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Highly improved visible-light-induced photocatalytic performance over BiOI/Ag₂CO₃ heterojunctions†

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A novel BiOI/Ag₂CO₃ composite was synthesized through the co-precipitation method and well characterized by X-ray diffraction, Fourier transform infrared spectroscopy, X-ray photoelectron spectroscopy, scanning electron microscopy, transmission electron microscopy, energy dispersive X-ray spectroscopy, UV-vis diffuse reflectance spectroscopy and photoluminescence spectroscopy. Its photocatalytic activity was evaluated for degrading various pollutants (rhodamine B, methylene blue, methyl orange) and phenol aqueous solution. Experimental results indicated that Ag₂CO₃ nanoparticles anchored on the BiOI sheet surface promoted the enhanced photocatalytic activity. Moreover, when the mass ratio of BiOI in BiOI/Ag₂CO₃ composites was 20%, the as-prepared BiOI/Ag₂CO₃ (20 wt%) composite exhibited the optimal photocatalytic activity for degrading rhodamine B; its rate constant was approximately 6.75 and 4.3 times higher than the separate BiOI and Ag₂CO₃. The enhanced photocatalytic performance could be attributed to the heterojunctions between BiOI and Ag₂CO₃. Furthermore, the possible mechanism for photodegradation over the BiOI/Ag₂CO₃ composite is proposed.

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1. Introduction

Semiconductor photocatalysis has received a great deal of attention because it represents a promising alternative technology for efficient utilization of solar energy to solve energy and environmental problems.¹ Among all kinds of semiconductor photocatalysts, TiO₂ has been the most widely investigated due to its low cost, non-toxicity, strong oxidizing activity and high chemical stability. Nevertheless, the large band gap and the inefficient separation of photoinduced hole-electron pairs result in its unsatisfactory photocatalytic performance.² Accordingly, to take full advantage of solar energy, it is essential to exploit effective and sustainable photocatalysts with visible-light-induced photocatalytic capability.

Recently, Ag-based photocatalysts, including Ag₂O,³ Ag₃PO₄,^{4,5} AgX (X = Cl, Br, I),^{6–8} AgVO₃,⁹ Ag₂CrO₄,¹⁰ and Ag₂WO₄,¹¹ have been regarded as promising photocatalysts. Among them, Ag₂CO₃ has exhibited highly efficient photocatalytic property for decomposing methylene blue, rhodamine B and methyl orange dyes.^{12,13} However, due to self-

photocorrosion, Ag₂CO₃ possesses weak activity after recycling.^{14,15} Hence, it is urgent to develop some method to improve the stability of Ag₂CO₃.

A group of efficient visible-light-driven photocatalysts, BiOX (X = Cl, Br, and I), has shown superb visible light activity for energy conversion and environmental remediation, attributed to particular physicochemical properties.^{16–18} Among the BiOX catalysts, BiOI presents the lowest band gap (1.7–1.9 eV), revealing excellent visible-light responsiveness and photocatalytic capacity.¹⁹ However, high recombination of photo-generated electron-hole pairs restricts its photocatalytic performance. Previous reports implied that heterojunctional structure could promote the separation of photogenerated electrons and holes.^{20–22} Hence, it is possible that the coordination of BiOI and Ag₂CO₃ might produce better photocatalytic activity than pure BiOI or Ag₂CO₃. However, there are few works focusing on the preparation and photocatalytic performance of BiOI/Ag₂CO₃ composites.

In this work, we successfully synthesized BiOI/Ag₂CO₃ heterojunction at room temperature. The obtained BiOI/Ag₂CO₃ composites were well characterized by XRD, FTIR, XPS, SEM, TEM, ESX, UV-vis DRS and PL. Various pollutants, such as rhodamine B (RhB), methylene blue (MB), methyl orange (MO) and phenol, were selected as model molecules to investigate the photocatalytic ability of the resultant BiOI/Ag₂CO₃ composite. Experimental results indicated that as-prepared BiOI/Ag₂CO₃ composite exhibited clearly enhanced photocatalytic activity for degrading various pollutants compared with pure Ag₂CO₃ and BiOI, which could be attributed to the heterojunction between

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BiOI and Ag_2CO_3 . In addition, the BiOI/ Ag_2CO_3 composite retained excellent photostability; the activity decreased slightly after five recycles. Moreover, the possible mechanism for the enhancement of the photocatalytic activity over the BiOI/ Ag_2CO_3 composite is also proposed.

