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Facile fabrication of porous BiVO₄ hollow spheres with improved visible-light photocatalytic properties†

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Bismuth vanadate (BiVO₄) hollow spheres with porous structure have been successfully fabricated by a one-step wet solution method with no surfactant and template. The structure, morphologies, and composition of the as-prepared products were studied with X-ray powder diffraction (XRD), transmission electron morphology (TEM), Brunauer–Emmett–Teller (BET), X-ray photoelectron spectroscopy (XPS) and UV-vis spectroscopy. Based upon the time-dependent experimental results, BiVO₄ nanospheres with hollow and solid structures can be controlled effectively through the reaction time, and a reasonable formation process was suggested in this work. Moreover, the experiment of degrading methyl orange (MO) under visible-light illumination was conducted to evaluate the photocatalytic performance of the obtained BiVO₄ samples. The porous BiVO₄ hollow spheres exhibit superior visible-light photocatalytic properties for MO degradation than other photocatalysts under irradiation, and could be reused for up to five times without significant reduction in the photocatalytic activity. In addition, based on active group trapping experiments, ·OH radicals as the main active species from H₂O₂ molecules play a vital role in the photocatalytic degradation of MO, and a photocatalytic mechanism for the BiVO₄ system was proposed. High photocatalytic activity, universality and stability suggest that the porous BiVO₄ hollow spheres may have potential applications in wastewater treatment.

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1. Introduction

The rapid growth of the economy will inevitably give rise to environmental pollution and energy shortages. The large discharge of colored wastewater from textile, paper, rubber and other industries has posed a threat to people's health. Semiconductor photocatalysis utilizes free and inexhaustible solar energy to convert these pollutants to carbonaceous products, which provides an effective avenue for environmental purification and solar energy utilization.^{1,2} As a green technology, photocatalysis has been an attractive alternative approach to treat wastewater containing colorants in the last few years.^{3–5} The widely used semiconductor-based photocatalysts include zinc oxide (ZnO) and titanium dioxide (TiO₂).^{6,7} However, only ultraviolet or near ultraviolet fractions of sunlight can be

absorbed by ZnO and TiO₂ because of their broad bandgaps (3.0–3.2 eV). So, the development of photocatalysts with enhanced solar energy utilization efficiency is urgent.⁸

Among various kinds of visible-light photocatalysts, bismuth vanadate (BiVO₄) with a bandgap of about 2.4 eV was recognized as a promising visible-light-driven photocatalyst to degrade colorants.^{9,10} The morphology, particle size and crystal structure of the samples significantly affect the photocatalytic properties. In the past few years, BiVO₄ with various micro- and nano-structures, such as fibers,⁹ quantum dots,¹¹ nanosheets,¹² olive-like structures,¹³ microtubes,¹⁴ and hollow spheres,¹⁵ have been prepared by some controlled methods to enhance the photocatalytic activity. And some remarkable achievements have been obtained. Compared with the solid materials, the porous and hollow structures have been extensively investigated because of their widespread promising application scenarios in multiple areas, for example catalysis,¹⁶ molecular separation,¹⁷ photonics,¹⁸ and gas sensors.¹⁹ In general, the preparation of hollow structure utilizes the removable or sacrificial hard and soft templates,^{20,21} which limits the crystallization, the grain size-distribution and the purity of products because of the high temperature heat treatment. Therefore, it is scientific and practical essential to develop a template-free facile synthesis approach of porous BiVO₄ with hollow structure.

In this paper, bismuth vanadate (BiVO₄) nanospheres with porous and hollow structures were prepared with a facile and

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† Electronic supplementary information (ESI) available: (1) SEM images of BiVO₄ hollow spheres; (2) XPS spectra; (3) SEM images of BiVO₄ solid spheres; (4) XRD patterns; (5) effect of H₂O₂ amount on photocatalytic degradation rate of MO in the presence of BiVO₄ hollow spheres; (6) PL spectra. See DOI: 10.1039/d0ra00698j

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effective template-free method, which differed from other synthesis approaches of BiVO₄ hollow spheres^{13,22,23} in the utilization of template. To reveal the impact of morphologies on the photocatalytic activity of BiVO₄ samples, solid spheres were also fabricated for comparison. The results indicated the as-synthesized porous BiVO₄ hollow spheres presented better photocatalytic activity and stability in degrading dyes under visible-light illumination.

2. Experiment section

2.1 Reagents

Deionized water and as-received analytical grade chemical reagents were used without further purification throughout the experiment. Reactive dyes, such as reactive black R-2BG and reactive orange R-2RLN, were purchased from Zhejiang Runtu Co., Ltd, China.

2.2 Preparation of BiVO₄ samples

Typically, NH₄VO₃ (1.0 mmol) and Bi(NO₃)₃·5H₂O (1.0 mmol) were dispersed in 1 mL concentrated nitric acid and 15 mL deionized water under vigorous stirring. After stirring for 10 min, NaHCO₃ (1.56 g) was slowly added into the obtained solution with constant stirring. Another 0.5 h stirring was performed before the above suspension solution was sealed in a stainless-steel autoclave (volume 25 mL) with Teflon liner. Then, the autoclave was placed in the oven at 120 °C for 2 h, and then naturally cooled to ambient air temperature. Finally, the light yellow samples obtained by centrifugation were washed repeatedly with ethanol and distilled water for five times, and dried at 60 °C for 12 h in vacuum. The BiVO₄ solid spheres were prepared with the similar method to that of the porous BiVO₄ hollow spheres but at the reaction time of 10 min.

