


 Cite this: *RSC Adv.*, 2023, **13**, 13142

In situ formation of red/black phosphorus-modified SiO₂@g-C₃N₄ multi-heterojunction for the enhanced photocatalytic degradation of organic contaminants†

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A new heterojunction material BP/RP-g-C₃N₄/SiO₂ was obtained by a one-step ball milling method, and its photocatalytic capacity was researched by the degradation of Rhodamine B (RhB) and ofloxacin (OFL) in simulated sunlight. The construction of an *in situ* BP/RP heterojunction can achieve perfect interface contact between different semiconductors and effectively promote the separation of photogenerated carriers. The composite material was well characterized, which proved that the multi-heterogeneous structure was prepared. Furthermore, the type II heterojunction was formed between the g-C₃N₄ and BP/RP interface, playing an important role in the degradation and promoting electron transfer. The degradation effect of BP/RP-g-C₃N₄/SiO₂ on RhB reached 90% after 26 min of simulated solar irradiation, which was 1.8 times that of g-C₃N₄/SiO₂. The degradation of OFL by BP/RP-g-C₃N₄/SiO₂ reached 85.3% after illumination for 50 min, while the degradation of g-C₃N₄/SiO₂ was only 35.4%. The mechanisms were further discussed, and 'O₂⁻ and h⁺ were found to be the main active substances to degrade RhB. The catalyst also revealed distinguished stability of catalyst and recyclability, and the degradation effect of RhB can still realize 85% after 4 runs of experiment. Thus, this study provided a novel method for the design and preparation of multi-heterojunction catalysts in the removal of organic pollutants from wastewater.

 Received 21st March 2023
 Accepted 14th April 2023

DOI: 10.1039/d3ra01850d

rsc.li/rsc-advances

1. Introduction

Dyes discharged with industrial wastewater as the main organic pollutants cause harm to the environment. Carcinogenic dyes endanger human health.¹ Antibiotics are widely used to treat bacterial infections in humans and animals.^{2–4} Ofloxacin (OFL), one of the fluoroquinolones, in medical wastewater is not biodegradable.⁵ As a result, OFL will accumulate in surface water.⁶ Therefore, the development of treatment methods for the removal of dyes and antibiotics from wastewater is urgently required.

Various traditional methods have been used to degrade organic pollutants. However, there will be problems such as

poor degradation effect or high costs. Adsorption and coagulation techniques remove dye and antibiotics by converting them to solid substances from a liquid state, which will cause secondary damage to the environment.⁷ Alternatively, advanced oxidation processes (AOPs), such as electrochemical oxidation, ultraviolet (H₂O₂), gamma ray/electron beam radiation, photochemical oxidation, ozonation (O₃/H₂O₂), Fenton/photo-Fenton, persulfate-based oxidation, and ultrasonic oxidation, have been widely used as advanced treatment processes for the degradation of organic pollutants in wastewater.^{8–11} The removal of both antibiotics^{12–14} and organic dyes^{15–19} by various AOPs has been reported. Interestingly, semiconductor photocatalysis has been considered as one of the most promising clean technologies for the removal of organic pollutants in a short period of time.²⁰ Photocatalytic technology has the characteristics of mild reaction conditions and green environmental protection and has attracted much attention in dye wastewater treatment technology.²¹

As an inorganic non-metallic material, graphitic carbon nitride (g-C₃N₄, CN) has been widely used in the degradation of organic pollutants due to its superior physical and chemical properties.^{22–24} However, the photocatalytic efficiency of g-C₃N₄ is low due to its low utilization of visible light and high recombination rate of photogenerated electron-hole pairs in

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† Electronic supplementary information (ESI) available. See DOI: <https://doi.org/10.1039/d3ra01850d>



photocatalytic reactions.^{25–27} At present, g-C₃N₄ is modified by metal deposition,²⁸ element doping,²⁹ and heterojunction construction.³⁰ Among them, the construction of a heterojunction based on g-C₃N₄ is a feasible method to solve the problem of rapid recombination of g-C₃N₄ photogenerated carriers.^{31–33}

As the most abundant substance on the earth, SiO₂ not only promotes the adsorption of organic matter, but also promotes the migration of photogenerated carriers on the surface of g-C₃N₄ when forming a heterostructure with g-C₃N₄.^{34–36} On the basis of the previous research of the research group, the addition of SiO₂ also helps to increase the yield of g-C₃N₄. Although SiO₂ has this effect in the formation of a heterojunction, it does not fully release the potential in the photocatalytic degradation of g-C₃N₄.³⁷ Therefore, we need to introduce additional materials to overcome the current difficulties and integrate the advantages of all components in the hope of achieving better performance.

The catalytic activity of g-C₃N₄ is enhanced when added to RP. The visible light utilization capacity of RP/g-C₃N₄ is 1.33 times greater than that of the original g-C₃N₄, indicating that the heterojunction can effectively utilize the enhanced light, highlighting the importance of the type I heterojunction formed between RP and g-C₃N₄ (accelerating the separation of photogenerated carriers and broadening the absorption range of visible light).³⁸ It was reported recently that black phosphorus (BP), as an emerging nonmetallic two-dimensional (2D) material, has an adjustable band gap, fast photogenerated carrier mobility ($\sim 1000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$) and high conductivity (approximately 10^2 S m^{-1}).^{39–42} In the field of optoelectronics, BP nanosheets prepared by mechanical method have been applied.⁴³ This is due to the fact that BP-based heterostructures can efficiently separate photogenerated carriers, while maintaining the stability of BP.⁴⁴ For example, Zhu *et al.* used the excellent electron transfer ability of BP/CN in the photolysis of water for hydrogen evolution.⁴⁵ Eroglu *et al.* used the synergistic effect of the FLBP/g-CN heterojunction interface to photo-oxidize organic compounds.⁴⁶ He *et al.* used BP-CN to efficiently kill bacteria in water.⁴⁷ In all heterojunctions, heterostructures formed by a single element can produce strong interfacial forces and close contacts.⁴⁸ Using ball milling technology to convert RP into BP/RP heterostructure can prolong the service life of electron–hole pairs and improve the degradation efficiency of pollutants. It is possible to combine BP/RP with g-C₃N₄/SiO₂ to form an efficient heterostructure.

In our work, a novel multi-material heterostructure BP/RP-g-C₃N₄/SiO₂ was prepared by ball milling. RhB and OFL were selected as typical organic compounds to study the photoelectric properties of BP/RP-g-C₃N₄/SiO₂ and electron transfer in multi-heterogeneous structures. Due to the formation of the P–C bond between g-C₃N₄/SiO₂ and BP/RP, the composites showed good photocatalytic performance. The P–C bonds extend the life of the photogenerated electrons in the whole system. Finally, the mechanism of photocatalysis is estimated and the active substances are tested.

2. Experimental sections

2.1. Chemical reagents

The principal chemicals include urea (Tianjin Fengchuan Chemical Reagent Technology Co. Ltd), ethanol, silica dioxide (Aladdin), RP (Sinopharm Chemical Reagent Co. Ltd), RhB (C₂₈H₃₁ClN₂O₃, Sinopharm Chemical Reagent Co. Ltd), OFL (C₁₈H₂₀FN₃O₄, Maya Reagent), acetonitrile (C₂H₃N, Maya Reagent) and others.

2.2. Synthesis of composite

The synthesis of BP/RP-g-C₃N₄/SiO₂ catalytic materials is shown in Fig. 1. In a typical synthesis, deionized water was added to the ceramic crucible, 3.0 g urea and a certain amount of SiO₂ were added, and ultrasonic stirring was performed at room temperature for 0.5 h. The ceramic crucible was placed on a magnetic stirrer and heated at a speed of 150 rpm for 0.5 h to obtain a solid material. A total of 5.0 g urea was placed into a ceramic crucible and heated at 550 °C for 2 h with a heating speed of 5 °C min⁻¹ in a muffle furnace, then cooled naturally to room temperature. The g-C₃N₄ containing 200 mg of SiO₂ is denoted as g-C₃N₄/SiO₂.

A total of 3 g of red phosphorus was placed in a Teflon-lined reaction kettle with 60 ml of deionized water (200 °C with a heating rate of 5 °C for 12 h, and cooled down to room temperature naturally). After filtration, the samples were dried in a vacuum oven at 30 °C. The solid powder with oxide layer removed was then obtained.

