Enhancement of photocatalytic activity for BiPO$_4$ via phase junction$^\dagger$

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BiPO$_4$ with a phase junction was synthesized by calcinating hexagonal BiPO$_4$(HBIP) at different temperatures. The phase structures of BiPO$_4$ were gradually transformed from HBIP to monazite monoclinic BiPO$_4$ (nMBIP) and monoclinc BiPO$_4$ (mMBIP) with increasing calcination temperature. The enhancement of the photocatalytic performance and photocurrent were ascribed to the formation of phase junction. A nMBIP–mMBIP surface-phase junction was formed in BiPO$_4$ when HBIP was calcined at 500 °C, and its photocatalytic activity was 28.7 times as high as that of HBIP. Moreover, radical trapping experiments confirmed that the hole was the active species for BiPO$_4$ on the degradation of methylene blue.

The phase structure is a major factor that influences the photocatalytic activity. For traditional TiO$_2$, the activity of anatase is better than that of rutile, but the photocatalytic activity of P25 consisting of 80% anatase and 20% rutile is superior to that of pure anatase TiO$_2$. The correlation between the phase junction of TiO$_2$ and the photocatalytic activity is not fully understood. In recent years, the phase junction of TiO$_2$,\textsuperscript{20,23} α–β phase junction of Ga$_2$O$_3$ (ref. 22) and Bi$_2$O$_3$ nanowires\textsuperscript{23} were formed by different methods. The formation of a phase junction efficiently accelerated the separation efficiency of the photo-generated charges and further improved the photocatalytic performance. For BiPO$_4$, there are three main phase structures: hexagonal BiPO$_4$ (HBIP, space group: P3121), monazite monoclinic BiPO$_4$ (nMBIP, space group: P21/n) and monoclinic BiPO$_4$ (mMBIP, space group: P21/m). Among them, nMBIP has the highest photocatalytic activity because it possesses the most distorted PO$_4$ tetrahedron and the largest dipole moment, and the HBIP has the lowest photocatalytic activity.\textsuperscript{7,24–27} Is it possible to obtain a more efficient photocatalyst by forming the phase junction of BiPO$_4$?

In this work, BiPO$_4$ with a phase junction was synthesized by calcinating HBIP at different temperatures, and the enhancement of photocatalytic activity was explored. Moreover, the mechanism for the improved photocatalytic performance by phase junction is discussed.

1. Introduction

Semiconductor photocatalysis has attracted considerable attention owing to its superiority in environmental purification and photocatalytic hydrogen generation from water splitting in recent years.\textsuperscript{1–17} BiPO$_4$ is a new type of oxy-acid salt photocatalyst, its electrostatic field formed by the PO$_4$ tetrahedron on the surface promotes the separation efficiency of photo-generated charges and it exhibits excellent photocatalytic activity.\textsuperscript{4,5} Moreover, it also possesses merits such as a stable chemical structure, exceptional optical and electronic properties, low-cost, nontoxicity and fast settlement separation speed. BiPO$_4$ nanorods and nanocrystals were synthesized by hydrothermal and solvothermal methods, and their photocatalytic activities on the degradation of methylene blue were 2.0 and 3.6 times as high as that of P25.\textsuperscript{6,7} To overcome the narrow absorption of BiPO$_4$, many wide absorption semiconductors such as Ag$_3$PO$_4$,\textsuperscript{8} BiVO$_4$,\textsuperscript{8,9} C$_3$N$_4$,\textsuperscript{10} Cds,\textsuperscript{11} AgBr\textsuperscript{12} were coupled with it. The results showed that the absorption range was enlarged, and the photocatalytic activity was also enhanced. The photocatalytic performance of BiPO$_4$ was further improved by adjusting the surface oxygen vacancy\textsuperscript{14,15} and doping with fluorine\textsuperscript{16} or Ag.\textsuperscript{17,18} However, for the practical use of BiPO$_4$ in the environment, some problems need to be solved, including the complicated synthetic method, low yield, and low specific surface area.

2. Experimental section

2.1 Chemical reagents

Bismuth nitrate pentahydrate (Bi(NO$_3$)$_3$·5H$_2$O), sodium dihydrogen phosphate dihydrate (NaH$_2$PO$_4$·2H$_2$O) and ethanol were purchased from Beijing Chemical Works of China. Glycerol was purchased from Tianjin Fuchen Chemical Reagents Factory of China. Methylene blue, methyl orange and rhodamine B were
purchased from Tianjin Chemical Reagent Limited Corporation of China. All chemical reagents used were of analytic grade and used without further purification.