2.3 Characterization

The morphologies of the samples were characterized by scanning electron microscopy (SEM, Sigma300) and transmission electron microscope (TEM, JEM-1011). X-ray powder diffraction (XRD) patterns were collected by an Empyrean X-ray diffractometer with Cu K α radiation source ($\lambda = 0.15406$ nm) for revealing the crystal phase of the samples. A X-ray photoelectron spectroscopy (XPS) in a Physical Electronics PHI 1600 spectrometer with Al K α X-ray source ($E = 1486.6$ eV) was used, and the XPS analysis was carried out at a pass energy of 187.85 eV, and the C 1s peak at 284.6 eV was used to calibrate all the binding energies of the composing elements. A Micromeritics TriStar 3020 instrument was used to measure N₂ adsorption-desorption isotherms. The Brunauer-Emmett-Teller (BET) surface areas and the pore size distribution of the samples were determined by the BET method and the Barrett-Joyner-Halenda (BJH) method. A spectrophotometer (UV-2550, Shimadzu, Japan) was employed to measure the UV-vis diffused reflectance spectra of the samples with BaSO₄ as a reference. A Fluoromax-3 spectrometer (Horiba Scientific) was employed to measure the photoluminescence (PL) emission spectrum of samples at room temperature.

For photoelectrochemical characterizations, a CHI760E electrochemical workstation (Chenhua, Shanghai, China) was utilized to perform conventional three-electrode tests. The working electrode was prepared by ultrasound dispersion of the powder sample (1 mg) in ethanol (1 mL) for 30 min. The slurry was suspended on an F-doped tin oxide (FTO) glass substrate with 0.196 cm² active area drop by drop. The uniform electrode film was dried by air and then transferred to oven at 300 °C for 3 h. And a platinum wire and Ag/AgCl (saturated KCl) acted as counter electrode and reference electrode, respectively. The photocurrent properties of the photocatalysts were measured in a Na₂SO₄ aqueous solution (0.5 mol L⁻¹) at 0.6 V (vs. Ag/AgCl). The light source was a 300 W xenon arc lamp and placed at 10 cm distance from the electrochemical cell. All light wavelengths below 420 nm were eliminated with glass filter.

2.4 Photocatalytic activity

Typically, 10 mg of photocatalysts were suspended in the dye aqueous solution (20 mg L⁻¹, 20 mL), such as methyl orange (MO), rhodamin B (RhB), methylene blue (MB), reactive black R-2BG (RB) and reactive orange R-2RLN (RO), with the pH value of about 2.0 adjusted by concentrate hydrochloride under ultrasonication for 5 min. To reach the adsorption-desorption equilibrium on catalyst particles, the suspensions were well magnetically stirred at 300 rpm for 0.5 h in the dark before irradiation. 0.05 mL of H₂O₂ solution (30 wt%) was added into the above suspension. Then a 250 W xenon arc lamp as the light source was switched on to initiate the photocatalytic reaction and a glass filter was adopted to eliminate UV wavelengths below 420 nm. The degradation experiments were conducted at room temperature with a continuous magnetic stirring. The samples were taken from the suspensions at different time intervals, and then analyzed after the photocatalyst particles were removed by centrifugation immediately. The absorption of the centrifuged aqueous solution was measured with a UV-vis spectrophotometer to monitor the MO concentration. The photodegradation ratio (η) was obtained according to the following equation (eqn (1)).

$$\eta = \frac{C_0 - C_t}{C_0} \times 100\% \quad (1)$$

where C_0 and C_t are the concentrations of MO solution at initial time and certain irradiation time (t).

2.5 Active species trapping experiments and recycle measurements

In order to detect the active species in the photocatalytic reaction, *tert*-butyl alcohol (TBA, 1 mmol L⁻¹), benzoquinone (BQ, 1 mmol L⁻¹), or disodium ethylenediaminetetraacetate dehydrate (EDTA-2Na, 1 mmol L⁻¹) were added to the photocatalytic system to make clear the function of hydroxyl radical (\cdot OH), superoxideradical (\cdot O₂⁻) and hole (h⁺), respectively. The tests for the stability of BiVO₄ photocatalysts were performed according to the photocatalytic degradation experiments of MO. The recycling experiments were performed 5 times with the same experimental procedure and conditions as above. After



every photocatalytic cycle test, the catalysts obtained by centrifugation for the test were dried with a vacuum oven.

3. Results and discussion

3.1 Morphology and structure

SEM and TEM were adopted to observe the morphologies of the as-prepared samples, and the results are shown in Fig. S1† and 1. As shown in Fig. S1,† the sphere-like nanoparticles of about 50 nm are fabricated on a large scale. The above results are further proved by TEM image in Fig. 1a that the BiVO_4 particles are almost spherical nanoparticles and are intertwined with each other. Interestingly, the further enlarged TEM image in Fig. 1b shows that BiVO_4 nanoparticles are hollow structures with the diameter and wall thickness of about 20 nm and 5 nm. The aggregates of hollow structures with small size in Fig. 1b are favorable for the entry and exit of chemical species, and the recovery and reuse of catalyst. At the same time a big specific surface area will be created in the inner space. Therefore, it is a reasonable candidate for photocatalysts.

Fig. 1c presents the XRD pattern of the as-prepared BiVO_4 hollow spheres. All measured diffraction peaks in the XRD spectrum can be referred to monoclinic BiVO_4 according to the standard data of JCPDS file number 14-0688. The strong and sharp peaks imply that the as-prepared BiVO_4 hollow spheres are well crystallized. The absence of peak from other phases suggests the successful preparation of pure and single phase BiVO_4 crystal.