BP/RP-g-C₃N₄/SiO₂ was prepared by ball-milling. The oxide-free RP and g-C₃N₄/SiO₂ were placed in a tank with agate balls of different diameters, and ball-milled at a speed of 450 rpm. A certain amount of RP to remove oxidation layer was added to g-C₃N₄/SiO₂ for ball milling. A total of 10% of RP was added and denoted as 10RP-g-C₃N₄/SiO₂. The ratio of agate ball to sample was 30 : 1. A total of 40% RP material was added to g-C₃N₄/SiO₂ and ball-milled for 12 h at 450 rpm, and called BP/RP-g-C₃N₄/SiO₂.

2.3. Characterization

The synthesized catalysts were analyzed and characterized by X-ray diffraction (XRD, X'Pert-3, Panalytical, Netherlands), transmission electron microscopy (TEM, Tecnai G2 F20, FEI, USA), Raman spectroscopy, X-ray photoelectron spectroscopy (XPS, K-Alpha, Thermo Fisher Scientific, USA), Fourier transform infrared (FT-IR, Tensor, Bruke) spectroscopy, thermogravimetric analysis (TGA, STA449, Netzsch), UV-vis diffuse reflectance spectroscopy (UV-vis, TU-1901, Persee, China), photoluminescence spectra (PL, FLS1000, Edinbrugh), Raman spectroscopy (Renishaw, UK) and other methods.

2.4. Photoelectrochemistry experiments

Electrochemical impedance spectroscopy (EIS), photocurrent test (*I*–*t*) and a conventional three-electrode electrochemical workstation were used to test the Mott–Schottky plots. Details are provided in the ESI.†

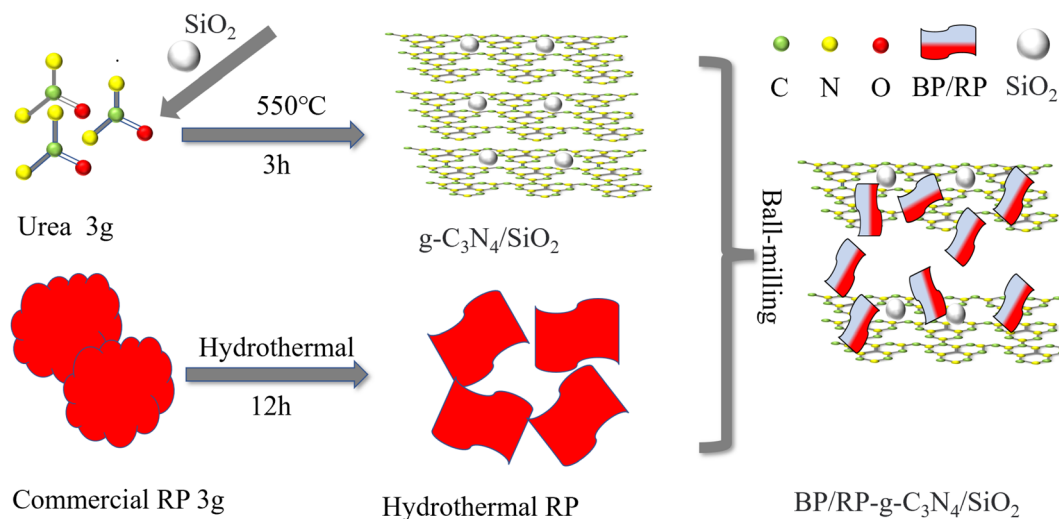


Fig. 1 Schematic diagram of the BP/RP-g-C₃N₄/SiO₂ composites.

2.5. Photocatalytic degradation experiment

The prepared catalyst was tested. Before photodegradation, dark adsorption equilibrium experiments were first performed on organic matter. It was found that the adsorption equilibrium of RhB was reached in 10 min, and the proportion of adsorption equilibrium was not more than 5%. The results showed that the adsorption equilibrium of OFL was reached within 30 min, and the adsorption equilibrium ratio was not more than 20%. Then, the photocatalytic experiment was carried out under a 350 W

xenon lamp, and a sample was taken every 4 min, and centrifugation was carried out. The experimental operation was carried out with an ultraviolet spectrophotometer. The calculation of photocatalysis is determined by the following eqn (1) and (2):

$$y = C/C_0 \quad (1)$$

$$-\ln(C/C_0) = kt \quad (2)$$

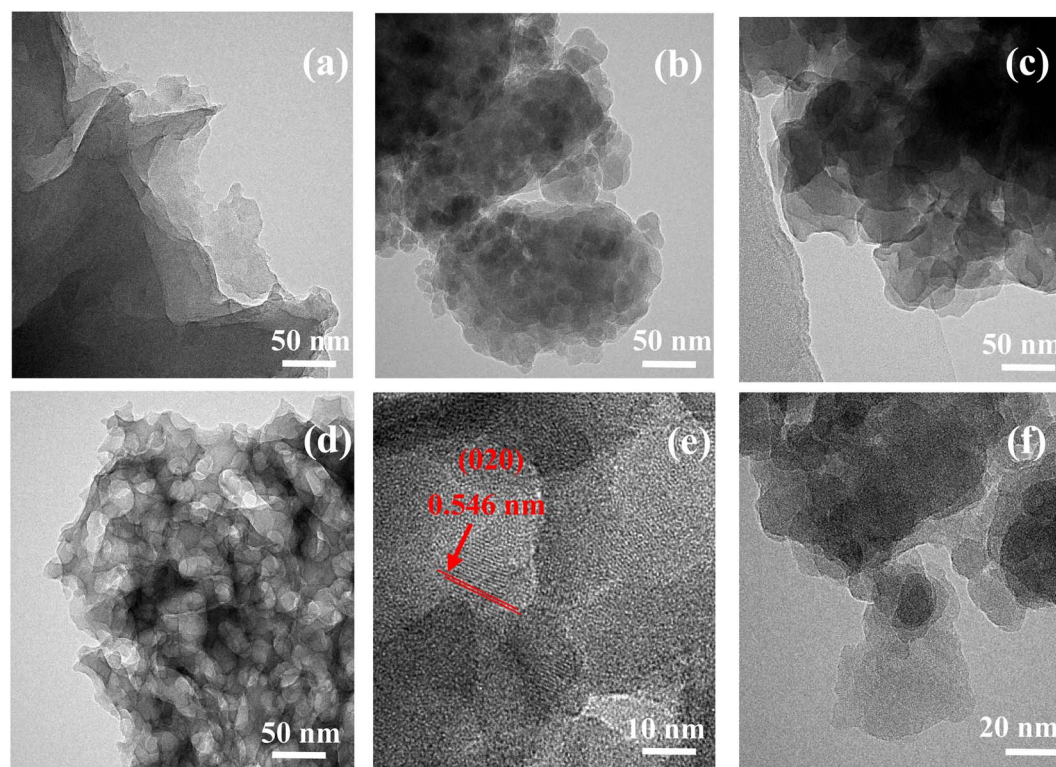


Fig. 2 TEM of (a) g-C₃N₄, (b) g-C₃N₄/SiO₂, (c) RP, (d) and (e) BP/RP, (f) BP/RP-g-C₃N₄/SiO₂.

