One-pot preparation of hierarchical Cu$_2$O hollow spheres for improved visible-light photocatalytic properties†

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As visible light photocatalysts, narrow bandgap semiconductors can effectively convert solar energy to chemical energy, exhibiting potential applications in alleviating energy shortage and environmental pollution. Cu$_2$O hollow spheres with a narrow band gap and uniform hierarchical structures have been fabricated in a controlled way. The one-pot solvothermal method without any template is simple and facile. The morphologies, crystal structures, composition, specific surface areas, and optical and photoelectric properties of the products were analyzed by various techniques. The hollow and solid Cu$_2$O spheres could be fabricated by controlling the reaction time, and a possible growth process of the Cu$_2$O hollow spheres was revealed. The degradation of methyl orange (MO) was used to investigate the visible-light catalytic properties of the Cu$_2$O samples. More than 90% of MO is degraded under visible light illumination of 20 min, exhibiting a quick catalytic reaction. The rate constant of the Cu$_2$O hollow spheres was 2.54 times and 46.6 times larger than those of the Cu$_2$O solid spheres and commercial Cu$_2$O powder, respectively. The possible photocatalytic mechanism of MO was revealed over Cu$_2$O hollow spheres through the detection of active species. The as-prepared Cu$_2$O hollow spheres display improved visible-light catalytic activity and stability, indicating their potential application in wastewater treatment.

1. Introduction

Over the years, large-scale architectures of micro- and nano-structured building components with specific morphology have always been of interest to material scientists and chemists. In particular, hierarchical and hollow structures have aroused significant attention because of their distinctive functions, novel properties and extensive applications in drug delivery, photonic crystals, catalysis and other areas. In comparison with bulk and nanoparticles, the special hollow self-assembly should be helpful for constructing functional nano-devices and to go deep into the formation of hollow assemblies.

Water sources are becoming increasingly polluted by the rapid expansion of chemical, paper and textile industries, resulting in a global threat to human health. Due to the emission of coloured and toxic pollutants from various industrial branches into water bodies, dye compounds as the main pollutant sources in wastewater have caused serious environmental contamination. Therefore, it is very urgent to develop a feasible and inexpensive technology for water treatment. Among a number of chemical and physical methods for wastewater treatment, semiconductor-based photocatalysis displays the rapid and complete mineralization of coloured contaminants. Unique semiconductors with tailored electronic structures have high photocatalytic activities and are getting more and more attention, which has been an effective approach for wastewater remediation. However, some wide band gap photocatalysts such as TiO$_2$ micro- and nanomaterials are limited in the solar application for their response under UV light, occupying only about 4% of the whole solar spectrum. Because about 43% of sunlight belongs to visible light, for the purpose of utilizing solar energy efficiently, it is necessary to fabricate narrow band gap photocatalysts with hollow and porous structures to improve photocatalytic activity.

As a p-type semiconductor, cuprous oxide (Cu$_2$O) with a narrow band gap of about 2.0 eV is of special importance to degrade coloured dyes under sunlight. It is common knowledge that a photocatalytic reaction generally takes place on the surface of the catalyst in close contact with organic pollutants. Thus, the photocatalytic behaviour of Cu$_2$O largely depends on
the morphology, surface structures and specific surface area. Various Cu2O micro- and nanomaterials, such as nanoparticles, wires, tubes, cubes and octahedrons, have been effectively synthesized in a shape-controlled way. Among them, the hierarchical and hollow structures not only have high activities belonging to the nanomaterials, but also have large internal cavities from the hollow structures, facilitating the entry and exit of reactants and products. In addition, the unique hierarchical structures with large sizes can prevent the aggregation of nanoparticles more easily, which contributes to the separation and recycling of the catalyst in practical application. Therefore, it is very important to improve the preparation route for hierarchical Cu2O hollow structures composed of nanoparticles with an intention to enhance the photocatalytic activity.