2.2 Synthesis of BiPO₄ with phase junction

4.85 g (10 mmol) Bi(NO₃)₃·5H₂O was dissolved in 900 mL 10% glycerol–H₂O mixed solution. The mixture was sonicated for 1 h until Bi(NO₃)₃·5H₂O was dissolved completely, and then 7.8 g (50 mmol) NaH₂PO₄·2H₂O was added to the solution. A white suspension was formed immediately and then stirred for 1 h. A white precipitate was obtained by centrifugation and washed with ethanol and deionized water for three times. Finally, the white precipitate was dried at 120 °C for 12 h and was identified as HBIP. BiPO₄ with different phase structure were prepared by calcinating HBIP at several different temperatures in the range of 350–650 °C for 4 h and at 500 °C for different times in a muffle furnace in air.

2.3 Photocatalytic activity and photoelectrochemical performance

The photocatalytic activities of as-prepared BiPO₄ were evaluated on the degradation of methylene blue in solution under a 15 W 254 nm UV germicidal lamp and the average light intensity was 0.90 mW cm⁻². 25 mg photocatalyst was added to the as-prepared 50 mL 3.0 × 10⁻⁵ mol L⁻¹ methylene blue aqueous solution. Prior to UV irradiation, the suspension was ultrasonically dispersed for 0.5 h, and then magnetically stirred for 1.0 h in the dark to ensure the establishment of adsorption–desorption equilibrium. At each given time interval, 3.0 mL suspension was taken and separated through centrifugation (4000 rpm, 10 min). The concentration of the methylene blue solution was analyzed at the absorption band maximum (663 nm) using a Hitachi U-3010 UV-Vis spectrophotometer. The methods for the photocatalytic degradation of methyl orange, rhodamine B and phenol were the same as above, but the concentration of phenol was 10.0 mg L⁻¹. Note that the concentration of phenol was monitored by HPLC analysis with a UV detector at 270 nm. The mobile phase was methanol and water (6 : 4), and the flow rate was 1.0 mL min⁻¹.

The photocurrents and electrochemical impedance spectroscopy (EIS) were performed on a CHI-660B electrochemical system (Shanghai, China) using a standard three-electrode cell comprising a working electrode (20 mm × 45 mm, ITO/BiPO₄), a standard calomel electrode (SCE) as the reference electrode and a platinum wire as the counter electrode. ITO/BiPO₄ was prepared comprising a working electrode (20 mm × 45 mm, ITO/BiPO₄), a standard calomel electrode (SCE) as the reference electrode and a platinum wire as the counter electrode. ITO/BiPO₄ was prepared on a Hitachi U-3010 UV-Vis spectrophotometer, and BaSO₄ was used as the reference sample. Thermogravimetric analysis (TG) and differential scanning calorimetry (DSC) were carried out using a NETZSCH STA 449F3 simultaneous thermal analyzer in dry air in the range of 50–900 °C at a heating rate of 10 °C min⁻¹. Transmission electron microscopy (TEM) was performed on a HITACHI HT7700 electron microscope at an accelerating voltage of 100 kV. The scanning electron microscopy (SEM) images were obtained on a LEO1530 thermal field-emission scanning electron microscope operating at an accelerating voltage of 10.0 kV. The photoluminescence (PL) emission spectra of the as-prepared samples were measured on Aqualog® absorbance and 3D fluorescence scanning spectrophotometer with 150 W of 250 nm exciting light.