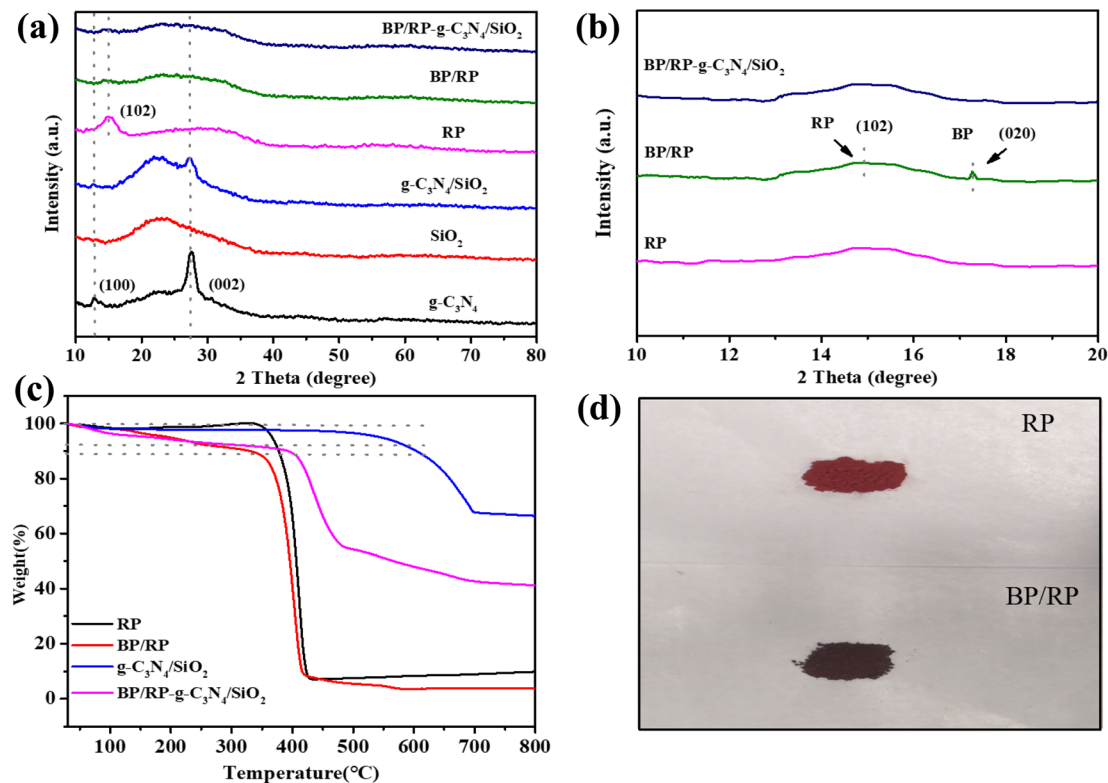


Fig. 3 XRD patterns of (a) $g-C_3N_4$, SiO_2 , $g-C_3N_4/SiO_2$, RP, BP/RP, BP/RP- $g-C_3N_4/SiO_2$ samples, (b) enlarged XRD of RP, BP/RP and BP/RP- $g-C_3N_4/SiO_2$ samples, (c) TGA curves of $g-C_3N_4/SiO_2$, RP, BP/RP, BP/RP- $g-C_3N_4/SiO_2$ samples, (d) comparison before and after ball milling RP.

where C is the solubility of the solution after the light time t , C_0 is the concentration before dark reaction adsorption, and k is the rate constant (min^{-1}).

In each of the degradation experiments, the prepared 2 mg solid catalyst was added to 40 ml of solution containing RhB (60 mg L^{-1}). OFL was degraded, the amount of catalyst was 5 mg/40 ml, the amount of OFL was 10 mg L^{-1} , and the samples were tested by liquid chromatography. The mobile phase was

acetonitrile and 0.8% glacial acetic acid (75:25). The test wavelength was 289 nm.

3. Results and discussion

3.1. Construction of BP/RP- $g-C_3N_4/SiO_2$

The TEM image shows the morphology of the material in Fig. 2. As displayed in Fig. 2a, $g-C_3N_4$ has a layered fold morphology. In

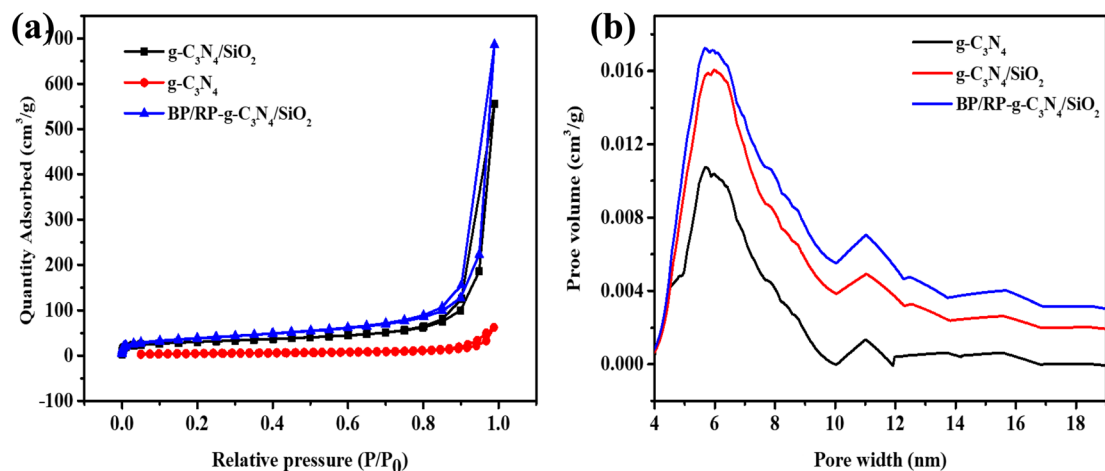


Fig. 4 (a) N_2 adsorption-desorption curve of $g-C_3N_4$, $g-C_3N_4/SiO_2$ and BP/RP- $g-C_3N_4/SiO_2$. (b) Pore size distribution of $g-C_3N_4$, $g-C_3N_4/SiO_2$ and BP/RP- $g-C_3N_4/SiO_2$.

Fig. 2b, the addition of spherical SiO₂ leads to the presence of speckles on the surface of g-C₃N₄. In the same amorphous lamellar RP (Fig. 2c), stripping occurred after ball milling and a (020) BP lattice fringe was formed (Fig. 2d and e), indicating that the BP/RP heterostructure was successfully prepared. A multi-component composite containing BP/RP can be observed in Fig. 2f. All of the materials have a layered structure, which is also consistent with the previous literature. SEM shows that the BP/RP-g-C₃N₄/SiO₂ lamella decreased, and all kinds of substances were evenly distributed (Fig. S1 and S2†).

The crystal structures of the as-prepared g-C₃N₄, SiO₂, g-C₃N₄/SiO₂, RP, BP/RP, and BP/RP-g-C₃N₄/SiO₂ were investigated using XRD. For pure g-C₃N₄, the distinct characteristic diffraction peaks at 13.7° and 27.6° were indexed to the typical triazine interring accumulation peak (100) and interlayer accumulation peak (002), respectively.⁴⁹ The structures of g-C₃N₄ are usually stacked in layers.^{50,51} After adding SiO₂, a new characteristic peak of g-C₃N₄/SiO₂ appeared at 23°, which is consistent with the characteristic peak position shown in the XRD pattern of pure SiO₂. In addition, no other characteristic peaks were found, indicating that the structure of g-C₃N₄ did not change with the addition of SiO₂. Fig. 3a shows the XRD patterns of RP. It is known that RP forms peaks at 15.2°, 30.0° and 57.5° (JCPDS 44-0906). The characteristic peak of 17.2° in the XRD of BP is the

(020) plane, 28.8° is the (021) plane and 33.9° is the (040) plane.⁵² In BP/RP, there is a 17.2° peak in addition to 15.2° (Fig. 3b). According to the TEM characterization (Fig. 2e), 17.2° in BP/RP represents the (020) plane of BP (JCPDS 73-1358). In BP/RP-g-C₃N₄/SiO₂, the characteristic peak of BP was not obvious. The reason for this phenomenon may be that less BP is produced during the formation of the heterojunction. The color change of the sample after ball milling is also a good indication (Fig. 3d).

