Special Fund Project of Jiangxi Provincial Education Department (YC2022-s779).

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