3. Results and discussions

3.1 Formation of the BiPO₄ phase junction

BiPO₄ with a phase junction was synthesized by a gradual phase transformation from HBIP to nMBIP and mMBIP via calcination in the range of 350–650 °C (Fig. 1A). BiPO₄ lost some P atoms and O atoms and transformed into Bi₆.67(PO₄)O₄ when the calcination temperature was increased to 650 °C. All the diffraction peaks of the precursor BiPO₄ were indexed to the pure HBIP (P2₁12₁, JCPDS 015-0766), but no impurity peaks were observed. The peaks at 19.0°, 21.4° and 27.2° emerged after 350 °C calcination, which were ascribed to the (011), (−111) and (200) lattice planes of nMBIP (P2₁/n, JCPDS 089-0287), but the proportion of nMBIP was negligible (Fig. 1A and B). The proportion of nMBIP was more than that of HBIP and its percentage was 54.4% at 400 °C. The characteristic peaks of mMBIP (P2₁/m, JCPDS077-2208) at 18.3°, 22.2° and 37.1° ascribed to (100), (110) and (200) lattice planes emerged after increasing the calcination temperature to 450 °C. At the same time, the three kinds of phase structures BiPO₄ (HBIP, nMBIP and mMBIP) existed simultaneously and their percentages were 5.9%, 89.2% and 4.9%, respectively. HBIP disappeared completely and the proportion of nMBIP was increased to 94.5% at 500 °C, and its crystal compositions were almost the same as that of BiPO₄ calcined at 550 °C. The calcination times
hardly affected the composition of BiPO₄ when the calcination temperature was set to 500 °C (Fig. S1†). mMBIP composition rapidly increased with further elevating the calcination temperature above 550 °C. nMBIP completely disappeared in BiPO₄ calcined at 650 °C, which lost some P atoms and O atoms and transformed into Bi₆.67(PO₄)₄O₄. The result is similar to other semiconductor photocatalysts. TiO₂ with different phase structures was prepared by phase transformation from anatase to rutile when the calcination temperatures were in the range of 500–800 °C.²⁰ Ga₂O₃ and Bi₂O₃ could formed an α–β phase junction by adjusting the calcination and hydrothermal temperatures.²²,²³

For the HBIP precursor, the 2.0% obvious weight loss occurring from 90 °C to 150 °C could be attributed to the desorption of surface bound water,²⁷ and an endothermic peak around 100 °C in the DSC curve consisted of the surface bound water (Fig. S2†). Moreover, a sharp exothermic peak at 550 °C resulted from the phase transformation of BiPO₄. Because TG and DSC analysis were processed at continuous heating-up, the information of measurement could not reflect the transformation details of the three kinds of BiPO₄ phase structures. The phase transformation of BiPO₄ only changed the arrangement direction of Bi and P atoms and did not destroy the relevance of the phase structure and topology;²⁹ therefore, there was no weight loss when the phase transformation of BiPO₄ occurred.

The transformation of BiPO₄ phase structures could be confirmed by HRTEM (Fig. 2). The lattice fringes with d-spacings of 0.442 nm, 0.349 nm and 0.307 nm were in good agreement with the (101), (110) and (111) lattice planes of HBIP [JCPDS 015-0766] (Fig. 2A). BiPO₄ calcined at 400 °C only possessed (−212) and (200) lattice planes of nMBIP [JCPDS 089-0287] with d-spacings of 0.243 nm and 0.328 nm (Fig. 2B). Upon further increasing the calcination temperature to 500 °C, BiPO₄ mainly possesses the (−212) lattice plane of nMBIP with a d-spacing of 0.243 nm and a small quantity of the (020) lattice plane (d-spacing = 0.354 nm) of mMBIP [JCPDS077-2208] emerged on the edge of the nMBIP (020) lattice plane (Fig. 2C). Thus, it was observed that the surface-phase junction between nMBIP and mMBIP was formed. In general, the formation of a phase junction was from the two kinds of crystal phases with very close lattice parameters. The (−212) lattice plane of nMBIP with a d-spacing of 0.243 nm and the (020) lattice plane of mMBIP with a d-spacing of 0.354 nm emerged simultaneously in Fig. 2C. The specific crystal plane of the phase junction was formed because of lattice mismatch during the process of calcination. The lattice fringe of the mMBIP (020) lattice plane was not very clear on the edge of the nMBIP (020) lattice plane because the phase transformation occurred from nMBIP to mMBIP in the surface region. BiPO₄ possessed the (020) and (101) lattice planes of mMBIP with a d-spacing of 0.354 nm and 0.320 nm with the calcination...
temperature increasing to 600 °C (Fig. 2D). As can be known from XRD (Fig. 1A), BiPO₄ calcined at 400 °C consisted of HBIP and nMBIP, and when BiPO₄ was calcined at 600 °C, it consisted of nMBIP and mMBIP. At the same time, the proportions of the two different phases were almost equal; however, the HRTEM images only showed the nMBIP and mMBIP lattice fringes in BiPO₄ calcined at 400 and 600 °C, respectively. The results indicated that the transformation of the BiPO₄ phase structure at elevated temperatures was from outer surface region to the inner bulk region; thus, the HBIP and nMBIP lattice plane could not be observed because they were covered by nMBIP and mMBIP completely in the outer region. However, the nMBIP and mMBIP lattice fringes could be observed simultaneously in BiPO₄ calcined at 500 °C. The result indicated that a surface-phase junction formed between nMBIP and mMBIP.