In this paper, a facile solvothermal approach is proposed to fabricate uniform porous Cu2O hollow spheres self-assembled by nanocubes with a high specific surface area. Compared with other synthesis methods of Cu2O hollow spheres, our method may not be the best, but it provides another way to construct the Cu2O hollow self-assembly. In addition, it is a very novel and effective method for synthesizing the hollow materials on a large scale. For obtaining a clear relationship between the special morphology and catalytic properties, the Cu2O solid spheres have been controllably synthesized for comparison. Meanwhile, the photocatalytic performance of the Cu2O samples was studied by the degradation of methyl orange (MO), exhibiting high catalytic efficiency and stability under visible light.

2. Experimental section
2.1. Materials
Copper nitrate trihydrate [Cu(NO3)2·3H2O], 1-butyl-3-methylimidazolium tetrafluoroborate ([BMIM]BF4), ethylene glycol (EG), methyl orange (MO) and other chemical reagents (J&K Chemical, Ltd.) were of analytical grade without further purification. Distilled water was used throughout the experiments.

2.2. Synthesis of Cu2O samples
In a typical experiment, 0.2416 g of Cu(NO3)2·3H2O and 0.2260 g of [BMIM]BF4 were successively dispersed in 20 mL of EG under vigorous stirring for 24 h. Next, the mixture was transferred and sealed in a Teflon-lined stainless steel autoclave (25 mL capacity), and placed in an oven at 170 °C for 2 h. After the reaction, the obtained product was collected by centrifugation and rinsed at least five times with ethanol and distilled water, and then dried under vacuum at 60 °C for 12 h. The Cu2O solid spheres were fabricated in a similar way, but the reaction time was only 45 min.

2.3. Characterization
The microstructures and morphologies of the products were investigated by scanning electron microscopy (SEM, JSM-6360LV), transmission electron microscopy (TEM, JEM-1011), and high-resolution transmission electron microscopy (HRTEM, JEM-2100F). The crystal phase of the obtained sample was obtained using X-ray powder diffraction (XRD, Empyrean, Holland PANalytical Company) with Cu Kα radiation source (λ = 0.15406 nm). X-ray photoelectron spectroscopy (XPS) measurements of the obtained samples were performed on a Physical Electronics PHI 1600 ESCA system by an Al Kα X-ray source (E = 1486.6 eV). All binding energies of the constituent elements were referenced to the C 1s peak at 284.6 eV. The Brunauer–Emmett–Teller (BET) surface area and pore size distribution of the samples were measured by nitrogen adsorption on the Empyrean Apparatus (Micromeritics Corp., USA). The optical absorption performance was recorded on a UV-vis diffuse reflectance spectrometer (UV-2550, Shimadzu, Japan) with BaSO4 as a reference and a photoluminescence (PL) spectrometer (Fluoromax-3, Horiba Scientific) at room temperature.

The degradation product was analyzed by LC-MS/MS (Triple TOF 5600, AB SCIEX, USA). Separations were obtained by using an Agilent 5 18C-18 column (250 × 4.6 mm) and the mobile phase composed of 0.1 vol% formic acid aqueous solution and acetonitrile with a flow rate of 0.5 mL min⁻¹. The spectra were acquired in the negative ion scan mode.

2.4. Photoelectrochemical measurements
The photoelectrochemical properties (PEC) of the Cu2O samples were characterized by cyclic voltammetry and the photocurrent curves on an electrochemical workstation (CHI760E, Chenhua Instruments, Shanghai, China). Generally, in a standard three-electrode cell, a platinum wire was employed as the counter electrode, an Ag/AgCl (saturated KCl) electrode as the reference electrode, and a Cu2O-modified F-doped tin oxide (FTO) glass as the working electrode, respectively. The FTO glass was cut into 1 cm × 3 cm slices, and successively bathed in a NaOH solution (1.0 mol L⁻¹) for 10 min and acetone for 30 min, respectively. After that, it was washed with water and dried prior to use. 5 mg of the as-prepared powder sample was dispersed ultrasonically in 5 mL of absolute ethanol for 30 min. In addition, 20 μL of the slurry (1 mg mL⁻¹) described above was suspended onto a piece of FTO slice with a fixed active area of 0.196 cm² drop by drop. After the FTO slice with electrode film was dried in air at room temperature, it was transferred to an oven at 300 °C for 3 h to construct the Cu2O-modified FTO working electrode. The photoelectrochemical properties were measured in a Na2SO4 aqueous solution (0.5 mol L⁻¹) at 0.6 V (vs. Ag/AgCl) under a 250 W xenon arc lamp with a 420 nm cutoff filter.