TGA was used to roughly estimate the weight percent of BP in the heterostructure (Fig. 3c). SiO₂ has a high melting point, and g-C₃N₄ can be thermally exfoliated at a certain temperature, releasing gas and causing mass loss of g-C₃N₄.⁵³ The mass of RP began to decrease until 350 °C. At 150 °C, the masses of the BP/RP and BP/RP-g-C₃N₄/SiO₂ composites began to decrease. The decrease in the low temperature region may be due to the presence of BP in the composites. The mass fraction of BP in BP/RP and BP/RP-g-C₃N₄/SiO₂ can then be calculated by the following formula:⁵⁴

$$\text{BP (\%)} = \frac{M_s - M_{\text{RP}}}{M} \times 100\% \quad (3)$$

where BP (%) represents the mass fraction of BP in the composite, M_s represents the residual mass of the composite

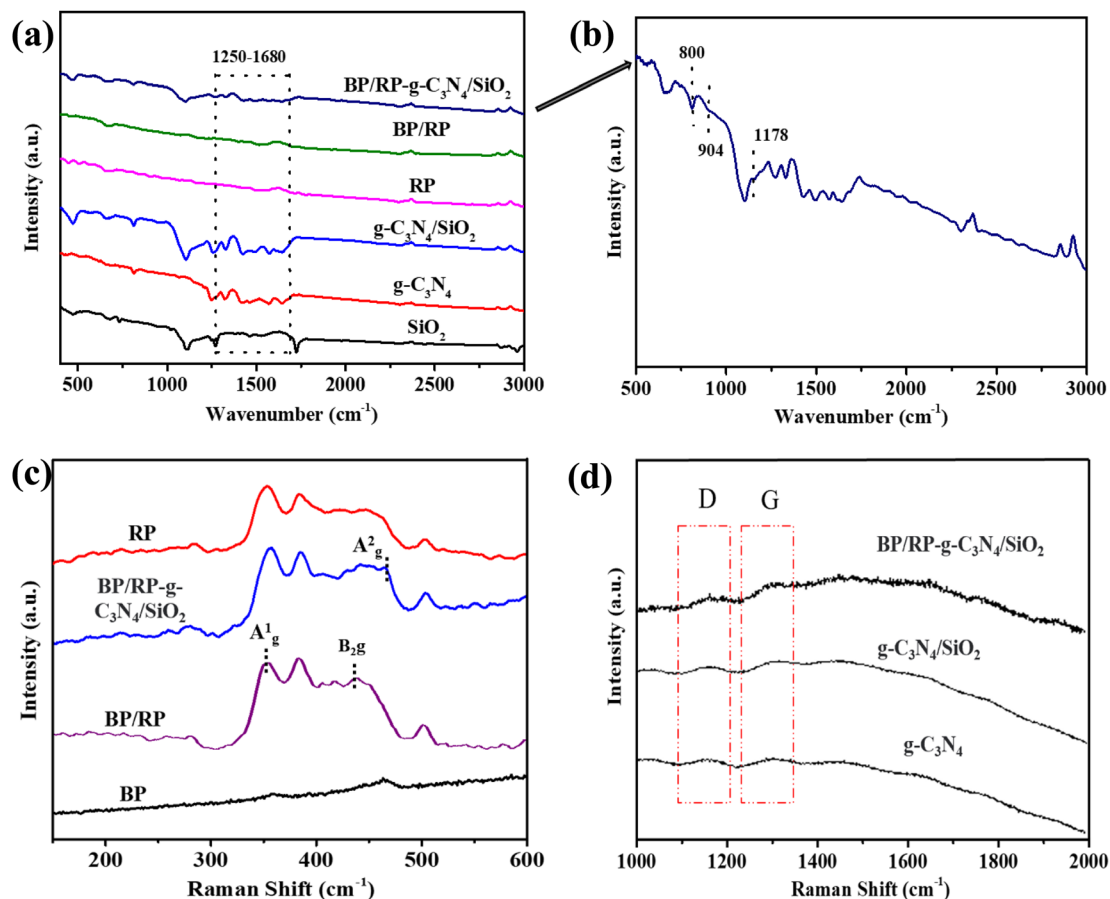


Fig. 5 (a) FT-IR spectra of g-C₃N₄, g-C₃N₄/SiO₂, RP, BP/RP and BP/RP-g-C₃N₄/SiO₂. (b) FT-IR enlarged spectra of BP/RP-g-C₃N₄/SiO₂. (c) Raman shift of RP, BP, BP/RP and BP/RP-g-C₃N₄/SiO₂. (d) Raman shift of g-C₃N₄, g-C₃N₄/SiO₂ and BP/RP-g-C₃N₄/SiO₂.

when the heat loss begins, M_{RP} represents the residual mass of the composite when the heat loss begins, and M represents the total mass. Therefore, BP may contain 8% in BP/RP and 4% in BP/RP-g-C₃N₄/SiO₂.

The N₂ adsorption–desorption isotherms of g-C₃N₄, g-C₃N₄/SiO₂ and BP/RP-g-C₃N₄/SiO₂ were measured. As shown in Fig. 4a, the N₂ adsorption isotherms of g-C₃N₄, g-C₃N₄/SiO₂ and BP/RP-g-C₃N₄/SiO₂ have a typical H3-type hysteresis loop, which belongs to the type IV isotherm.^{55–57} The pore sizes of g-C₃N₄, g-C₃N₄/SiO₂ and BP/RP-g-C₃N₄/SiO₂ are mostly distributed in the range of 4–10 nm (Fig. 4b), indicating that mesoporous structures exist in g-C₃N₄, g-C₃N₄/SiO₂ and BP/RP-g-C₃N₄/SiO₂. Compared with g-C₃N₄, g-C₃N₄/SiO₂ and BP/RP-g-C₃N₄/SiO₂ possess a higher N₂ adsorption capacity and pore volume (Table S1†). It was found that the specific surface area of g-C₃N₄/SiO₂ (70.291 m² g⁻¹) and BP/RP-g-C₃N₄/SiO₂ (96.603 m² g⁻¹) was 2.16 times and 2.97 times that of g-C₃N₄ (32.482 m² g⁻¹). The larger specific surface area and pore volume provide more adsorption and active sites.

From the FT-IR analysis in Fig. 5a, the broad peak between 2900–3000 cm⁻¹ is caused by the -NH vibration in the material or the -OH vibration in the absorbed water. The fine characteristic peaks between 1250 and 1680 cm⁻¹ in g-C₃N₄/SiO₂ and BP/RP-g-C₃N₄/SiO₂ are the C–N and C=N vibrations of g-C₃N₄.⁵⁸ The enlarged image of the BP/RP-g-C₃N₄/SiO₂ composite is shown in Fig. 5b. The peak at 800 cm⁻¹ represents the N–H deformation and typical bending vibration of the tris-triazine ring system of g-C₃N₄.⁵⁹ In composite BP/RP-g-C₃N₄/SiO₂, P–O–C and P=O correspond to the peaks at 904 cm⁻¹ and 1178 cm⁻¹, respectively.^{60,61} Noticeably, the appearance of vibrational bands of BP/RP and g-C₃N₄/SiO₂ in the BP/RP-g-C₃N₄/SiO₂ heterojunctions indicated that BP/RP and g-C₃N₄/SiO₂ had been incorporated successfully.

We conducted Raman spectroscopy analysis, shown in Fig. 5c, and found that the hybridization mode of P⁰ changed at different values. RP has two distinct peaks in the Raman spectrum at 350.3 cm⁻¹ and 380.5 cm⁻¹, respectively. Then, after RP milling, two new peaks appeared at 445.5 cm⁻¹ and 466.5 cm⁻¹,