2. Experimental section

2.1 Synthesis of BiOI/ Ag_2CO_3 photocatalysts

All the reagents were supplied from Sinopharm Chemical Reagent Co. Ltd, China. Deionized water was used throughout the study.

The preparation of BiOI was as follows: 1.212 g of $\text{Bi}(\text{NO}_3)_3 \cdot 5\text{H}_2\text{O}$ was added into 40 mL deionized H_2O . After stirring for 1 h, 20 mL of H_2O containing 0.415 g KI was dropped slowly into the above mixed solution. The resultant solution was vigorously stirred for 1 h at room temperature. Finally, the obtained products were collected by filtration, then washed with water and absolute alcohol thoroughly, and dried at 60 °C.

A series of BiOI/ Ag_2CO_3 composites were produced through the co-precipitation method. In a typical experimental process, 0.340 g AgNO_3 was dissolved in 30 mL of deionized H_2O , then a certain amount of BiOI was added into the above solution. After stirring for 20 min, 10 mL of deionized water containing 0.106 g of Na_2CO_3 was dropped slowly into the suspension solution. After continuous stirring for 1 h, the suspension was filtered, washed with water and absolute alcohol, and dried at 35 °C. According to the mass ratio of BiOI in the BiOI/ Ag_2CO_3 composite, the as-made samples were denoted as BiOI/ Ag_2CO_3 (10 wt%), BiOI/ Ag_2CO_3 (20 wt%) and BiOI/ Ag_2CO_3 (50 wt%). The pure Ag_2CO_3 was synthesized in the same way without the addition of BiOI.

2.2 Characterizations

The X-ray diffraction (XRD) patterns were obtained on a Bruker D8 Advance X-ray powder diffractometer with Cu $K\alpha$ radiation (40 kV, 30 mA) for phase identification. Fourier transform infrared spectra (FTIR) were recorded on Thermo Fisher Scientific IS10. The X-ray photoelectron spectroscopy (XPS) analysis was performed using the Thermo Fisher Scientific Escalab 250. The scanning electron microscopy (SEM) images were taken using a HITACHI SU8010 scanning electron microscope. The transmission electron microscope (TEM) was carried out *via* JEM-2100F with energy dispersive X-ray spectroscopy (EDX). The UV-vis diffuse reflectance spectra (DRS) were recorded using an Agilent Cary 5000 UV-vis spectrometer. The photoluminescence spectra (PL) were collected by PerkinElmer LS55 spectrometer with the excitation wavelength of 220 nm. Transient photocurrent response of the samples was detected using an electrochemical system (CHI760, China) with three-electrode quartz cells. The counter electrode was Pt wires, and a saturated calomel electrode was used as the reference electrode. The working electrode was the sample films (BiOI, Ag_2CO_3 and BiOI/ Ag_2CO_3 (20 wt%) composite) coated on ITO glass. The light source was a 300 W Xe lamp with 400 nm filter to

exclude the UV light, and 0.1 M Na_2SO_4 was used as the electrolyte.

2.3 Photocatalytic testing for pollutant degradation

The photocatalytic activity of the as-made BiOI/ Ag_2CO_3 composites was evaluated in degrading RhB, MB, MO and phenol under visible light. A 300 W Xe lamp with a 400 nm cutoff filter was applied as the visible-light source. 50 mg sample was dispersed into 50 mL of 5 mg L^{-1} pollutant and stirred in the dark for 1 h to reach the adsorption-desorption equilibrium. Then, 4 mL of solution was collected every given time interval under irradiation, and the catalyst was removed by centrifugation (12 000 rpm, 5 min). The concentration of RhB, MB, and MO was detected *via* UV-vis spectrophotometer at the wavelength of 552, 664 and 464 nm. The concentration of phenol was detected through colorimetric method using 4-aminoantipyrine as the colour-developing agent at 510 nm.²³