2.5. Photocatalytic activity
The photocatalytic activities of the catalysts were evaluated by MO decomposition at ambient temperature. In a typical reaction, 10 mg of catalyst powder was dispersed ultrasonically into 50 mL of MO solution (20 mg L⁻¹) in a 100 mL quartz photocatalyst with no hydrogen peroxide (H2O2). The above suspension was stirred under dark conditions for at least 30 min to reach an adsorption/desorption equilibrium of dye molecules on the photocatalysts. After that, the suspension was exposed to a 250 W xenon arc lamp with a 420 nm cutoff filter (about 100
mW cm\(^{-2}\)). The photocatalytic degradation experiments were detected by collecting the suspensions at different irradiation times, which were centrifuged immediately to remove the catalyst particles for analysis. The characteristic absorption intensity of about 465 nm as a monitored parameter on a UV-vis spectrometer was detected to measure the MO concentration.

2.6. Trapping experiments of active species and recycle measurements

To find out the active species, some scavengers were added in the reaction system for quenching tests. tert-Butyl alcohol (TBA), benzoquinone (BQ) or disodium ethylenediaminetetraacetate dehydrate (EDTA-2Na) with the same concentration of 1 mmol L\(^{-1}\) were used as the scavengers for hydroxide radicals (\(\cdot\)OH), superoxide radicals (\(\cdot\)O\(_2^-\)) and photogenerated holes (h\(^+\)), respectively. The stability tests of the Cu\(_2\)O samples were investigated by recycling experiments. The photocatalytic experiments described above were repeated 5 times under the same experimental conditions. After every photocatalytic cycle test, the powder samples were collected by centrifugation and then dried under vacuum for the next test.

3. Results and discussion

3.1. Morphology and crystal structure analysis

The as-obtained sample (by the solvothermal reaction at 170 °C for 2 h) was investigated by SEM and TEM observations (Fig. 1 and S1†). In Fig. 1a, the as-prepared sample shows a uniform sphere-like morphology with diameters ranging from 400 nm to 600 nm. It hardly had any impurity, indicating a high yield and purity. It was obviously observed from some damaged spheres that the as-prepared sample has a hollow structure, which is further proved by the TEM characterization shown in Fig. 1b and S1†. The strong contrast between the dark edge and the pale center was evidence of the hollow nature of the spheres (Fig. S1†). Further observation showed that the hollow spheres have rough surfaces with cubic convex structures. The spherical shell with a thickness of about 80 nm was constructed randomly by a large amount of nanocubes, thereby forming the hollow hierarchical structures. Based on the lattice fringes from the HRTEM image (Fig. 1c) of the hollow spheres, the clear lattice fringes were measured as 0.246 nm. This corresponded to the (111) crystal planes of Cu\(_2\)O, further confirming the good crystallization.

The XRD pattern of the as-prepared hollow spheres is displayed in Fig. 1d. According to the Cu\(_2\)O standard card (JCPDS no. 78-2076), the diffraction peaks at about 29.5°, 36.4°, 42.3°, 52.5°, 61.4°, 73.5° and 77.4° can be indexed to the crystal planes of (110), (111), (200), (211), (220), (311) and (222) of the primitive cubic crystalline Cu\(_2\)O, respectively. According to the line width analysis of the (111) diffraction peak based on the Scherrer formula, an average crystallite size of about 18.7 nm was estimated, which is basically consistent with the particle size observed in the TEM images (Fig. 1b and S1c†). It was considered that the presence of the (111) crystal planes could make Cu\(_2\)O a stable photocatalyst.28

In order to further verify the composite and the valence states of the elements, the hierarchical hollow spheres were
of Cu to O element in Cu$_2$O and CuO, further indicating the
2.37 : 1, which was much higher than the theoretical ratio value
the Cu to O element on the surface of the hollow spheres was
easy to be reduced by ionic liquid. The atom ratio of
was distributed on the surface of the hollow spheres, which may
be observed (Fig. S5a and d). At the reaction temperature
2.37 : 1, which was much higher than the theoretical ratio value
of Cu to O element in Cu$_2$O and CuO, further indicating the
existence of Cu(0) on the surface of the sample.