In order to further confirm the chemical composition and the surface chemical status of elements, the prepared BiVO_4 hollow spheres were further characterized by XPS, as shown in Fig. S2.† The typical XPS survey spectrum of BiVO_4 hollow spheres with distinct peaks of Bi 4f, V 2p and O 1s is displayed in Fig. S1a.† The characteristic peaks of Bi 4f_{7/2} and Bi 4f_{5/2} located at 158.9 eV and 164.5 eV prove the presence of Bi³⁺ in BiVO_4 hollow spheres.²⁴ The peaks of V 2p_{3/2} and V 2p_{1/2} at 516.5 eV and 524.0 eV are ascribed to the V⁵⁺ species, confirming that the element V in the sample was in pentavalent state.²⁴ Also, the sample showed similar XPS signals of O 1s at 529.8 eV and 532.2 eV from the O²⁻ anions in BiVO_4 hollow spheres.²⁴

The formation process of BiVO_4 hollow spheres was investigated with time-dependent experiments, and the evolution

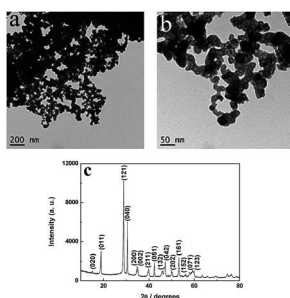


Fig. 1 TEM images (a and b) and XRD pattern (c) of the as-synthesized product.

process was clearly presented by the TEM images of the intermediate products, as shown in Fig. 2. At the beginning, the nanoparticles with sphere-like shape were formed after reacting for 10 min in Fig. S3.† Further observation showed that the spherical nanoparticles with about 50 nm were solid structure (Fig. 2a). These nanoparticles were intertwined with each other, which leads to a large number of pores in the product. With the increasing reaction time to 30 min (Fig. 2b), the nanoparticles with similar morphology has no changes in size. At the same time close observation shows that some small pores appear inside a small amount of nanoparticles. As shown in Fig. 2c and d, this feature became more manifest with the increase of reaction time. The inner parts of spherical nanoparticles have more and larger pores. The formation of spherical nanoparticles with uniform hollow structures was finally completed 2 h after the reaction (Fig. 1a and b). The crystalline structure of the products prepared at the reaction time of 10 min, 30 min, 60 min and 90 min were determined by XRD measurements presented in Fig. S4.† As depicted in Fig. S4,† all diffractions peaks of the as-prepared samples at the different reaction time can be well assigned to monoclinic BiVO_4 , which is in accordance to BiVO_4 hollow spheres (JCPDS 14-0688). Based on the further observation of Fig. S4a and b,† it is found that the position and intensity of the diffraction peaks are almost unchanged with the extension of reaction time, indicating that the crystal structure of the products can be independent of reaction time.

The formation mechanism of BiVO_4 hollow spheres can be deduced as follows. When NaHCO_3 was slowly added in the reaction system, a large amount of CO_2 gas was generated. The gas molecules would congregate at the BiVO_4 nuclei and limit the further growth of crystal nucleus at the early stage. With the

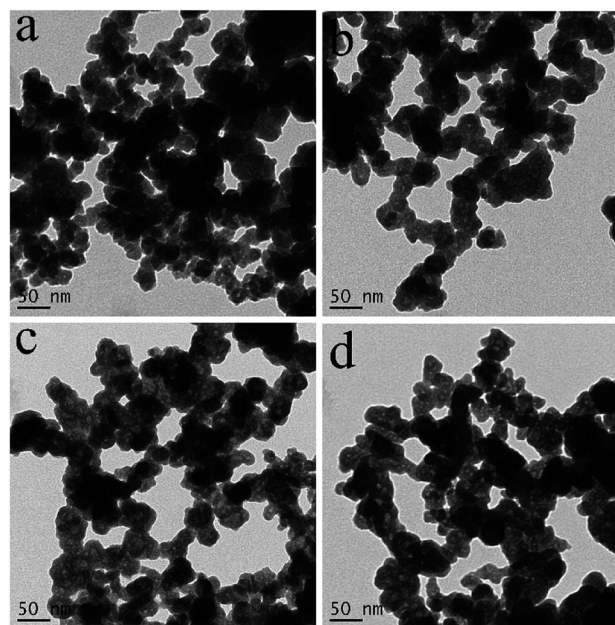


Fig. 2 TEM images of the as-prepared products at the different reaction times, (a) 10 min, (b) 30 min, (c) 60 min and (d) 90 min.



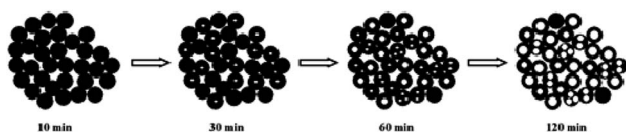
increasing reaction temperature, the expansion of gas molecules led to the appearance of holes in the interior of the product, which eventually forms the BiVO_4 hollow nanospheres. The evolution process of the morphologies of the as-synthesized products is described in Scheme 1. During the formation process of hollow structures, the internal and external pores are intertwined with one another so that BiVO_4 hollow spheres have a larger specific surface area, indicating the potential application in the photocatalytic field. And BiVO_4 hollow spheres and solid spheres can be controllably synthesized by adjusting the reaction time.