The three kinds of BiPO₄ phase structures were all constructed by the building blocks of PO₄ tetrahedra and BiO₈ polyhedra, but the arrangements of the polyhedral were different. In the HBIP precursor (Fig. 3), two intense bands at 1060 cm⁻¹ and 957 cm⁻¹ were ascribed to the v3 asymmetric and v1 symmetric stretching modes of the P-O bonds in the PO₄ units, respectively. The bands at 581 cm⁻¹, 544 cm⁻¹ and 436 cm⁻¹, and 394 cm⁻¹ were attributed to the O-P-O bending modes of v4 and v2 in PO₄ units. The intense band at 190 cm⁻¹ may be assigned to an O–Bi–O symmetric bending mode. With increase in the calcination temperature, the characteristic Raman bands of BiPO₄ changed significantly. When BiPO₄ was calcined at 350 °C, three new bands at 915 cm⁻¹, 376 cm⁻¹ and 271 cm⁻¹, corresponding to the v1 symmetric stretching modes, v2 bending modes and Bi–O stretching modes were observed. These characteristic Raman peaks ascribed to nMBIP gradually strengthened with the calcination temperature increasing in the range of 350–550 °C. At the same time, the v1 symmetric stretching modes showed a blue shift to 1030 cm⁻¹, and the v4 and v2 bending modes of PO₄ units showed a red shift to 586 cm⁻¹ and 451 cm⁻¹, respectively. Upon increasing the calcination temperature to 600 °C or above, the bands positioned at 971 cm⁻¹, 597 cm⁻¹, 536 cm⁻¹, 471 cm⁻¹, and 331 cm⁻¹ were observed, and the strongest band at 218 cm⁻¹ was assigned to PO₄ units and Bi–O stretching modes, which were the typical Raman peaks of nMBIP.

The UV-Vis DRS of BiPO₄ calcined at different temperatures are shown in Fig. 4. According to the spectra, the optical absorption of HBIP started at around 325 nm and increased steeply at around 275 nm, which is consistent with the literature. Moreover, it was found that BiPO₄ after calcination at different temperatures showed two absorption steps at about 275 nm and 330 nm. The optical band gap for all these photocatalysts can be calculated by Tauc’s plot. Absorption (or absorption²) versus energy, which may help to distinguish the direct or indirect transition of BiPO₄ crystal phases. From the calculated of Tauc’s plot, the band gaps of HBIP and BiPO₄ calcined at 400 °C, 500 °C and 600 °C were 4.6 eV, 4.5 eV, 4.34 eV and 4.4 eV, respectively, as shown in Fig. S3.† This may be caused by charge-transfer interaction between the two different phase structures of BiPO₄ with a phase junction. The absorption maximum of HBIP and BiPO₄ calcined at different temperatures appeared at about 218 nm and 258 nm, which could be assigned to the inter-band transition dominantly from the hybrid electrons of Bi³⁺ and O²⁻ rather than those of P⁵⁺.

The calcination temperature also affected the morphology and particle size of BiPO₄. The precursor HBIP was totally composed of homogeneous rod-like particles about 500 nm in diameter and several micrometers in length. The morphologies of BiPO₄ formed at different calcination temperatures (in the range of 350–500 °C) were basically the same, and their particles aggregated and became larger in size (Fig. S4 and S5†). The particles of BiPO₄ melted and became larger with increasing calcination temperature above 550 °C. High temperature calcination could also destroy the particles of other materials.

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**Fig. 3** Raman spectra of HBIP and BiPO₄ calcined at different temperatures for 4 h (excitation at 514.5 nm).