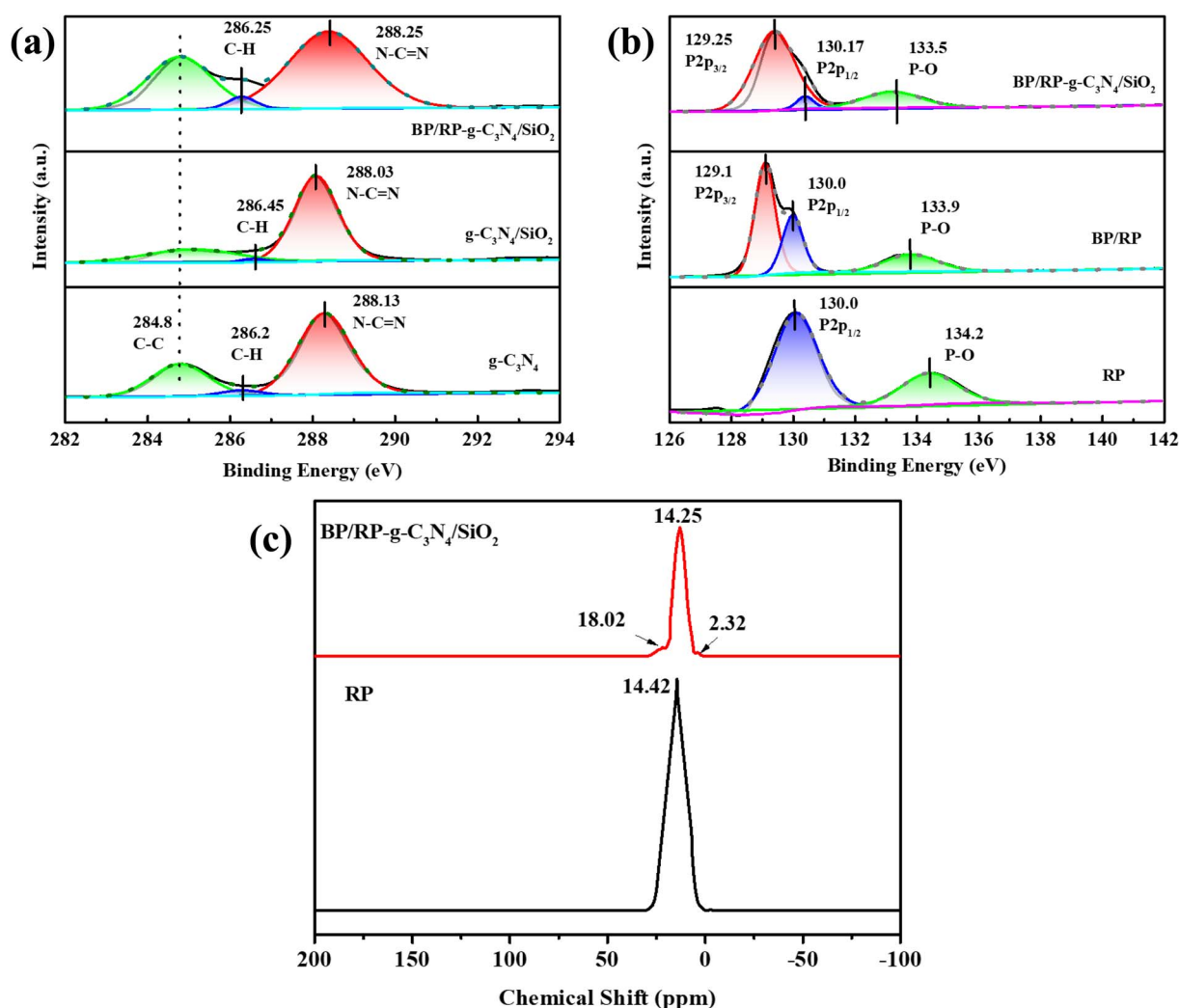


Fig. 6 XPS spectra of (a) C 1s of g-C₃N₄, g-C₃N₄/SiO₂ and BP/RP-g-C₃N₄/SiO₂, (b) P 2p of RP, BP/RP and BP/RP-g-C₃N₄/SiO₂, (c) solid-state NMR of RP and BP/RP-g-C₃N₄/SiO₂.

which were attributed to the B_{2g} and A_g^2 patterns of BP, respectively.^{62,63} The presence of A_g^2 in BP/RP-g- C_3N_4/SiO_2 indicates the generation of BP.⁶⁴ In BP/RP-g- C_3N_4/SiO_2 (Fig. 5d), the change of D/G indicates that the hybridization mode of C has changed, which is caused by the formation of the P–O–C bond.⁶⁵

The bonding and chemical states of elements in BP/RP-g- C_3N_4/SiO_2 were further studied by XPS. In the C spectrum (Fig. 6a), the characteristic peaks at 284.8 eV and 288.13 eV correspond to C–C/C=C and N–C=N bonds in g- C_3N_4 , respectively, and the characteristic peak between C–C/C=C and N–C=N is 286.2 eV, corresponding to the C–H bond in g- C_3N_4 .^{66–68} Compared with g- C_3N_4 and g- C_3N_4/SiO_2 , the value of the N–C=N bond composite of BP/RP-g- C_3N_4/SiO_2 moves to the right, indicating that g- C_3N_4 in the composite loses electrons. According to the XPS of RP, BP/RP and BP/RP-g- C_3N_4/SiO_2 in Fig. 6b, only a peak value of 130.0 eV and 134.2 eV can be displayed in pure RP. The two weak peaks at 130.0 eV and 133.9 eV in BP/RP represent P 2p_{1/2} and the P–O bond, respectively. Among them, 129.1 eV represents the peak value of black phosphorus,³⁷ thus indicating that our experiment successfully prepared the BP/RP heterostructure, which is consistent with the above characterization results.

In the P 2p spectrum of BP/RP-g- C_3N_4/SiO_2 , the characteristic peak at 129.25 eV is caused by P 2p_{3/2} of BP, and the characteristic peak at 130.17 eV is P 2p_{1/2}.⁶⁹ The characteristic peak at

135 eV represents the P–O bond in the BP/RP-g- C_3N_4/SiO_2 composite, which lays a foundation for the formation of the P–O–C bond. In the P 2p spectra of RP, BP/RP and BP/RP-g- C_3N_4/SiO_2 , the characteristic peaks change between 133 eV and 135 eV. The characteristic peaks of BP/RP-g- C_3N_4/SiO_2 in P–O shift to the left by 0.7 eV and 0.4 eV compared with RP and BP/RP, respectively. This shows that BP/RP is gaining electrons in the composite. The formation of P–C bonds by ball milling can be confirmed by ³¹P solid-state NMR. As shown in Fig. 6c, the formation of P–C is represented by the feature at 2.32 ppm, and the existence of the BP peak is found at 18.02 ppm. The generation of BP during ball milling is confirmed. Furthermore, compared with RP, BP/RP-g- C_3N_4/SiO_2 moves to the right, which is the chemical shift caused by the formation of BP and P–C bonds by RP.^{70,71}

3.2. Photocatalytic degradation experiment

The variation curve of the RhB concentration (C/C_0) with irradiation time (t) under visible light irradiation is shown in Fig. 7a. The degradation effect of BP/RP-g- C_3N_4/SiO_2 on RhB was the best, which was 90%. The degradation effects of g- C_3N_4/SiO_2 and BP/RP on RhB were 51% and 79.3%, respectively. The degradation effect of BP/RP-g- C_3N_4/SiO_2 on OFL was the best, which was 85.3%, as shown in Fig. 7b. The degradation effects of g- C_3N_4/SiO_2 and BP/RP on OFL were 35.4% and 35.6%,

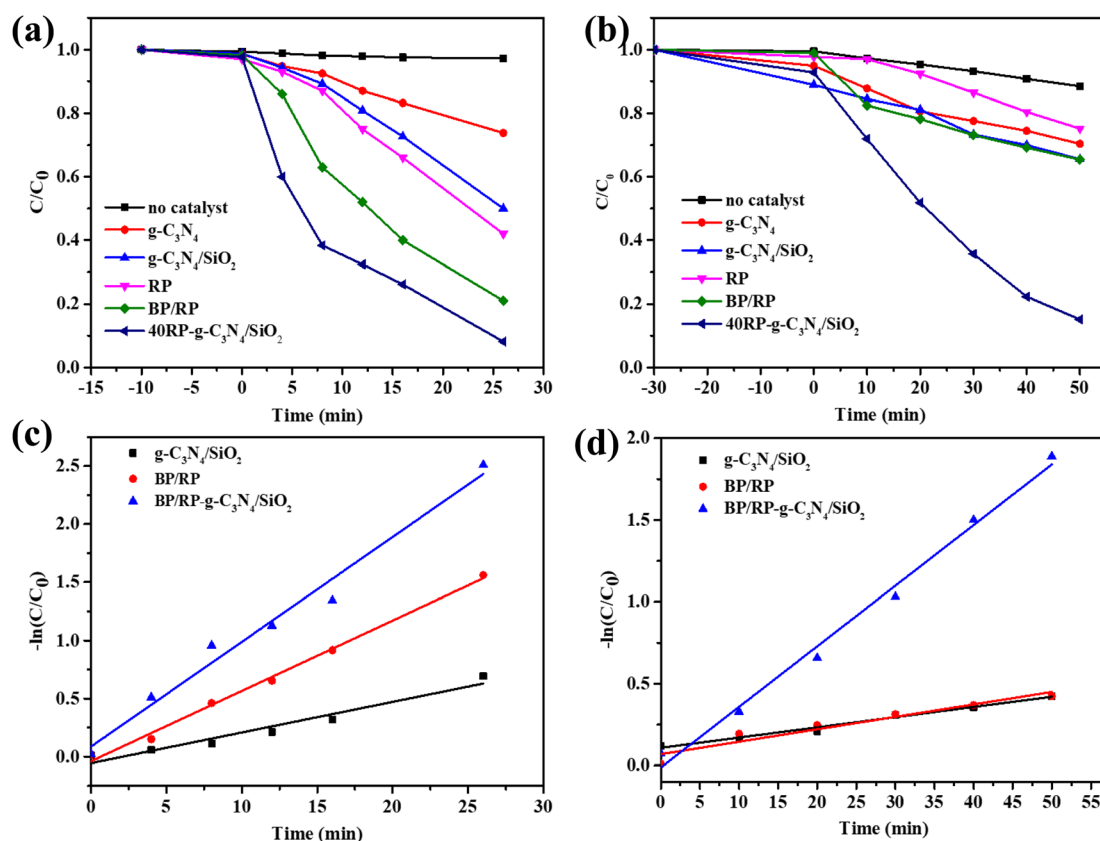


Fig. 7 (a) RhB degradation experiment, (b) OFL degradation experiment, (c) in the pseudo-first-order kinetic curve of RhB, (d) in the pseudo-first-order kinetic curve of OFL.