3.2 Nitrogen adsorption–desorption isotherms

The porous properties of the as-prepared BiVO_4 hollow spheres and solid spheres clearly revealed by the TEM images are further investigated by the nitrogen adsorption–desorption isotherms and the distribution of pore size. The BiVO_4 samples showed the presence of porous structure and gave type IV isotherms according to the BET classification, as shown in Fig. 3.²⁵ The BET specific surface area of the obtained product is $17.46 \text{ m}^2 \text{ g}^{-1}$ and $4.42 \text{ m}^2 \text{ g}^{-1}$ for BiVO_4 hollow spheres and BiVO_4 solid spheres, respectively. The increased surface area of BiVO_4 hollow spheres could be attributed to the porous and hollow structure. The presence of macropores and mesopores in the as-synthesized samples is indicated by the hysteresis loop in the relative pressure (p/p_0) range of 0.7 to 1 and proved by the pore size distribution (inset of Fig. 3). The calculated pore size of the BiVO_4 hollow spheres with BJH method ranges very widely and about at 3.8 nm, 31 nm and 117 nm, according to the adsorption branch. However, the pore size of the BiVO_4 solid spheres is mainly at about 70 nm. In addition, a very small number of pores are observed at about 2.5 nm. It is worth to mention here that the presence of a large number of pores will lead to a high specific surface area. A transport pathway to the interior of photocatalyst for reactants would be provided by the porous properties of the sample, and so its catalytic performance in wastewater treatment could be enhanced at the same time.

3.3 UV-vis diffuse reflection spectra

The UV-vis absorbance spectra of the obtained BiVO_4 samples can be found in Fig. 4. Both BiVO_4 hollow spheres and BiVO_4 solid spheres exhibit a strong photoabsorption from UV light to visible light. The steep shape of the spectra proves that the visible-light absorption was contributed to the band gap transition instead of the impurity level transition.²³ The significant visible light absorption of BiVO_4 hollow spheres indicates that



Scheme 1 Formation mechanism of the as-prepared BiVO_4 hollow spheres.

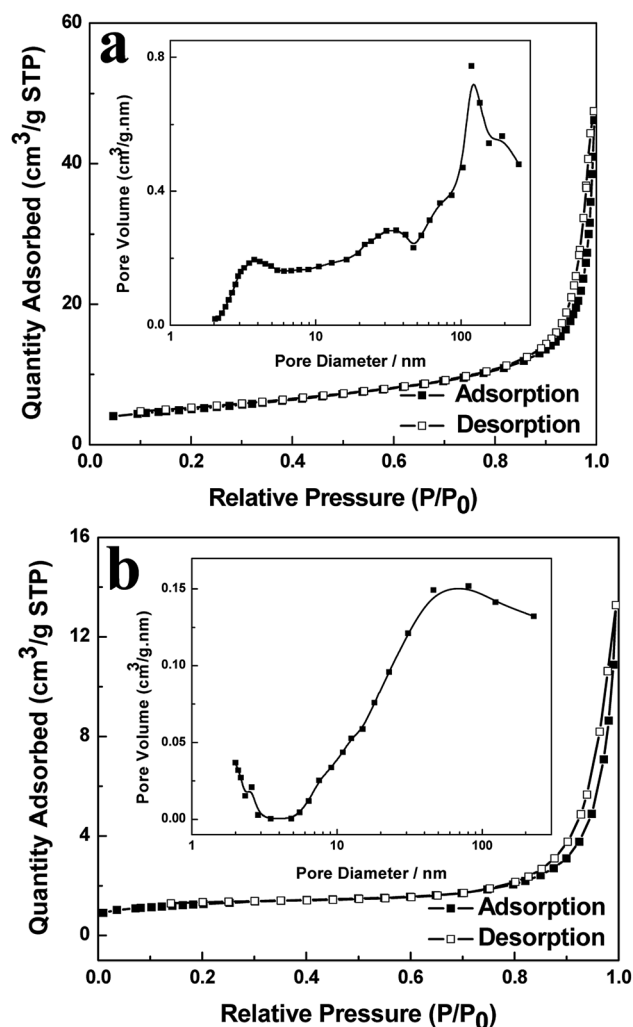


Fig. 3 Nitrogen adsorption–desorption isotherms and pore size distribution curve (inset) of BiVO_4 hollow spheres (a) and BiVO_4 solid spheres (b).

hollow structure is a better candidate than solid material in the visible-light photocatalysis. From inset of Fig. 4, the band gap energies of BiVO_4 hollow spheres and solid spheres could be

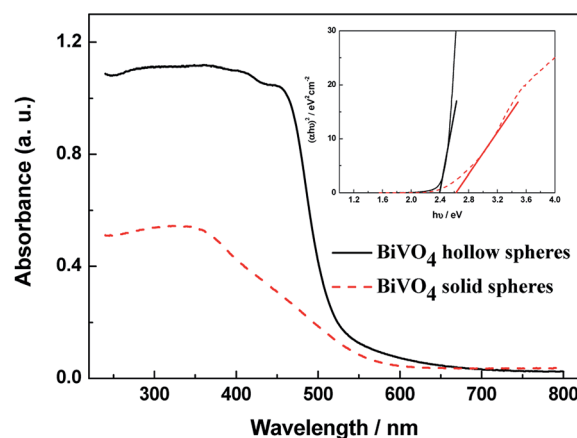


Fig. 4 UV-vis diffuse reflection spectra and plots of $(\alpha h\nu)^2$ versus the photon energy ($h\nu$) curves (inset) of the as-prepared BiVO_4 samples.



estimated from the linear fitting of the linear part of $(\alpha h\nu)^2$ vs. $(h\nu)$ plot,²² and are about 2.39 eV and 2.62 eV, respectively. The absorption of UV- and visible-light for exciting valence band electrons to the conduction band due to the narrow bandgap of BiVO₄ samples will improve the effective solar energy utilization. The band gap of BiVO₄ hollow spheres is narrower than that of solid ones, so the absorption and utilization of visible light energy will be stronger for BiVO₄ hollow spheres, thus, the higher photocatalytic activity BiVO₄ hollow spheres will be expected.