3. Results and discussion

3.1 The structure and property characterizations of BiOI/ Ag_2CO_3 composite

Fig. 1 gives the XRD patterns of resultant BiOI, Ag_2CO_3 and BiOI/ Ag_2CO_3 (20 wt%) composite. Sharp and high diffraction peaks were observed in all samples, indicating that all the resultant samples were well crystallized. For BiOI, the four main diffraction peaks appeared at 29.8°, 31.9°, 45.6° and 55.4°, which are good agreement with the (012), (110), (020) and (122) diffraction planes of the tetragonal phase of BiOI (JCPDS no. 10-0445).²⁴ Ag_2CO_3 presented obvious diffraction peaks at 20.7°, 32.8°, 33.8°, 37.2° and 39.8°. These diffraction peaks could be indexed to the crystallite planes of (110), (-101), (-130), (200) and (031) of monoclinic Ag_2CO_3 (JCPDS no. 26-0339).²⁵ Obviously, both BiOI and Ag_2CO_3 were found in the BiOI/ Ag_2CO_3 (20 wt%) composite. No impurity peaks were observed, implying the high purity of the composite.

The FTIR spectra of pure BiOI, Ag_2CO_3 and BiOI/ Ag_2CO_3 (20 wt%) composite are shown in Fig. 2. Clearly, Ag_2CO_3 and BiOI/ Ag_2CO_3 (20 wt%) composite presented similar stretching



Fig. 1 XRD patterns of various samples. (a) BiOI, (b) Ag_2CO_3 and (c) BiOI/ Ag_2CO_3 (20 wt%) composite.





Fig. 2 FTIR spectra of (a) BiOI, (b) Ag_2CO_3 and (c) BiOI/ Ag_2CO_3 (20 wt%) composite.

vibrations and bending vibrations. The peaks at 1449, 1382, 883 and 705 cm^{-1} were assigned to the characteristic peaks of carbonate ion.²⁶ Compared with bare Ag_2CO_3 , a new peak near 487 cm^{-1} could be observed in the BiOI/ Ag_2CO_3 (20 wt%) composite. This peak was assigned to the absorption peak of Bi–O,²⁴ which also further revealed that BiOI was successfully composed with Ag_2CO_3 .

The elemental composition and state of BiOI/ Ag_2CO_3 (20 wt%) composite were analyzed using XPS. In Fig. 3A, the survey spectra demonstrate that the composite contains Ag, C, O, Bi and I elements, proving that the sample is composed of Ag_2CO_3 and BiOI. Fig. 3B shows that the peaks of Ag 3d are observed at 367.8 and 373.8 eV, ascribed to Ag ions of Ag_2CO_3 .²⁷ C 1s peak was deconvoluted into three peaks at 284.6, 286.5 and 288.4 eV in Fig. 3C. The peak at 284.6 eV is attributed to the C–C and/or adventitious carbon; the peaks at 286.5 and 288.4 eV correspond to the carbonate ion in the sample.²⁸ The wide XPS of O 1s peak (Fig. 3D) could be divided into three peaks; the peak at 530.7 eV corresponds to Bi–O,²⁹ the peaks at 532.3 and 533.3 eV are respectively attributed to the crystal lattice oxygen of Ag_2CO_3 and surface adsorbed oxygen species.³⁰ The peaks at binding energies of 164.1 and 158.8 eV (Fig. 3E) belong to Bi $4f_{5/2}$ and Bi $4f_{7/2}$ of Bi^{3+} ions.³¹ For I 3d in Fig. 3F, the two peaks located at 619.4 eV and 630.8 eV are associated with I $3d_{5/2}$ and I $3d_{3/2}$, respectively.³²

For observation of the morphology of as-prepared samples, firstly, SEM images of pure Ag_2CO_3 , BiOI and BiOI/ Ag_2CO_3 (20 wt%) composite are provided in Fig. 4. A large number of Ag_2CO_3 particles with irregularity were observed (Fig. 4A), and the size of Ag_2CO_3 particles is between 0.2–1 μm . Pure BiOI is composed of abundant sheets with micron size (Fig. 4B). For as-prepared BiOI/ Ag_2CO_3 (20 wt%) composite in Fig. 4C, Ag_2CO_3 nanoparticles with 20–200 nm are attached on the surface of BiOI (labeled by red circles). Further information about the microstructure of the resultant samples was supplied from the TEM and HRTEM images. Clearly, the obtained results were