3.2. Growth mechanism
The time-dependent experiments were used to make clear the
formation of the Cu$_2$O hollow spheres by SEM and TEM char-
acterization. Fig. 2 clearly displays the evolution process. At the
beginning reaction of 45 min, the as-obtained crystals assem-
bled together to construct the loose solid aggregates with
a diameter of approximately 350 nm (Fig. 2a). The solid spheres
were clearly seen by TEM (Fig. 2d). As the reaction proceeded to
60 min, the aggregates had a slight increase in size and dis-
played better uniformity (Fig. 2b). In addition, it was found that
the spherical wall was in good condition, while the sphere was
gradually dissolved from the outer part to the inner part of the
spheres (Fig. 2e). This phenomenon was further strengthened based
on the observation of the bright part near the inside of the
sphere shell at the reaction time of 90 min (Fig. 2c and f). At the
same time, the spheres with the similar size had the rougher
surface, and the cubic convex structures could be clearly found
in Fig. 2f. According to the X-ray line broadening analysis of the
(111) diffraction peaks (Fig. S4†) via the Scherrer formula, the
Cu$_2$O samples had an average size of 15.8, 16.2 and 17.5 nm at
the reaction times of 45, 60 and 90 min, respectively, which were
smaller than that of the Cu$_2$O hollow spheres. After a reaction
time of 2 h, the uniform hollow spherical self-assembly con-
structed by nanocubes was finally formed, as shown in Fig. 1a
and b.

The shape-evolution process of the as-prepared hierarchical
Cu$_2$O hollow spheres with increasing reaction time is a disso-
lution–recrystallization process. The Ostwald ripening process,
where crystallites grow at the expense of the smaller ones, can
be used as the underlying mechanism to explain the hollowing
process. As shown in Scheme 1, during the ripening process,
a large number of nuclei are first formed in a short amount of
time. With the reaction progressing, a slow crystal growth trig-
gers the formation of solid spheres, which might last for several
minutes. After that, the interior of the solid spheres is gradually
dissolved due to the higher surface energies. Based on further
reaction with the remaining ions in the solution, the spherical
shell becomes rougher and rougher. At the same time, the
rough hierarchical surface hinders further dissolution of the
spherical shell and promotes the migration of the inner core to
the outside driven by high energy. At last, the Cu$_2$O hollow
spheres are observed with the hierarchical shells constructed by
nanocubes (Fig. 1a and b). The solid and hollow spheres can be
selectively fabricated by controlling the reaction time.

In addition, the effects of other experimental parameters on
the morphology evolution were investigated in detail. The
reaction temperature has an important impact on the formation
of the Cu$_2$O hollow spheres (Fig. S5†). When it rose to 150 °C,
the Cu$_2$O hollow spheres of about 300 nm with a coarse surface
could be observed (Fig. S5a and d†). At the reaction temperature
of 160 °C, the hierarchical Cu$_2$O hollow spheres grew in size and
shell thickness with a diameter of about 400 nm and a shell of
50 nm (Fig. S3b and e†). With the reaction temperature up to
170 °C, the hollow spheres developed in size, and the hollow
and porous spheres were formed (Fig. 1a and b). At the temperature of 180 °C, the uniformity and integrity of the Cu$_2$O
hollow spheres were destroyed. A large amount of irregular
particles could be observed in Fig. S5c and f† So, at the reaction
temperature above 170 °C, the hollow structures became
unstable and the sphere shell collapsed into separated particles
(Fig. S5f†). Based on the above experiments, the dissolution–
recrystallization process that is essential for the preparation of
a hollow self-assembly can only take place in the temperature
range from 150 to 170 °C. It is very important for the size and
shell thickness of the hollow spheres to be adjusted by
controlling the reaction temperature.