3.4 Photocatalytic properties

The MO degradation experiments under the visible-light irradiation were conducted to evaluate the photocatalytic activity of the as-prepared photocatalyst, as shown in Fig. 5. To demonstrate the photodegradation of MO, UV-vis spectra were taken over certain time in the presence of BiVO₄ hollow spheres (Fig. 5a). The photocatalytic degradation process was monitored through the intensity of characteristic absorption peak around 500 nm. With the increasing irradiation time, the characteristic peak decreases continuously in intensity and blue shifts in wavelength, indicating the decomposition of MO. And the characteristic absorption peak at about 500 nm disappears at the irradiation time of 240 min, indicating the complete degradation of MO.

Fig. 5b shows the photocatalytic performance of MO in the presence of various photocatalysts. The degradation rate of

20 mg L⁻¹ MO solution with 0.05 mL of H₂O₂ (30 wt%) after 4 h reaction was only about 7.27% in the absence of various photocatalyst, indicating that the photocatalyst is crucial in the photocatalytic reaction. In the presence of H₂O₂ and photocatalysts, the degradation rate of MO increases rapidly at first, then increases gently, and keeps stable finally as illumination time increased. The degradation rates of MO for as-prepared BiVO₄ hollow and solid spheres after 3.0 h reaction were 95.3% and 57.2%, respectively. For comparison, degrading MO experiment is conducted with the photocatalyst of P25. And about 74.2% MO was degraded under visible-light irradiation for 3 h, which is lower than BiVO₄ hollow spheres and slightly higher than BiVO₄ solid spheres. But, the degradation of MO for BiVO₄ hollow spheres without H₂O₂ was only 33.1% at the same irradiation conditions. The effect of H₂O₂ amount on the photocatalytic performance of MO in the presence of BiVO₄ hollow spheres is investigated in Fig. S5.† It can be found that with the increasing amount of H₂O₂, the photocatalytic degradation rate of MO first goes up rapidly and then tends to stabilize gradually. The further increase of H₂O₂ over 0.075 mL inhibits the photocatalytic activity, which may mainly due to the quenching of [•]OH group by the excess H₂O₂.^{26,27} The degradation of organic molecules with the BiVO₄ photocatalysts can be greatly accelerated by the radical precursor H₂O₂,²⁸ because H₂O₂ molecules can react with photogenerated electrons as an electron trapping reagent and the produced [•]OH radicals will further react with MO and increase degradation of MO. Thus, the recombination

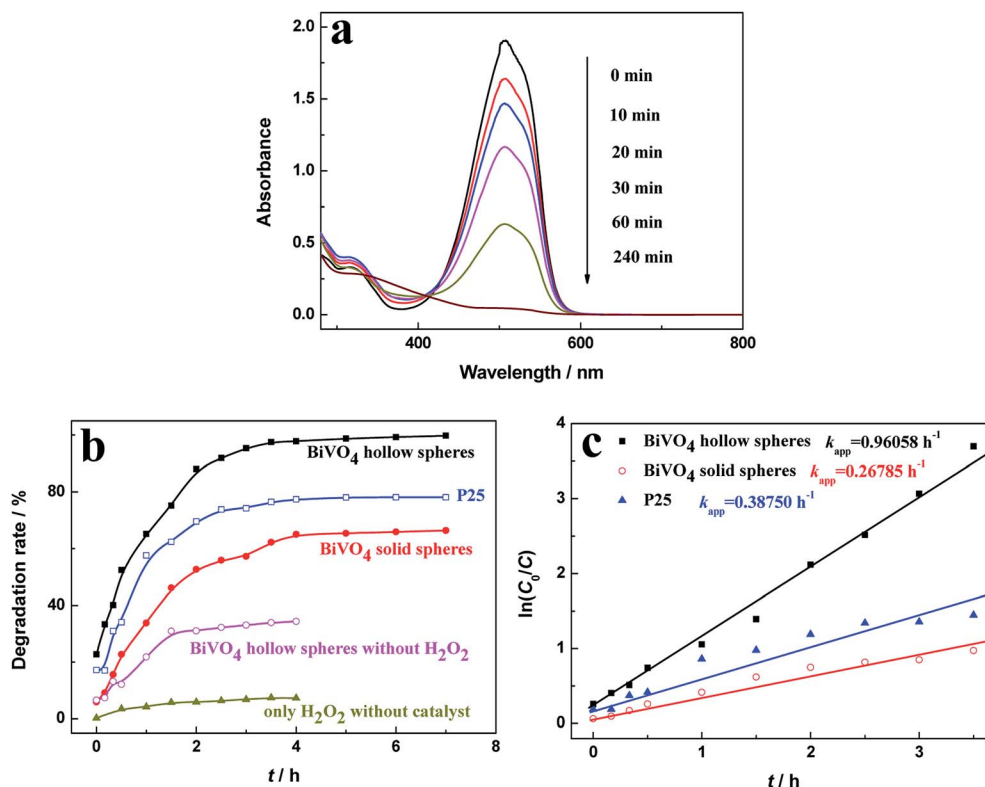


Fig. 5 (a) Absorption spectra of MO aqueous solutions in the presence of BiVO₄ hollow spheres, (b) degradation rate of MO at different intervals and (c) pseudo-first-order kinetic plots of MO in the presence of various photocatalysts.



of photogenerated electrons and holes will be effectively suppressed assisted by H₂O₂, leading to a high photocatalytic efficiency. In addition, the photogenerated charges must migrate to the surface of photocatalyst for the photocatalytic degradation of dyes, so large specific surface area will enhance the catalytic efficiency. Compared with BiVO₄ solid spheres, the significantly superior performance in the degradation of MO with BiVO₄ hollow spheres could be contributed to the large specific surface area due to the unique hollow and porous structures of the samples.