respectively. In the pseudo-first-order kinetic curve of RhB degradation, the reaction rate of BP/RP-g-C₃N₄/SiO₂ is 0.0901 min⁻¹, while the reaction rate of g-C₃N₄/SiO₂ is 0.0263 min⁻¹, and the reaction rate of BP/RP-g-C₃N₄/SiO₂ is 3.43 times that of g-C₃N₄/SiO₂ (Fig. 7c). In the pseudo-first-order kinetic curve of OFL degradation, the reaction rate of BP/RP-g-C₃N₄/SiO₂ is 0.03704 min⁻¹, the reaction rate of BP/RP is 0.00761 min⁻¹, and the reaction rate of g-C₃N₄/SiO₂ is 0.00625 min⁻¹ (Fig. 7d). The photocatalytic experiment has a better effect on the degradation of RhB than OFL, and the prepared catalyst is more inclined to the degradation of dyes. A total of 2 mg BP/RP-g-C₃N₄/SiO₂ can degrade 90% of 60 mg L⁻¹ RhB in 26 min of illumination, but 5 mg BP/RP-g-C₃N₄/SiO₂ can only degrade 85.3% of 20 mg L⁻¹ OFL in 50 min of illumination. This indicates that in the process of photocatalysis, the chemical reaction between active substances and dyes is stronger, and the prepared catalyst is more practical for dye degradation.

When adding 10%, 20%, 30%, 40%, and 50% RP for ball milling, the mass ratio of SiO₂ in the xRP-g-C₃N₄/SiO₂ material is 0.508, 0.451, 0.395, 0.338, and 0.282, respectively. The results showed that the sample containing 200 mg SiO₂ had a better catalytic effect on RhB containing 60 mg L⁻¹, and could degrade 51% of the pollutant within 26 min (Fig. S3†). The ball milling time was investigated. The degradation of RhB by adding 40%

RP with a ball milling time of 3 h reached the best value at 66%, and the degradation of RhB by adding 40% RP with a ball milling time of 6 h reached the best value at 86% (Fig. S4†). Among the ball milled samples at 12 h, xRP-g-C₃N₄/SiO₂, 40RP-g-C₃N₄/SiO₂ has the best degradation effect on RhB and OFL (Fig. S5†).

Stability and recyclability are extremely important factors that control the practical applicability of catalysts in photocatalysis. Four RhB degradation cycle experiments were carried out, and the results are shown in Fig. 8a. After four cycles, the degradation of RhB by BP/RP-g-C₃N₄/SiO₂ reached 85%. After four degradation cycles, the degradation of OFL by BP/RP-g-C₃N₄/SiO₂ reached 76% (Fig. 8b). We also observed that there was no obvious change in the color of the sample after the experiment. After four cycles of experiment, there is no significant change in the test Raman results, indicating that the material has good stability (Fig. 8c). In the experiment of degrading RhB, the liquid color changed significantly (Fig. 8d).

3.3. Photocatalytic reaction mechanism

It can be seen from UV-vis that the boundary of the absorption spectrum of the composite BP/RP-g-C₃N₄/SiO₂ is increasing (Fig. 9a). This shows that there is a strong force between the substances. According to Fig. 9b, the energy gap (E_g) width of

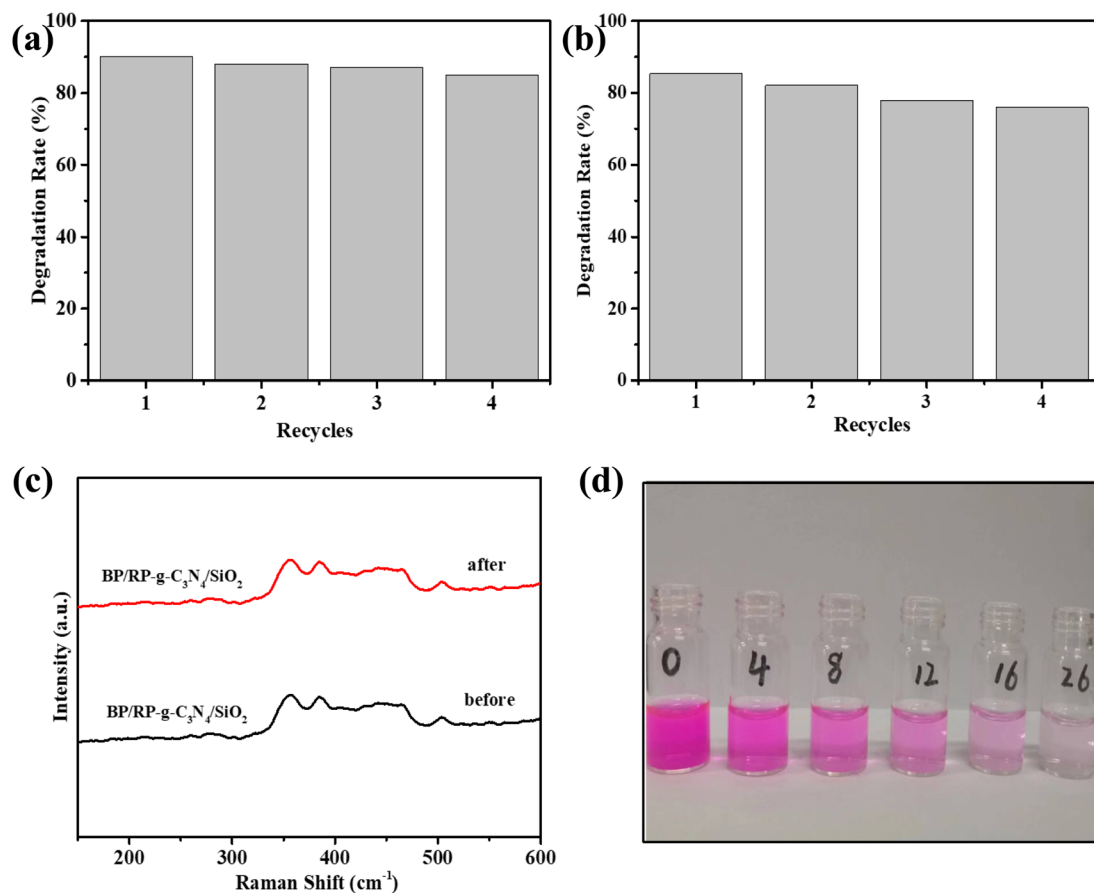


Fig. 8 (a) Degradation RhB cycle experiments, (b) degradation OFL cycle experiments, (c) Raman shift of BP/RP-g-C₃N₄/SiO₂ before and after the RhB degradation cycle reaction, (d) the color change of RhB degradation by BP/RP-g-C₃N₄/SiO₂.