Apart from the reaction temperature, the [BMIM]BF$_4$ concentration also has a significant effect on the as-prepared
Cu$_2$O products (Fig. S6†). Without [BMIM]BF$_4$, no product was
collected. At the [BMIM]BF$_4$ concentration of 0.0125 mol L$^{-1}$,
only irregular nanoparticles were found, as shown in Fig. S6a
and f† With increasing [BMIM]BF$_4$ concentration, the spherical
particles gradually grew in size and uniformity, as shown in the
SEM images of Fig. S6b–d† The corresponding TEM images
further proved the above phenomena and the nanoparticles gradually became empty (Fig. S6g–i†). When the [BMIM]BF₄ concentration was increased to 0.15 mol L⁻¹/C₀, the sphere size was not consistent and the solid microspheres were found (Fig. S6e and j†). The addition of ionic liquid could lead to the interaction between the Cu²⁺ ion and [BMIM]BF₄, which played a significant role in the growth and nucleation rates of the nanocrystals, resulting in the formation of various micro- and nano-crystals.

3.3. Nitrogen adsorption-desorption isotherms

The porous and hollow Cu₂O self-assembly was clearly characterized by SEM and TEM, and further investigated by the N₂ adsorption-desorption isotherms and pore size distribution (Fig. 3a). In order to demonstrate the increased specific surface of the as-prepared hollow spheres due to the hollow and porous structures, the Cu₂O solid spheres (Fig. 2a and d) were fabricated at the reaction time of 45 min and used as a reference. The BET specific surface areas were 21.83 and 14.88 m² g⁻¹ for the Cu₂O hollow spheres and solid spheres, respectively. The Cu₂O hollow spheres and solid spheres both displayed type IV isotherms, which are characteristic of most mesoporous materials. The hysteresis loop at the low relative pressure (P/P₀) from 0.4 to 0.9 might be attributed to the mesoporous structures in the interleaving nanocubes or cavities of the hollow spheres, and the hysteresis loop at P/P₀ of 0.9 to 1 might be attributed to the inter-nanoparticle space. The mesopore filling, monolayer coverage and accumulation of particles might lead to the porous structures of the sample, which were further confirmed by the pore size distribution from the Barrett-Joyner-Halenda (BJH) method (inset of Fig. 3). In a very wide range, the pore diameters of the Cu₂O hollow spheres were mainly divided into two categories. One was the mesopore at about 2.9 nm from the surface structure of the sample itself; the other was the micropore from the disordered aggregation of nanocubes in the range of 20–150 nm. For the Cu₂O solid spheres, the corresponding pore size distributions were mainly centered at about 2.2, 32.6 and 125.6 nm due to the existence of mesopores and the aggregation of nanoparticles. Although the Cu₂O solid spheres had smaller pore sizes, the Cu₂O hollow spheres had far more pores than solid ones, resulting in a higher specific surface area. The porous properties of the hollow Cu₂O spheres would increase the specific surface area of the samples, indicating that more reaction sites could be provided and their photocatalytic activities would be improved.

3.4. UV-vis diffuse reflection spectra

The strong absorption in the region of 200–700 nm was observed from the UV-vis spectra of the hollow and solid Cu₂O spheres, indicating the bandgap transition, not from the

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**Fig. 2** SEM (a–c) and TEM (d–f) images of the as-prepared products at the different reaction times, (a and d) 45 min, (b and e) 60 min, and (c and f) 90 min.

**Scheme 1** Formation process of the hierarchical Cu₂O hollow spheres.
impurity levels (Fig. 4). The absorption edges of the hollow and solid Cu$_2$O spheres were about 627 nm and 617 nm, respectively. The corresponding bandgap energies (inset of Fig. 4) of the hollow and solid Cu$_2$O spheres were calculated at about 1.98 and 2.01 eV, respectively, which were identical. Compared with the solid spheres, the hierarchical Cu$_2$O hollow spheres with special morphology had little effect on the bandgap. In addition, the Cu$_2$O samples were conductive to efficiently utilize the solar energy and exhibit the high photocatalytic activity.