similar to the SEM results. Ag_2CO_3 still exhibited ruleless structure and was aggregated, and BiOI presented sheet structure with the size of 1–3 μm . From the TEM image of BiOI/ Ag_2CO_3 (20 wt%) (Fig. 4F), Ag_2CO_3 nanoparticles adhered to the surface of the BiOI sheet, significantly decreasing the size of Ag_2CO_3 compared with pure Ag_2CO_3 . HRTEM image (Fig. 4G) shows that the Ag_2CO_3 nanoparticles tightly loaded on the BiOI sheet surface. The lattice fringe spacings of 0.280 and 0.199 nm respectively corresponded to the (110) and (020) planes of tetragonal BiOI, and those at 0.264 and 0.226 nm are due to the (–130) and (031) planes of the monoclinic Ag_2CO_3 , respectively. Obviously, this result indicates that the heterojunctions between Ag_2CO_3 and BiOI have formed, and that there was a clear interface contact between Ag_2CO_3 and BiOI, which might contribute to facilitating the photogenerated electron transfer between Ag_2CO_3 and BiOI, thus leading to the improved photocatalytic property. Moreover, the EDX spectrum of the BiOI/ Ag_2CO_3 (20 wt%) composite is also shown in Fig. 4H. The composite contains only C, O, Bi, Ag and I elements, except for element of Cu from the supports. The above results agree well with the XRD, FTIR and XPS results.

The light harvest was investigated by UV-vis DRS (Fig. 5). Obviously, the absorption band edge of Ag_2CO_3 was estimated to be 574 nm, suggesting that Ag_2CO_3 exhibited good photo-absorption from UV region to visible light. The absorption band edge of BiOI was around 703 nm, presenting that BiOI had strong and broad absorption in the visible light region. After BiOI was combined with Ag_2CO_3 , the BiOI/ Ag_2CO_3 (20 wt%) composite showed enhanced photoharvest compared with pure Ag_2CO_3 . Furthermore, the band gap energy of as-prepared samples could be calculated through the equation $E_g = 1240/\lambda$ (where λ is the absorption edge and E_g is the corresponding band gap). Correspondingly, the band gaps of BiOI and Ag_2CO_3 were estimated to about 1.76 eV and 2.16 eV.

Photoluminescence spectra emission originates from the recombination of photogenerated electron–hole pairs; thus, PL might reveal the transfer and recombination processes of the photoinduced charge carrier.³³ Generally, a lower PL intensity denotes a higher separation probability of photogenerated charge carrier.^{34,35} Fig. 6 displays the PL spectra of BiOI and BiOI/ Ag_2CO_3 (20 wt%) with the excitation wavelength of 220 nm. Pure BiOI exhibited higher emission intensity than BiOI/ Ag_2CO_3 (20 wt%) composite, indicating that the coordination of BiOI and Ag_2CO_3 could promote the separation of photogenerated electrons and holes, and it is anticipated to contribute to the improved photocatalytic activity.

Photocurrent measurement is an efficient way to evaluate the separation efficiency of photocharges. Generally, higher photocurrent intensity means better separation efficiency of photocharges. As shown in Fig. 7, visible light irradiation could induce the BiOI, Ag_2CO_3 and BiOI/ Ag_2CO_3 (20 wt%) composite to generate photocurrent signals. BiOI/ Ag_2CO_3 (20 wt%) composite possessed stronger photocurrent intensity than pure BiOI and Ag_2CO_3 , suggesting that the former exhibited better separation efficiency for photogenerated electron–hole pairs, which was consistent with photoluminescence measurement results.





Fig. 3 XPS of BiOI/Ag₂CO₃ (20 wt%) composite. (A) Survey spectra, (B) Ag 3d, (C) C 1s, (D) O 1s, (E) Bi 4f and (F) I 3d.

3.2 Photocatalytic activity and stability

The photocatalytic activity of pure BiOI, Ag₂CO₃ and BiOI/Ag₂CO₃ composite for the degradation of RhB solution was measured under visible light. Fig. 8A exhibits the concentration changes of RhB. When bare BiOI and Ag₂CO₃ were used as photocatalysts, about 44% and 60% of RhB decomposed in 12 min, respectively. The BiOI/Ag₂CO₃ composites exhibited much higher photocatalytic activity under the same conditions; comparatively, BiOI/Ag₂CO₃ (10 wt%) and BiOI/Ag₂CO₃ (50 wt%) respectively possessed 95% and 97% degradation efficiency for

RhB. The BiOI/Ag₂CO₃ (20 wt%) composite presented the optimal photocatalytic activity, and almost 100% RhB was degraded within 12 min under visible-light irradiation. The significantly enhanced photocatalytic activity might be attributed to the following facts. Firstly, the induced BiOI played the role of photo-absorber to enlarge the photoharvest of BiOI/Ag₂CO₃ composites, leading to the enhanced photocatalytic degradation. Secondly, the heterojunction formed between BiOI and Ag₂CO₃ contributed to the electron transfer, promoting the separation of the photogenerated electrons and holes.