The pseudo first-order Langmuir–Hinshelwood (L–H) model for heterogeneous photocatalysis under low concentration dye is also used to investigate the photocatalytic degradation kinetic,^{29,30} and the degradation rate (r) is given by the following equation (eqn (2)).

$$r = -\frac{dC}{dt} = K_{app}C \quad (2)$$

where K_{app} is the apparent first-order rate constant (h⁻¹), C_0 and C are the concentrations of MO at adsorption–desorption equilibrium and various intervals of time (t). Fig. 5c shows K_{app} obtained from the gradient of the curve of $\ln(C_0/C)$ versus time (t), and the calculated K_{app} values are 0.9606, 0.2679 and 0.3875 h⁻¹ for BiVO₄ hollow spheres, BiVO₄ solid spheres and P25, respectively. The BiVO₄ hollow spheres exhibit the largest K_{app} value that is approximately 3.6 and 2.5 times higher than these of BiVO₄ solid spheres and P25, respectively. The higher photocatalytic performance of BiVO₄ hollow spheres over BiVO₄ solid spheres and P25 is agreement with that of Fig. 5b. The photocatalytic performances of BiVO₄ hollow spheres are further compared with other BiVO₄ hollow structures as summarized in Table 1. Various BiVO₄ samples with hollow structures can effectively degrade pollutants under their own photocatalytic reaction conditions. As compared to other BiVO₄ hollow catalysts, the as-prepared BiVO₄ hollow spheres can be highly beneficial for pollutants removal at the low concentration of photocatalyst and low light power, indicating superior performance in the visible-light photocatalysis.

In order to investigate the universality of photocatalytic performance of BiVO₄ samples, the photocatalytic activities of other dye aqueous solutions assisted by BiVO₄ hollow or solid spheres are shown in Fig. 6. At the similar experimental conditions, the degradation rates of RhB, MB, RB and RO for BiVO₄ hollow spheres under visible light irradiation of 4 h are more than 95%, which is obviously higher than those in the presence of BiVO₄ solid spheres. Based on the comparison with the BiVO₄ solid spheres, the BiVO₄ hollow spheres exhibit the outstanding photocatalytic properties for various dyes, indicating that the BiVO₄ nanospheres with porous and hollow structure have better universality and potential applications in visible light photocatalytic field.

To estimate the reproducibility and stability of the BiVO₄ samples, Fig. 7 presents the recycling test of catalyst for the visible light photocatalytic degradation of MO. The catalytic activities of BiVO₄ samples are almost unchanged after 5 test cycles of degradation of MO. It is found in Fig. 7 that after 5 cycles, the degradation rates of MO solution are 97.0% for

BiVO₄ hollow spheres and 64.0% for BiVO₄ solid spheres, which are 99.2% and 98.5% of the first degradation rate of MO solution, respectively. This suggests that BiVO₄ hollow spheres have slightly better cyclic stability than BiVO₄ solid spheres.

3.5 Photoelectrochemical analyses

To reveal the high efficiency separation of photogenerated electrons and holes, the transient photocurrent responses of BiVO₄ hollow spheres and solid spheres are recorded for a few on-off illumination cycles. The higher photocurrent density implies the efficient photogenerated charge separation and their transfer across interface.³⁸ The $I-t$ curves for BiVO₄ samples are shown in Fig. 8a for comparison. Reproducible increase under irradiation and quick recovery in the dark are observed from the photocurrent response of the BiVO₄ samples. Moreover, the increase of the photocurrent response of BiVO₄ hollow spheres is more significant in comparison with that of BiVO₄ solid spheres, suggesting the higher electron–hole pair separation efficiency and a smaller recombination possibility under visible-light illumination. Besides, PL spectra are used to disclose the migration, transfer, and recombination process of the photogenerated charges in the semiconductor.²² PL spectra of BiVO₄ samples were recorded with a pump of 325 nm wavelength, as shown in Fig. S6.† The emission intensity of BiVO₄ hollow spheres with similar emission peaks is weaker than that of BiVO₄ solid spheres, indicating the high efficiency separation of photogenerated electron–hole pairs.

Electrochemical impedance spectroscopy (EIS) measurement has been used to reveal the efficient charge transfer process in the traditional three-electrode system³⁹ and corresponding Nyquist plots of BiVO₄ samples with and without visible light irradiation can be found in Fig. 8b. The BiVO₄ hollow spheres show smaller semicircle as compared to the BiVO₄ solid spheres with and without visible light irradiation. And it can be seen clearly that for the same sample, the radii of semicircle at illumination is smaller in size than that at darkness, implying the generation of charge carriers and low resistance as compared to dark condition. The minimum semicircle of BiVO₄ hollow spheres under visible light irradiation indicates the easier interfacial charge transfer between solution and electrode, and excellent conductivity, which suppresses recombination of photogenerated charge and decreases resistance. Therefore BiVO₄ hollow spheres could exhibit superior photocatalytic activity.

3.6 Mechanism of photocatalytic activity

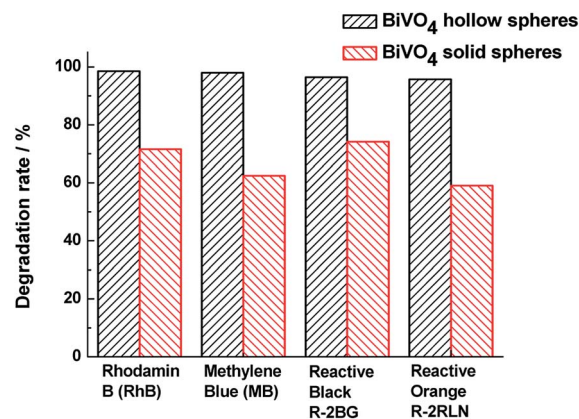
Studies on active group trapping experiments give further verification of the photocatalytic activities of BiVO₄ hollow spheres. During the photocatalytic degradation of organic pollutants, hydroxyl radiacals ([•]OH), superoxide radical ([•]O₂⁻) and hole (h⁺) are generally considered as the main active species. So the reactive species trapping experiments on the photocatalytic degradation of MO are conducted to further investigate the photocatalytic mechanism over BiVO₄ hollow spheres. *Tert*-butyl alcohol (TBA), benzoquinone (BQ) and disodium ethylenediaminetetraacetate dehydrate (EDTA-2Na)