3.5. Photocatalytic properties

Taking the degradation of MO as a model reaction, the photocatalytic activities of the Cu$_2$O samples were evaluated under visible light. The suspension was magnetically stirred in the dark for at least 30 min before illumination to reach the adsorption–desorption equilibrium. The adsorption capacities of the hierarchical Cu$_2$O hollow spheres, Cu$_2$O solid spheres, commercial Cu$_2$O and Degussa P25 were 32.1%, 18.9%, 0.750% and 0.551%, respectively. The hierarchical Cu$_2$O hollow spheres exhibited strong adsorption, which can be interpreted by the unique porous and hollow structures.

The UV-vis spectra were measured at regular intervals during the photodegradation of MO over the hierarchical Cu$_2$O hollow spheres (Fig. 5a). The characteristic peak intensity of MO at about 465 nm decreased with the prolonged irradiation time, indicating that the MO solution was gradually degraded under visible light irradiation. More than 90% of MO was decomposed after 20 min illumination, which exhibited a quick photocatalytic reaction in the presence of the Cu$_2$O hollow sphere assembly without H$_2$O$_2$. For comparison, the similar photocatalytic tests for the solid Cu$_2$O products, commercial Cu$_2$O powder and Degussa P25 TiO$_2$ were conducted under visible light irradiation (Fig. 5b). A visible light irradiation of 120 min, about 98.5%, 83.5% and 14.0% of the MO solution was degraded for the Cu$_2$O hollow and solid spheres, and commercial Cu$_2$O, respectively. The hierarchical Cu$_2$O hollow spheres showed the highest photocatalytic activities at various irradiation times. However, only about 8.8% of MO was degraded in the presence of P25 and about 3.5% without any photocatalysts, indicating that the Cu$_2$O photocatalysts were important in the promotion of the photocatalytic reaction of MO.

The MO degradation kinetics was also investigated by the linear simulation of a pseudo first-order Langmuir–Hinshelwood (L–H) mode.\textsuperscript{36–38} The L–H model is well established for heterogeneous photocatalysis at low dye concentration, and the kinetic equation (eqn (2)) is shown as follows:

$$ r = -\frac{dC_0}{dt} = K_{app} C $$

(2)

where $r$ is the degradation rate, and $C_0$ and $C$ are the MO concentrations at the adsorption–desorption equilibrium and various intervals of time ($t$), respectively. $K_{app}$ is the apparent first-order rate constant (min$^{-1}$), which can be calculated from the gradient of the curve of ln($C_0/C$) versus time ($t$). The $K_{app}$ values in Fig. 5c were estimated to be 0.1138, 0.0448 and 0.00244 min$^{-1}$ for the Cu$_2$O hollow and solid spheres, and the commercial Cu$_2$O powder, respectively. The hierarchical Cu$_2$O hollow spheres showed the largest $K_{app}$ value, which was
approximately 2.54 times and 46.6 times larger than that of the Cu$_2$O solid spheres and commercial Cu$_2$O powder. Based on the BET specific surface areas and $K_{\text{app}}$ values of the as-prepared Cu$_2$O samples, the surface area normalised rates ($A_{\text{surf}}/K_{\text{app}}$) of MO degradation in the presence of the same amount of photocatalyst (1 mg) were calculated as 5.21 and 3.01 min$^{-1}$ m$^{-2}$ for the hollow and solid Cu$_2$O spheres, respectively. The results demonstrate that the enhanced photocatalytic activity for the Cu$_2$O hollow spheres was not only determined by the high specific surface area, but also might be affected by the improved light absorption and doping of a small amount of CuO and Cu.

The photocatalytic activity of the as-prepared Cu$_2$O hollow spheres was compared to previously reported photocatalysts for the degradation of MO, as shown in Table S1.$^\dagger$ Various Cu$_2$O micro- and nano-materials can effectively degrade MO under their own photocatalytic reaction conditions. Compared with other Cu$_2$O samples, the as-prepared Cu$_2$O hollow spheres with the degradation rate as the specific activity of 0.825 mmol g$^{-1}$ h$^{-1}$ displayed satisfactory photocatalytic activity for MO degradation, indicating superior performance in the visible-light photocatalysis.