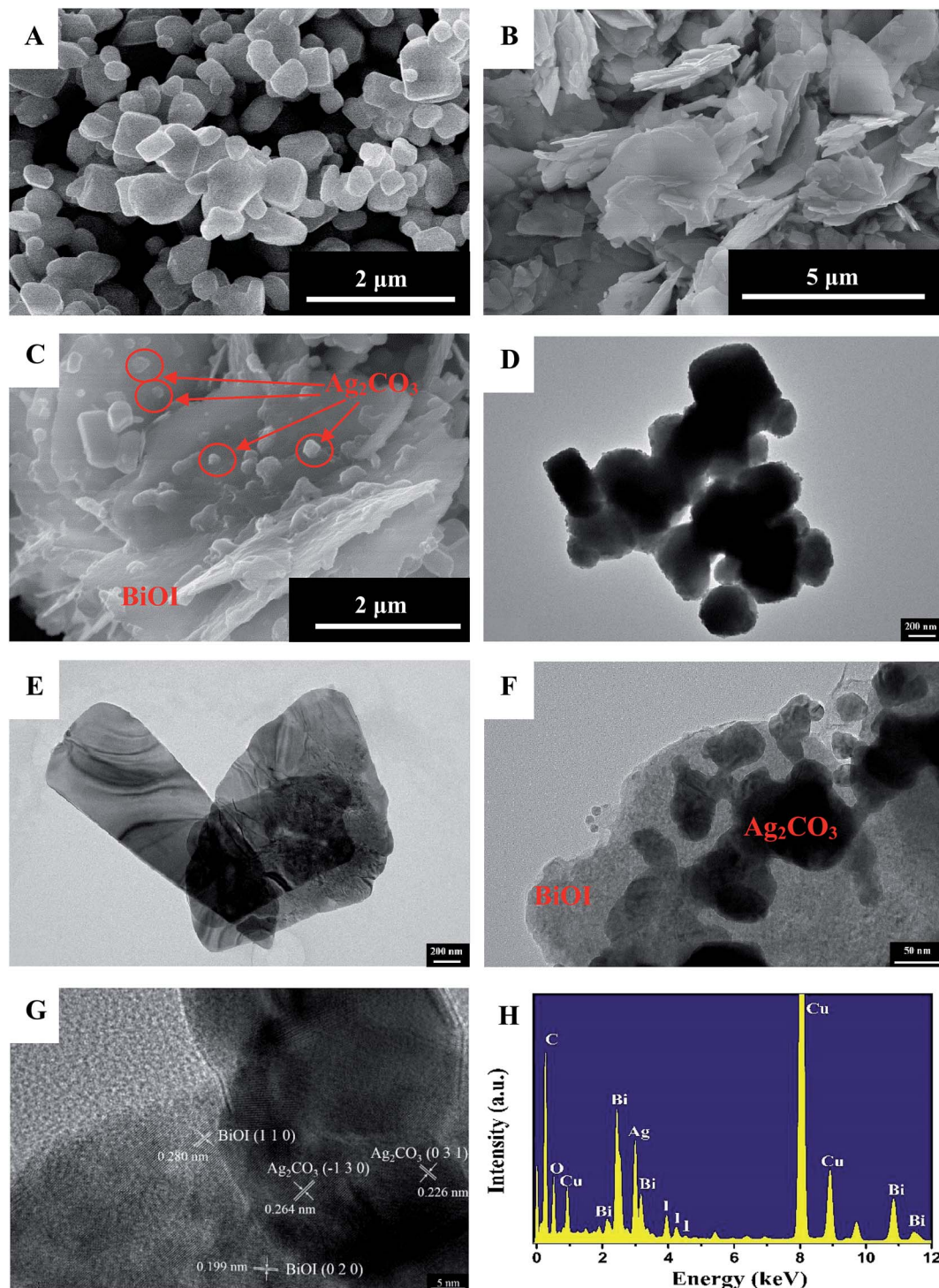


Fig. 4 The SEM images of (A) pure Ag_2CO_3 , (B) BiOI and (C) BiOI/ Ag_2CO_3 (20 wt%) composite; the TEM images of (D) pure Ag_2CO_3 , (E) BiOI, (F) BiOI/ Ag_2CO_3 (20 wt%) composite; (G) the HRTEM image and (H) EDX spectrum of BiOI/ Ag_2CO_3 (20 wt%) composite.