Table 1 Comparison of photocatalytic performances of BiVO₄ hollow structures

| Synthesis method | Morphology | Photocatalytic activity | Ref. |
|--|--|---|------------|
| Method: wet solution method Additive: no additives | Hollow nanospheres | Pollutant: MO, RhB, MB, RB, RO 10 mg photocatalyst, 20 mL 20 mg L ⁻¹ dye solutions Light source: 250 W Xe lamp ($\lambda > 420$ nm) Degradation: 97.8% for MO, 98.6% for RhB, 98.0% for MB, 96.5% for RB and 95.7% for RO in 4 h | This study |
| Method: hydrothermal route Additive: urea | Hollow microspheres | Pollutant: MB 0.1 g photocatalyst, 20 mL 3×10^{-5} M dye solution Light source: 350 W Xe lamp ($\lambda > 420$ nm) Degradation: color disappeared in 180 min | 31 |
| Method: a precursor solution mediated growth method Additive: polyvinyl alcohol (PVA) | Hollow spheres | Pollutant: RhB 0.5 g photocatalyst, 100 mL 10^{-4} M dye solution Light source: 120 W compact fluorescent lamp ($\lambda > 420$ nm) Degradation: characteristic peak disappears in 50 min | 32 |
| Method: solvothermal process under microwave irradiation Additive: EDTA | Hollow spheres with hierarchical microstructures | Pollutant: MO 0.2 g photocatalyst, 100 mL 0.01 g L ⁻¹ dye solution Light source: 300 W Xe lamp ($\lambda > 420$ nm) Degradation: characteristic absorption disappears in 180 min | 33 |
| Method: sacrificial template growth technique (calcination) Additive: carbonaceous microspheres | Multi-shell hollow spheres | Pollutant: MB 0.1 g photocatalyst, 100 mL 10^{-5} M dye solution Light source: 300 W Xe lamp ($\lambda > 420$ nm) Degradation: 100% in 80 min | 34 |
| Method: anchoring method (calcination) Additive: colloidal carbon spheres | Hollow nanospheres | Pollutant: RhB 0.1 g photocatalyst, 100 mL 10^{-5} M dye solution Light source: 500 W Xe lamp ($\lambda > 420$ nm) Degradation: completely degraded in 70 min | 23 |
| Method: hydrothermal method Additive: no additives | Core-shell structured hollow spheres | Pollutant: RhB 0.3 g photocatalyst, 600 mL 10^{-5} M dye solution Light source: 500 W Xe lamp ($\lambda > 400$ nm) Degradation: 99% in 4.5 h | 35 |
| Method: hydrothermal method Additive: ethylenediamine tetraacetic acid (EDTA) | Hollow polygon | Pollutant: MB 0.1 g photocatalyst, 100 mL 5 mg L ⁻¹ dye solution Light source: 500 W Xe lamp Degradation: 90.84% in 5 h | 36 |
| Method: reflux method Additive: no additives | Microtubes with flower-like morphology | Pollutant: RhB 0.5 mmol photocatalyst, 100 mL 10^{-5} M dye solution Light source: 500 W Xe lamp ($\lambda > 400$ nm) Degradation: 96% in 180 min | 14 |
| Method: ultrasound irradiation Additive: no additives | Spindle particles with hollow interior | Pollutant: RhB 0.2 g photocatalyst, 100 mL 10^{-5} M dye solution Light source: 500 W Xe lamp ($\lambda > 400$ nm) Degradation: 99% in 240 min | 37 |

are introduced as quenchers of $\cdot\text{OH}$, $\cdot\text{O}_2^-$ and h^+ to make clear the effective active species in the photocatalytic process. The photocatalytic degradation rates of MO over BiVO₄ hollow spheres without and with the help of H₂O₂ are shown in Fig. 9. As presented in Fig. 9a, experiments involving EDTA-2Na show a significant decrease in the degradation rate in comparison to the blank experiment of no quencher, implying h^+ is the predominant active species in the absence of H₂O₂. Besides, the addition of BQ into the photocatalytic system could also decrease the photocatalytic degradation MO, suggesting $\cdot\text{O}_2^-$ also plays an important role in the photocatalytic process. In order to make clear the importance of O₂ molecules, the photocatalytic reaction of MO is carried out under N₂ without any quencher. A fast deactivation of degradation rate under nitrogen suggests that O₂ molecules are involved in the photocatalytic reaction and promote the formation of $\cdot\text{O}_2^-$. Therefore

Fig. 6 Degradation rate of various dyes in the presence of BiVO₄ hollow or solid spheres.