According to the above experimental results, the hierarchical Cu$_2$O hollow spheres exhibited excellent catalytic activity for MO degradation, which can be interpreted as follows. First, it is possible that the porous and hollow architectures constructed by nanocubes could provide more active adsorption sites and have full contact with the MO molecules. Second, the existence of a small amount of CuO is helpful for improving the photocatalytic activities due to the efficient separation of photogenerated charges. Finally, a small amount of Cu in the sample can enhance the photocatalytic performance based on the localized surface plasmon resonance (LSPR) effect, referring to the collective oscillation of conductive electrons in metal nanoparticles.$^{39,40}$ Thus, as optical antennas or photosensitizers, the plasmonic Cu nanoparticles could be used to enhance the visible-light absorption of photocatalysts through the LSPR effects, so as to improve the photocatalytic reaction rates.$^{41,42}$

To clarify the photocatalytic mechanism of the hierarchical Cu$_2$O hollow spheres, the active species trapping experiments were performed. The main active species, such as ·OH, ·O$_2^-$ and h$^+$, are generally detected by TBA, BQ and EDTA-2Na, respectively. As shown in Fig. 6, when TBA was introduced,
the degradation of MO was significantly decreased, indicating that \( \cdot \text{OH} \) was a main active species throughout the photo-degradation reaction. With the addition of EDTA-2Na, the MO degradation was also obviously suppressed, implying that \( \text{h}^+ \) had an important impact on the photocatalytic reaction of MO.

In addition to TBA and EDTA-2Na, BQ also hindered the MO degradation and \( \cdot \text{O}_2^- \) was considered to be another active species in the photocatalysis. The reaction between the dissolved \( \text{O}_2 \) and photo-generated electrons (\( e^- \)) could hinder the recombination of photo-generated charges. For a further study on the influence of \( \cdot \text{O}_2^- \) on the photocatalytic reaction, the photocatalytic degradation of MO over the hierarchical Cu2O hollow spheres was performed under N2 atmosphere. Upon bubbling with N2, the degradation of MO displayed a slight decrease, indicating the relatively minor effect of \( \cdot \text{O}_2^- \) on the photocatalytic reaction.

After 60 min visible-light irradiation of the MO solution in the Cu2O hollow spheres, the colorless and transparent solution obtained by centrifugation was taken for LC-MS/MS analysis to identify the products. The mass value (\( m/z \)) of the main product detected was 156.996, corresponding to the phenylsulfonic radical,\(^1\) and the obtained chemical structure is shown in Fig. S7,\(^1\) indicating the incomplete mineralization. Based on the trapping experiments, the hydroxyl and superoxide radicals as the reactive species can attack a more labile oxidationazo (–N=–N–) group to break the dye molecules and decolorize the solutions. Subsequently, the benzene ring and branched chains would be broken under the continual attacks of the radical species.\(^2\) However, the oxidation reactions of the intermediates are very complex and the reaction mechanism is not clear.

The possible photocatalytic process of MO over Cu2O hollow spheres is drawn in Scheme 2. Accordingly, the reported conduction band (CB) (–0.28 V vs. NHE) and valence band (VB) (+1.92 V vs. NHE) of Cu2O is more negative than those (+0.46 and +2.16 V vs. NHE for CB and VB) of CuO.\(^3\) When irradiated by the visible light, the activated photo-generated electrons transfer from the CB of Cu2O to that of CuO, and the holes simultaneously migrate from the VB of CuO to that of Cu2O. So, based on the well-matched band structure, a desired hetero-junction between Cu2O and CuO can be established, leading to an improved separation and transfer of photo-generated electrons and holes. In particular, CuO and Cu2O can serve as different active sites for electron reduction and hole oxidation. Furthermore, the photo-generated electrons on the CB of CuO can reduce \( \text{O}_2 \) into \( \cdot \text{O}_2^- \) for the MO degradation. Moreover, with excellent conductivity as good electron acceptors, Cu also accepts the photoexcited electrons from the CB of Cu2O to produce \( \cdot \text{O}_2^- \). At the same time, the CuO with the more positive VB potential may be capable of oxidizing hydroxyl groups into \( \cdot \text{OH} \) radicals [\( E_{\text{OH -}} = +1.99 \text{ V vs. NHE} \)] for the enhanced photocatalytic activity.\(^4\) The \( \cdot \text{OH} \) radicals can also be generated from the \( \cdot \text{O}_2^- \) radicals by a photochemical reaction.\(^5\) So, the Cu2O hollow spheres with a small amount of CuO and Cu can effectively improve the photocatalytic properties.