Correspondingly, the RhB degradation rate constant was investigated in Fig. 8B. In general, the photocatalytic degradation of RhB fits well with a pseudo-first-order reaction within the low-concentration region, and its kinetics could be calculated as follows:

$$\ln(C_0/C) = kt \quad (1)$$

wherein C_0 is the equilibrium concentration of pollutant, C is the concentration of remaining dye solution at each irradiation time, k is the rate constant, and t is reaction time. As shown in Fig. 8C, the degradation rate constants (k) of RhB over BiOI/ Ag_2CO_3 (10 wt%), BiOI/ Ag_2CO_3 (20 wt%) and BiOI/ Ag_2CO_3 (50 wt%) were 0.251, 0.327 and 0.287 min^{-1} , respectively. Also, the BiOI/ Ag_2CO_3 (20 wt%) composite exhibited the highest rate



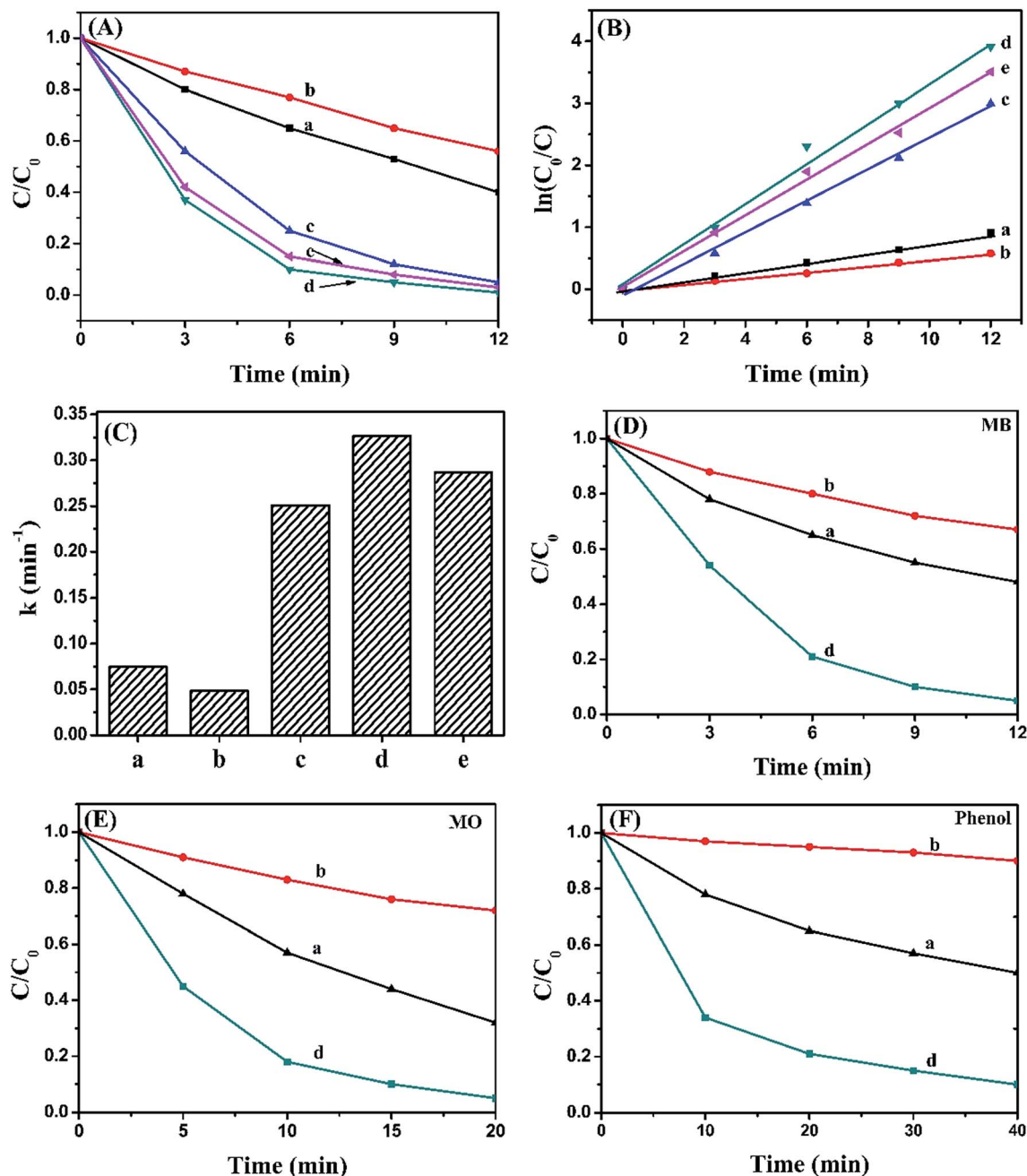


Fig. 8 (A) The photodegradation curves of RhB; (B) first-order kinetic plots for the photodegradation of RhB and (C) the corresponding rate constants; (D) the photodegradation curves of MB; (E) the photodegradation curves of MO and (F) phenol. (a) Ag_2CO_3 , (b) BiOI, (c) BiOI/ Ag_2CO_3 (10 wt%), (d) BiOI/ Ag_2CO_3 (20 wt%) and (e) BiOI/ Ag_2CO_3 (50 wt%).

In addition, the valence band (VB) and conduction band (CB) potentials of BiOI and Ag_2CO_3 were calculated based on the following empirical equations.^{42,43}

$$E_{\text{VB}} = X - E_{\text{e}} + 0.5E_{\text{g}} \quad (2)$$

$$E_{\text{CB}} = E_{\text{VB}} - E_{\text{g}} \quad (3)$$

where E_{VB} and E_{CB} are the valence and conduction band edge potentials. X is the electronegativity of the semiconductor, and the X values for BiOI and Ag_2CO_3 are 5.94 and 6.02 eV;^{44,45} E_{e} is

the energy of free electrons on the hydrogen scale at about 4.5 eV, and E_{g} is the band gap energy of the semiconductor (for BiOI, $E_{\text{g}} = 1.76$ eV; for Ag_2CO_3 , $E_{\text{g}} = 2.16$ eV). Thus, the E_{VB} and E_{CB} of BiOI were calculated to be +2.32 and +0.56 eV, and the E_{VB} and E_{CB} of Ag_2CO_3 were at +2.6 and +0.44 eV.