**Fig. 4** UV-Vis DRS of HBIP and BiPO₄ calcined at different temperatures.
For example, TiO$_2$ hollow spheres agglomerated into larger particles above 800 °C.$^{24}$ The morphology of FeTiO$_3$ changed from nanofibers to submicron particles with increasing in the calcination temperature in the range of 600–1000 °C.$^{24}$

3.2 Enhancement of the photocatalytic activity via phase junction of BiPO$_4$

The photocatalytic degradation of methylene blue under 254 nm UV light was carried out on BiPO$_4$ with a phase junction, the degradation process was fitted to pseudo first-order kinetics. The photocatalytic performance of BiPO$_4$ first increased and then decreased with increasing calcination temperature from 350 to 650 °C (Fig. 5A). HBIP had very low photocatalytic activity and its apparent rate constant ($k$) was only 0.0038 min$^{-1}$, which was consistent with the values reported in the literature.$^7$ The photocatalytic activity of BiPO$_4$ gradually increased when HBIP was calcined from 350 to 500 °C. The maximum activity was observed when BiPO$_4$ was calcined at 500 °C and the apparent rate constant $k$ reached 0.1043 min$^{-1}$, which was 27.4 times as high as that of HBIP. Furthermore, the photocatalytic activity of BiPO$_4$ calcined at 500 °C was also much higher than that of the physical mixed sample with the same phase ratio as the former one. This may be attributed to the formation of the nMBIP and mMBIP surface-phase junction and efficient separation of photo-generated charges.$^{20,22}$ The enhancement of photocatalytic performance in phase junction BiPO$_4$ can be confirmed by the superior photocatalytic

![Fig. 5](image-url)  
Fig. 5 Apparent rate constants ($k$) on the photocatalytic degradation of methylene blue for BiPO$_4$ calcined at (A) different temperatures for 4 h and (B) 500 °C for different times under 254 nm UV light irradiation.

![Fig. 6](image-url)  
Fig. 6 Photocatalytic degradation of different kinds of organic pollutants to HBIP and BiPO$_4$ calcined at 500 °C.

![Fig. 7](image-url)  
Fig. 7 Photocurrents of HBIP and BiPO$_4$ calcined under different conditions under 254 nm UV light irradiation.
performance of BiPO₄ calcined at 400 °C and 600 °C compared to their corresponding physical mixtures (Fig. S6†). The proportion of nMBIP increased, and it covered the surface region of nMBIP when further elevating the calcination temperatures above 550 °C. Moreover, the particles of BiPO₄ aggregated together. The two factors might lead to a gradual decrease in photocatalytic performance. The photocatalytic activity of BiPO₄ calcined at 650 °C was only slightly higher than that of HBIP because it was partly transformed to Bi₆.67(PO₄)₄O₄. When the calcination temperature was set to 500 °C, the highest photocatalytic activity of BiPO₄ with a phase junction could be obtained after calcination for 6 h. Its apparent rate constant \( k \) was 0.1089 min⁻¹, which was 28.7 times as high as that of HBIP. Parallel experiments of BiPO₄ calcined at 500 °C for 6.0 h were performed. As can be seen from the result, the photocatalytic activities of these samples are almost the same, which reveals that the preparation method of BiPO₄ with a phase junction via calcination was controllable and repeatable (Fig. S7†). However, when the calcination time was above 6 h, the photocatalytic activities of BiPO₄ decreased gradually. The apparent rate constant of BiPO₄ calcined at 500 °C for 10 h was decreased to 0.0761 min⁻¹. Note that the phase junction formed on the BiPO₄ surface could effectively enhance the photocatalytic performance.

Did the BiPO₄ with surface-phase junction have selectivity on the photocatalytic degradation of organic pollutants? It can be seen from Fig. 6, BiPO₄ calcined at 500 °C had much higher photocatalytic activity than HBIP during the degradation of the cationic dye methyl orange, anionic dye rhodamine B and the neutral colorless reagent phenol. This indicates that BiPO₄ with a surface-phase junction had no-selectivity and could effectively degrade different kinds of organic pollutants.

The photocatalytic activity is highly dependent on the separation efficiency of photo-generated electrons and holes. The UV photocurrent responses of BiPO₄ calcined at different temperatures for different times after deposition on ITO electrodes are provided in Fig. 7. The photocurrent was stable and reversible at light-on and light-off for all samples. The

**Fig. 8** EIS response of BiPO₄ thin films electrode in dark (A) and under UV irradiation (B); PL spectra of BiPO₄ synthesized by calcinating HBIP under different conditions (excitation wavelength was 250 nm) (C); the plots of photocatalytic degradation of methylene blue over BiPO₄ calcined at 500 °C with the addition of a hole, \( \cdot \)O₂⁻ and \( \cdot \)OH radical scavenger under the 254 nm UV light irradiation (D).
photocurrents of BiPO$_4$ calcined at 400 °C, 500 °C and 600 °C for 4 h were 14.6 μA, 33.6 μA and 20.4 μA, respectively, but that of HBIP was only 5.3 μA. The BiPO$_4$ calcined at 500 °C for 6 h showed a noticeable photocurrent, which was 43.6 μA and about 8.0 times as high as that of HBIP. The improvement of UV photocurrent indicated that the separation efficiency of photo-generated charges was improved greatly. This was in good agreement with the improvement in the photocatalytic activity.