### 3.6. Photocatalytic Measurements

The separation efficiency of photo-generated charges plays a vital role in improving catalytic activities. The photocurrent comes from the photo-generated electrons transferred from VB to CB excited by light. Therefore, the higher photocurrent suggests the larger separation efficiency of photo-generated charges and better photocatalytic activity. The photocurrent curves for the hollow and solid Cu2O spheres with chopped illumination are shown in Fig. 7. The photocurrent densities sharply rise to a stable value in the light-on state, but quickly fall to zero in the light-off state. The phenomena suggest that the photo-generated electrons could migrate to the electrode substrate under visible light irradiation to produce a photocurrent. The hierarchical Cu2O hollow spheres displayed a stronger photocurrent response than the Cu2O solid spheres. The photocurrent density of the hierarchical Cu2O hollow spheres with a stable intensity was about 4.6 times higher than that of the Cu2O solid spheres. This obvious photocurrent enhancement indicated that for the hierarchical Cu2O hollow spheres, the separation of the photo-generated charges was more effective, which helped to improve its catalytic activity. In addition,
the PL spectra of the Cu₂O samples were measured to reveal the process of migration, transfer and recombination of photo-generated charges in a semiconductor. As shown in Fig. S8, a strong emission peak of the Cu₂O samples was observed at about 650 nm, indicating the direct recombination of the electrons and holes. The Cu₂O hollow spheres exhibited a lower emission intensity than the Cu₂O solid spheres, indicating the efficient separation of the photo-generated charges.

3.7. Regeneration and reusability

It is important for practical application to study the reproducibility and stability of a photocatalyst throughout the catalytic reaction. In order to assess the regeneration and reusability, the recycling tests of the as-prepared Cu₂O samples were performed to observe the MO degradation under visible light (Fig. 8). For each test, the used photocatalysts were collected by centrifugation, washed with deionized water and dried in air. The MO degradation decreased by 0.46% and 3.5% after five consecutive experiments for the hollow and solid Cu₂O spheres, respectively. The photocatalytic activities showed almost no decrease for the hierarchical Cu₂O hollow spheres, indicating that the unique porous hollow assembly and the doping of a small amount of CuO and Cu were helpful for the recovery and reuse of the photocatalysts. Due to the existence of many deep and capacious pores, the Cu₂O sample could make full contact with the dye molecules, resulting in the improvement of the photocatalytic activities. So, the hierarchical Cu₂O hollow spheres displayed excellent photocatalytic stabilities and a prominent photocatalytic application.

4. Conclusions

Uniform hierarchical Cu₂O hollow spheres assembled by nanocubes were successfully fabricated on a large scale by the one-step solvothermal approach. Based on the time-dependent experiments, a possible mechanism was proposed to reveal the formation of the hierarchical Cu₂O hollow spheres. Moreover, in comparison with the solid Cu₂O spheres and commercial Cu₂O powder, the hierarchical Cu₂O hollow spheres displayed remarkable visible-light catalytic properties and stability toward MO degradation, which may be due to their distinctive morphology and the doping of a small amount of CuO and Cu. With these unique structures and composition, the hierarchical Cu₂O hollow spheres could be considered an excellent platform, which can significantly enhance the visible-light catalytic performance and open up an approach for wastewater treatment.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (NSFC, grant No. 51372154 and 20901051), Project of Science Technology Department of Zhejiang Province of China (grant No. 2017C33209) and the Science Foundation of Ministry of Housing and Urban-Rural Development of China (grant No. 2015-K4-003).

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