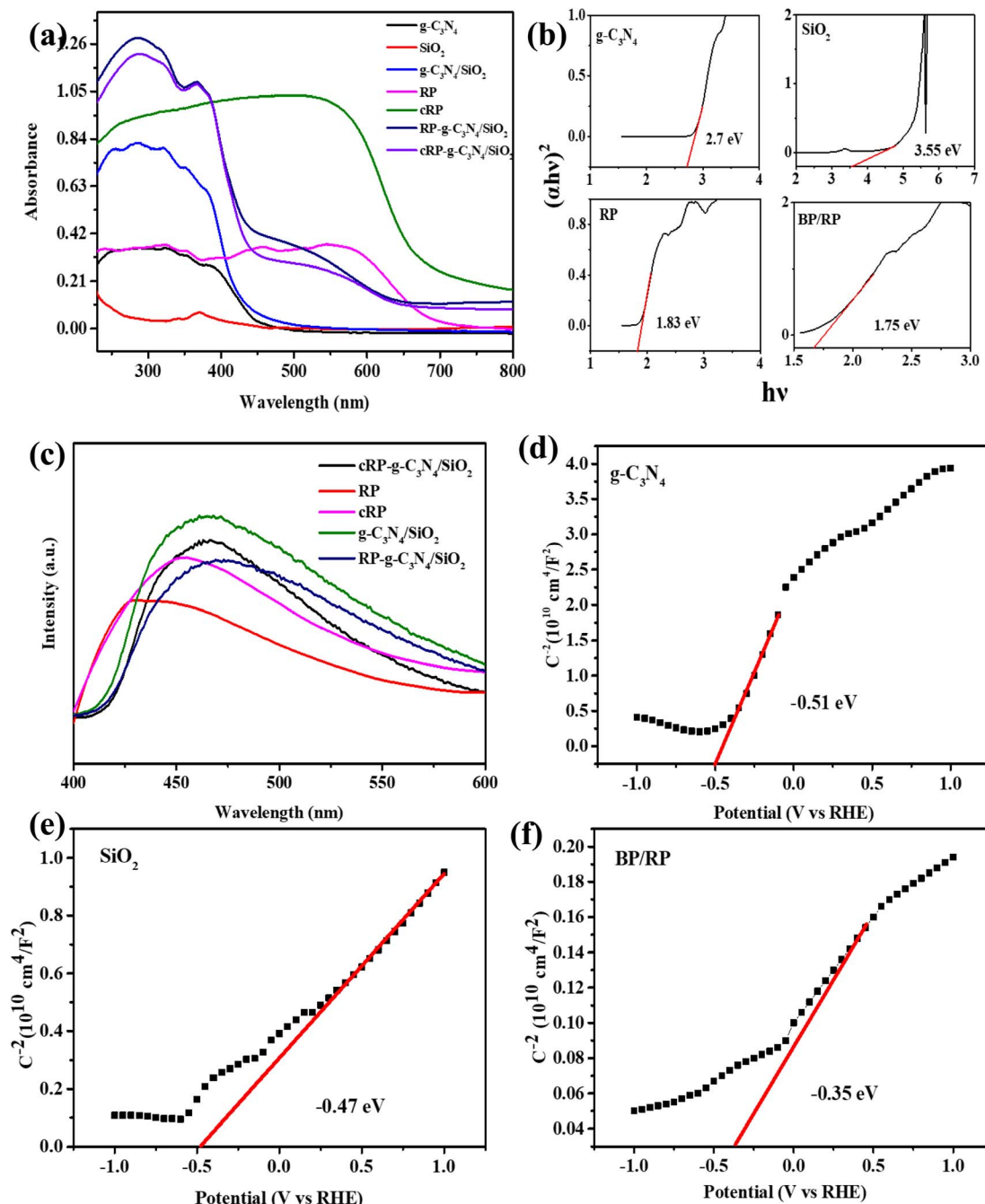


Fig. 9 (a) UV-vis of samples, (b) band gap test of $g\text{-C}_3\text{N}_4$, SiO_2 , RP and BP/RP, (c) the photoluminescence (PL) spectra of the catalyst sample, (d)–(f) Mott–Schottky plots of $g\text{-C}_3\text{N}_4$, SiO_2 and BP/RP.

SiO_2 itself is larger, which is 3.55 eV (vs. RHE). When SiO_2 is added to $g\text{-C}_3\text{N}_4$, the E_g width of $g\text{-C}_3\text{N}_4/\text{SiO}_2$ becomes smaller from 2.7 eV (vs. RHE) to 2.61 eV (vs. RHE). After ball milling, the E_g width of RP also decreases from 1.83 eV (vs. RHE) to 1.75 eV (vs. RHE). The final composite BP/RP- $g\text{-C}_3\text{N}_4/\text{SiO}_2$ is 1.6 eV (vs. RHE), and the reason this happens is because the matter forms a heterogeneous structure (Fig. S6[†]). The E_g of BP/RP- $g\text{-C}_3\text{N}_4/\text{SiO}_2$ is smaller than that of $g\text{-C}_3\text{N}_4$, SiO_2 and RP, indicating that the material can promote the transfer of electrons and holes

more quickly, and promotes the formation of more active substances.

The photoluminescence (PL) spectra of all samples are shown in Fig. 9c. The PL intensity of BP/RP- $g\text{-C}_3\text{N}_4/\text{SiO}_2$ can be intuitively seen to be lower than that of other catalyst samples, indicating that partial relaxation of BP/RP- $g\text{-C}_3\text{N}_4/\text{SiO}_2$ excitons may occur through charge transfer of electrons and holes, rather than through radiation paths.^{72,73} Thus, it can be inferred that BP/RP- $g\text{-C}_3\text{N}_4/\text{SiO}_2$ photogenerated carriers can prolong

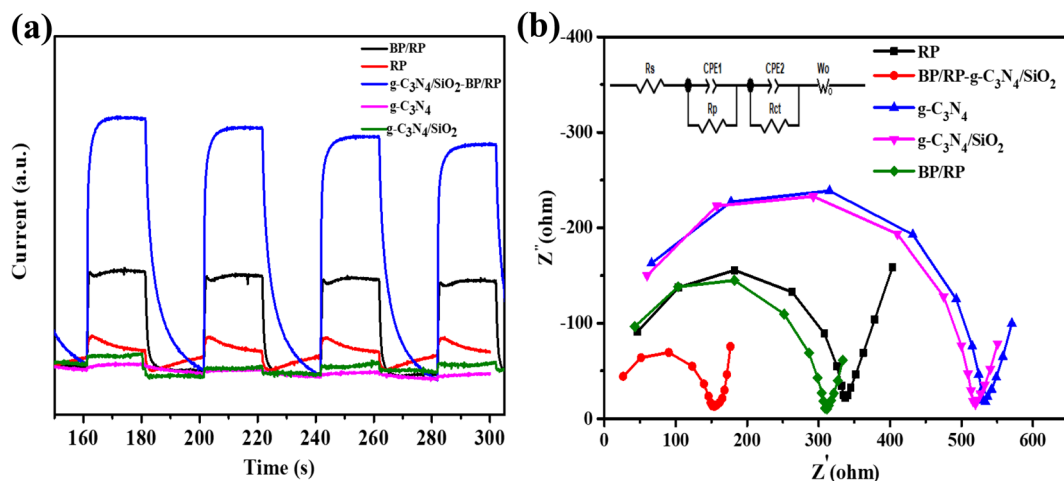


Fig. 10 (a) $I-t$ responses and (b) EIS of RP, BP/RP, g-C₃N₄, g-C₃N₄/SiO₂ and BP/RP-g-C₃N₄/SiO₂.

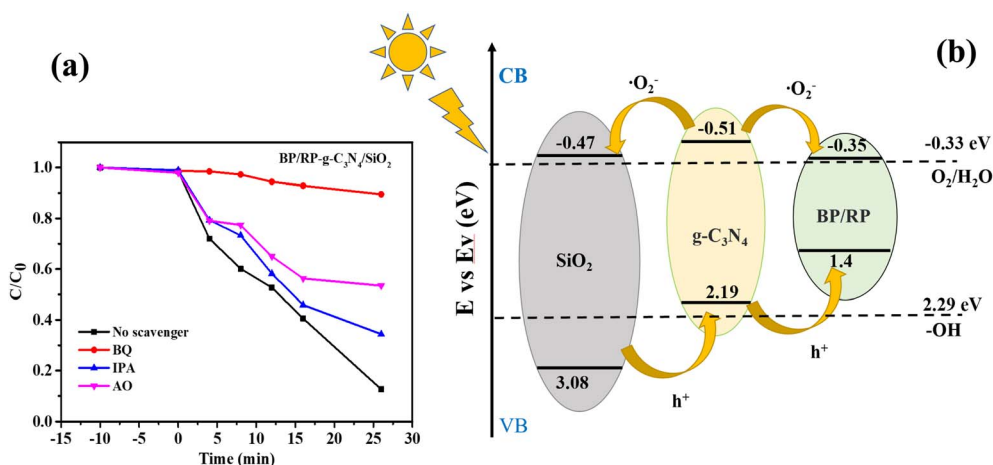


Fig. 11 (a) BP/RP-g-C₃N₄/SiO₂ degradation RhB active substance capture experiment. (b) The photocatalytic mechanism of BP/RP-g-C₃N₄/SiO₂.

their service life and enhance the degradation effect compared with others.