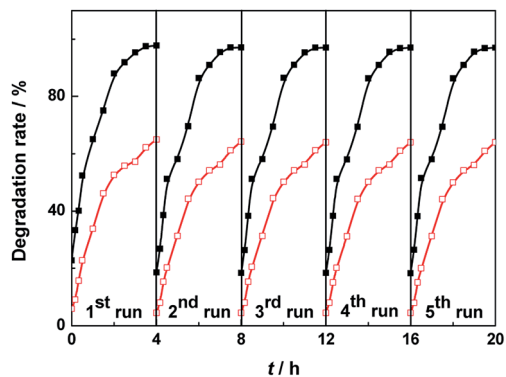


Fig. 7 Recycle curves of the BiVO₄ hollow spheres (black and solid) and BiVO₄ solid spheres (red and hollow) for the visible light photocatalytic degradation of MO.

h^+ and $\cdot O_2^-$ are the mainly active groups for the photodegradation of MO without the help of H₂O₂. Compared with Fig. 9a, the photocatalytic activity of MO is significantly inhibited with TBA and decreases to 14.6% from 95.3% with the help of H₂O₂, revealing the active role played by $\cdot OH$ mainly from H₂O₂. Similarly, the addition of BQ also reduces the activity and it drops to 52.4%, showing the significant impact of $\cdot O_2^-$ radicals, further proved by the N₂ experiments in Fig. 9b. Based on the above analysis, the proposed photodegradation mechanism of MO over BiVO₄ hollow spheres is depicted in Scheme 2. $\cdot OH$, $\cdot O_2^-$ and h^+ are all active groups for the

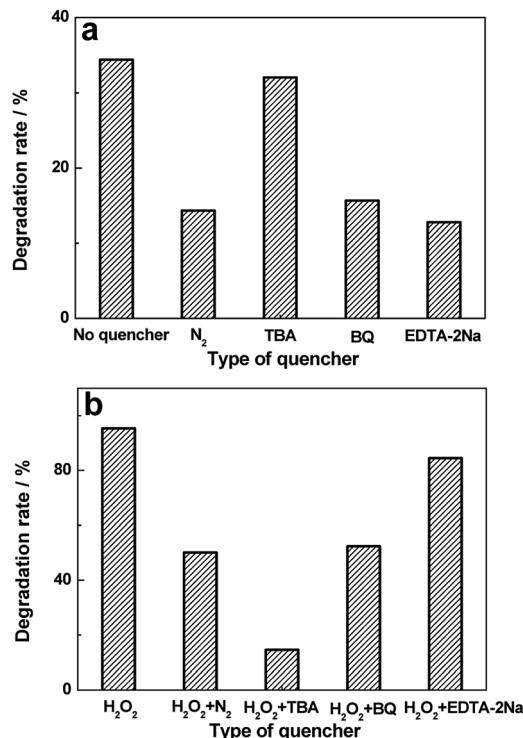


Fig. 9 Effects of a series of quenchers on the degradation rates of MO over BiVO₄ hollow spheres without (a) and with (b) the help of H₂O₂.

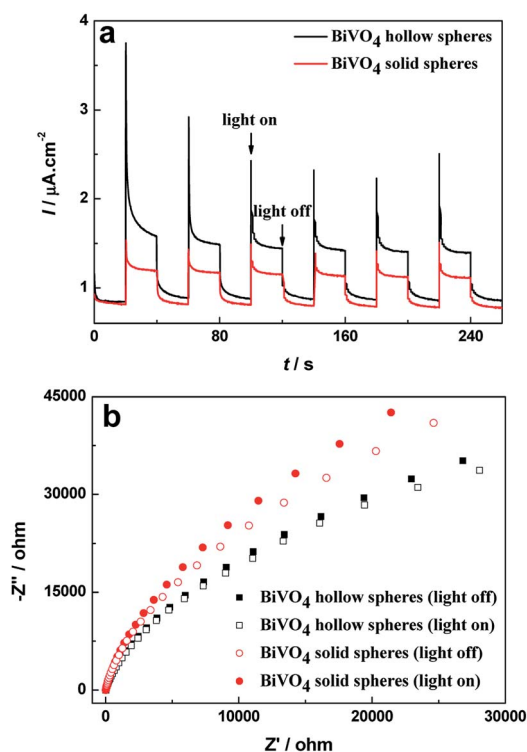
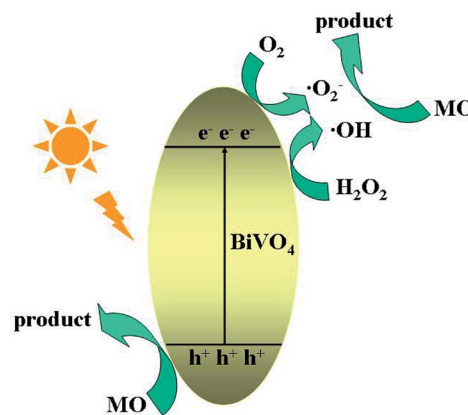


Fig. 8 (a) Transient photocurrent curves and (b) Nyquist plots of BiVO₄ hollow spheres and BiVO₄ solid spheres under dark and visible light irradiation.



Scheme 2 The schematic diagram of the proposed photocatalytic mechanism of MO for BiVO₄ hollow spheres.

photocatalytic degradation of MO. Among them, $\cdot OH$ radicals are predominantly active species with the help of H₂O₂. H₂O₂ plays an important role in the photocatalytic degradation of MO due to the presence of a large amount of $\cdot OH$ radicals from H₂O₂.

4. Conclusions

Bismuth vanadate (BiVO₄) hollow spheres with porous structures have been fabricated by a facile template- and surfactant-free one-step wet solution method, which could be adopted to



prepare hollow structures in a large scale. Based on the time-dependent experiments, BiVO₄ spheres with hollow and solid structures are controlled through the reaction time and the formation process behind the synthesis of BiVO₄ hollow spheres is proposed. In addition, due to the distinctive morphology and narrower bandgap, BiVO₄ hollow spheres exhibit the outstanding visible-light photocatalytic activities and stability in the MO degradation comparing with BiVO₄ solid spheres. In addition, the active species trapping experiments reveal the ·OH radicals are predominantly active groups for the photocatalytic degradation of MO at the presence of H₂O₂. Overall, the obtained porous BiVO₄ hollow spheres with high photocatalytic activities exhibit a promising application in wastewater treatment.

Conflicts of interest

There are no conflicts to declare.

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