Thus, a possible mechanism for the enhanced photocatalytic activity of BiOI/ Ag_2CO_3 composite is proposed. Apparently, the matched band edges of BiOI ($E_{\text{VB}} = 2.32$ eV, $E_{\text{CB}} = 0.56$ eV) and Ag_2CO_3 ($E_{\text{VB}} = 2.6$ eV, $E_{\text{CB}} = 0.44$ eV) could not be constructed so that it was difficult to promote the separation of the photoinduced carriers. Moreover, the experiments of active species indicated





Fig. 13 The possible degradation intermediate and the final products of RhB over BiOI/Ag₂CO₃ composites.

Their oxidation or reduction activities make RhB N-deethylated, destroying the conjugated structure. With prolonged light irradiation time, the effects of active intermediate species are improved, leading to further ring-opening and mineralization of less organic matter.

4. Conclusion

In summary, the novel BiOI/Ag₂CO₃ catalyst has been successfully fabricated and applied to photocatalytic degradation of various pollutants. The addition of BiOI significantly enhanced the photocatalytic activity of Ag₂CO₃, and the BiOI/Ag₂CO₃ (20 wt%) composite exhibited the highest catalytic activity. Moreover, BiOI/Ag₂CO₃ composite reduced the serious photo-corrosion of Ag₂CO₃ and showed excellent catalytic recycling stability. The enhanced photocatalytic activity is not only attributed to the narrow bandgap of BiOI and the extended optical response, but also to the enhanced photogenerated carrier separation on the heterogeneous interface between Ag₂CO₃ and BiOI. The developed heterojunction system of BiOI/Ag₂CO₃ composite could be extended to other silver-containing heterostructured photocatalysts with highly efficient catalytic performance for pollutant abatement.

Conflicts of interest

There are no conflicts of interest to declare.

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