Meanwhile, the conduction band gap width (E_{CB}) of each material can be obtained by producing a Mott-Schottky curve (Fig. 9d-f). During the test, the conduction band values of the three monomers were measured compared with the reversible hydrogen electrode. The conduction band gap widths (E_{CB}) of g-C₃N₄, SiO₂, BP/RP and BP/RP-g-C₃N₄/SiO₂ are -0.51 eV, -0.47 eV, -0.35 eV and -0.65 eV, respectively (Fig. S6[†]). In addition, the conduction bands (E_{VB}) of g-C₃N₄, SiO₂, BP/RP and BP/RP-g-C₃N₄/SiO₂ are 2.19 eV, 3.08 eV, 1.4 eV and 0.95 eV, respectively, based on the formula below:^{74,75}

$$E_{CB} = E_{VB} - E_g$$

According to the corresponding conditions of the photocurrent, we can clearly see that under the simulated sunlight of 350 W, the photocurrent response current of BP/RP-g-C₃N₄/SiO₂

is the largest, and the photocurrent response current of g-C₃N₄ is the smallest. Furthermore, the current generated by BP/RP-g-C₃N₄/SiO₂ is about 70 times stronger than that of g-C₃N₄ (Fig. 10a). This is understandable because the heterostructures are formed in the composites, which facilitate the transfer of electrons and holes and inhibit their recombination, indicating that the heterojunction was successfully prepared between the P atom and g-C₃N₄/SiO₂.

In Fig. 10b, the charge transfer of photocatalytic materials is revealed by the equivalent circuit diagram of electrochemical impedance spectroscopy (EIS).⁷⁶ The radius of the arc usually indicates the resistance of electron transport at the interface. A smaller radius means more rapid charge transfer.^{76,77} According to the EIS, the radius of BP/RP-g-C₃N₄/SiO₂ is the smallest, while that of g-C₃N₄ is the largest, which is consistent with the above photocurrent response results.

In the degradation of RhB, the active substances in the BP/RP-g-C₃N₄/SiO₂ system were determined by scavenger experiment. In the quenching experiment, isopropanol (IPA), 4-

benzoquinone (BQ) and ammonium oxalate (AO) were used as quenching agents of the hydroxyl radical ($^{\cdot}\text{OH}$), superoxide radical ($^{\cdot}\text{O}_2^-$) and hole (h^+) in the RhB degradation, respectively. In the $g\text{-C}_3\text{N}_4/\text{SiO}_2$ degradation of RhB, it can be seen that $^{\cdot}\text{O}_2^-$ dominates the degradation process, which can inhibit the degradation of pollutants by up to 30%, indicating that $^{\cdot}\text{O}_2^-$ is the main active substance in this case, and the inhibitory effect of h^+ is stronger than that of $^{\cdot}\text{OH}$ (Fig. S7†). In the BP/RP degradation of RhB, it was found that the same active substance $^{\cdot}\text{O}_2^-$ played a role in catalysis, but the role of $^{\cdot}\text{OH}$ was stronger than that of h^+ (Fig. S8†). In composite materials BP/RP- $g\text{-C}_3\text{N}_4/\text{SiO}_2$, $^{\cdot}\text{O}_2^-$ significantly inhibits the degradation of pollutants, and only 10% of pollutants are degraded, indicating that $^{\cdot}\text{O}_2^-$ is still dominant (Fig. 11a). On the whole, $^{\cdot}\text{O}_2^-$ is the main active substance to degrade RhB, and the degradation mechanism of BP/RP- $g\text{-C}_3\text{N}_4/\text{SiO}_2$ is similar to that of $g\text{-C}_3\text{N}_4/\text{SiO}_2$, but different from that of BP/RP.

According to the most relevant literature, the CB and VB values of BP/RP meet the requirements. Depending on the band structures of $g\text{-C}_3\text{N}_4$, SiO_2 , $g\text{-C}_3\text{N}_4/\text{SiO}_2$, BP/RP and RP, it can be speculated that BP/RP- $g\text{-C}_3\text{N}_4/\text{SiO}_2$ composites contain type I and type II heterostructures.

$g\text{-C}_3\text{N}_4$ and BP/RP were excited under simulated sunlight to produce photogenic charge carriers. The e^- in the VB was transferred to the CB, and left h^+ in the VB. In $g\text{-C}_3\text{N}_4/\text{SiO}_2$, the CB position of $g\text{-C}_3\text{N}_4$ is more negative than that of SiO_2 , and the VB position of SiO_2 is more positive than that of $g\text{-C}_3\text{N}_4$. The e^- in the CB of $g\text{-C}_3\text{N}_4$ could rapidly transfer to the CB of SiO_2 . In the meanwhile, the h^+ in the VB of SiO_2 could swiftly move to the VB of $g\text{-C}_3\text{N}_4$. Moreover, the CB position of $g\text{-C}_3\text{N}_4$ is more negative than that of BP/RP. The e^- in the CB of $g\text{-C}_3\text{N}_4$ could swiftly move to the CB of BP/RP. The CB potential of $g\text{-C}_3\text{N}_4$ is more negative than that of $^{\cdot}\text{O}_2^-$ (-0.33 eV). This situation tends to produce $^{\cdot}\text{O}_2^-$. However, the VB potential of SiO_2 is more positive than that of OH^-/OH ($+2.27$ eV), and h^+ in the VB of BP/RP could not oxidize H_2O and OH^- to form $^{\cdot}\text{OH}$. The $^{\cdot}\text{O}_2^-$ and h^+ could oxidize RhB directly. Thus, the heterostructure mechanism of the BP/RP- $g\text{-C}_3\text{N}_4/\text{SiO}_2$ composites is proposed in Fig. 11b.

4. Conclusion

In conclusion, a one-step ball-milling method was successfully used to achieve the BP/RP- $g\text{-C}_3\text{N}_4/\text{SiO}_2$ multi-heterojunction. The existence of BP and the formation of P-C bonds in BP/RP- $g\text{-C}_3\text{N}_4/\text{SiO}_2$ were confirmed by NMR. The degradation performance of BP/RP- $g\text{-C}_3\text{N}_4/\text{SiO}_2$ was superior compared to those of $g\text{-C}_3\text{N}_4$ and $\text{SiO}_2/g\text{-C}_3\text{N}_4$. The RhB removal efficiency of BP/RP- $g\text{-C}_3\text{N}_4/\text{SiO}_2$ reached 90%, which is 1.8 times greater than that of the $g\text{-C}_3\text{N}_4/\text{SiO}_2$ sample. The degradation of OFL by BP/RP- $g\text{-C}_3\text{N}_4/\text{SiO}_2$ is 3.41 times greater than that of the $g\text{-C}_3\text{N}_4/\text{SiO}_2$ sample. In addition, the BP/RP- $g\text{-C}_3\text{N}_4/\text{SiO}_2$ revealed distinguished stability of the catalyst and recyclability for practical applications in the process of degradation of RhB and OFL. The current work displays the potential of using carbon-based materials for environmental purification, particularly in removing dye from wastewater.

Data availability

Data will be made available upon request to the corresponding author.

Author contributions

Jiancheng Li: investigation, resources, writing—original draft, and visualization. Chi Wang: writing—review and editing, visualization, supervision. Yixing Ma: writing—review and editing. Kai Li: visualization and supervision. Yi Mei: supervision.

Conflicts of interest

The authors have no relevant financial or non-financial interests to disclose.

Acknowledgements

This study was financially supported by the National Natural Science Foundation of China (52260013, 22068019).

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