3.3 Mechanism for the enhanced photocatalytic activity via phase junction of BiPO$_4$

The typical EIS responses of HBIP and BiPO$_4$ calcined under different conditions were presented in Fig. 8. In each case, there was only one arc or semicircle on the EIS images. This suggests that the transfer of surface charges was the rate-determining step in the photocatalytic reaction. The smallest arc radius on the EIS Nyquist plot indicated efficient separation of the photo-generated electrons and holes, and vice versa.\textsuperscript{15,37,38} The arc radius of BiPO$_4$ with a phase junction after calcination at different temperatures was smaller than that of the HBIP electrode in dark and under UV-light irradiation, which demonstrates that calcined BiPO$_4$ had smaller electric resistance and higher efficiency of charge separation than HBIP. Among them, the arc radius of BiPO$_4$ calcined at 500 °C for 6 h was the smallest, which further proved that nMBIP–mMBIP surface-phase junction could effectively improve the separation and migration of photo-generated charges. Therefore, the photocatalytic activity of BiPO$_4$ calcined at 500 °C was the highest.

The PL spectra of BiPO$_4$ samples are shown in Fig. 8C. It was obviously seen that the two main emission peaks were at 290 and 395 nm. As is well known, the PL spectra can reflect the recombination rate of photo-generated electron–hole pairs. The emission peak intensity of HBIP was stronger than that of calcined BiPO$_4$, which indicates that the electron–hole pair recombination rate of HBIP was faster than that of calcined BiPO$_4$. The emission peak intensity of BiPO$_4$ calcined at 500 °C for 6 h was the weakest. This may be caused by the formation of surface-phase junction, which improved the separation efficiency of photo-generated charges. The result was proved by EIS.

The main oxidative species could be detected by the trapping experiments of active species, using EDTA-2Na as the hole scavenger, t-BuOH as the hydroxyl radical scavenger and purging N$_2$ as the ‘O$_2$’ radical scavenger.\textsuperscript{36} As shown in Fig. 8D, the photocatalytic activity of BiPO$_4$ calcined at 500 °C was slightly suppressed by the addition of hydroxyl radical scavenger, whereas this was significantly suppressed by hole scavenger. This indicates that the photo-generated holes were the major oxidative species in BiPO$_4$ calcined at 500 °C on the degradation of methylene blue.

A schematic for electron–hole separation and transfer at the heterojunction BiPO$_4$ photocatalyst interface is shown in Fig. 9. HBIP, nMBIP and mMBIP were all excited under 250 nm UV light irradiation and produced photo-generated electron–hole pairs. The CB of nMBIP was the minimum, and its photo-generated electrons would transfer to the CB of HBIP and mMBIP. At the same time, the VB of HBIP and mMBIP are all greater than nMBIP, and their photo-generated holes would transfer to the VB of nMBIP. This made photo-generated charges separation more efficient and restrained the recombination possibility of photo-generated electron–hole, and further improved the photocatalytic performance.

4. Conclusions

BiPO$_4$ with a phase junction was synthesized by calcinating HBIP at different temperatures. The enhancements of photocatalytic performance and photocurrent were attributed to the efficient separation and transfer of photo-generated charges across the phase junction of BiPO$_4$. The nMBIP–mMBIP phase junction was formed on the surface region of BiPO$_4$ after calcination at 500 °C, and it possessed the highest photocatalytic performance. Thus, simultaneous exposure of nMBIP and mMBIP phase in the outer region is crucial for the

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Fig. 9 Schematic of charge separation and photocatalytic activity of heterojunction BiPO$_4$ photocatalyst under UV light irradiation.
separation of photo-generated charges. An effective method to synthesize the higher active photocatalyst was obtained via the formation of a surface-phase junction.

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