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Self-assembly of TiO₂/ZIF-8 nanocomposites for varied photocatalytic CO₂ reduction with H₂O vapor induced by different synthetic methods†

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Photoreduction of carbon dioxide (CO₂) provides an effective perspective for solving the energy crisis and environmental problems. Herein, two types of composite photocatalysts (TiO₂/ZIF-8) based on ZIF-8 and TiO₂ have been designed and synthesized with the help of the grinding method and the solid-synthesis method. Both composite photocatalysts are employed for the photocatalytic reduction of CO₂. In composite photocatalysts prepared by the grinding method, ZIF-8 particles are distributed on the surface of TiO₂, and provide extra available spaces for storing CO₂, which is beneficial for improving their photoreduction performances. As a result, an enhanced CO formation rate of 21.74 μmol g⁻¹ h⁻¹ with a high selectivity of 99% is obtained for this family of composite photocatalysts *via* the solid–gas mode without photosensitizers and sacrificial agents. For comparison, the other family of composite photocatalysts synthesized *via* the solid-synthesis method possesses structures similar to ZIF-8, where TiO₂ is encapsulated inside the framework of ZIF-8. This structural feature obstructs the contact between the active sites of TiO₂ and CO₂, and leads to lower activities. The best CO formation rate of this family is only 10.67 μmol g⁻¹ h⁻¹ with 90% selectivity. Both the structural features of the two families of photocatalysts are described to explain their differences in photoreduction performances. The experimental finding reveals that different synthetic approaches indeed result in diversified structures and varied photocatalytic performances. This work affords a new scalable and efficient approach for the rational design of efficient photocatalysts in the area of artificial photosynthesis.

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1. Introduction

Carbon dioxide (CO₂) is mainly produced by the continuous combustion of fossil fuels, and has become a kind of greenhouse gas, which plays an important role in global warming. The growing concerns about global warming induced by the increase of CO₂ concentrations have drawn increasing attention in the CO₂ capture and conversion. Naturally, various approaches have been developed to overcome this problem.^{1–10} Among the reported technologies, the conversion of CO₂ into valuable chemical materials by means of efficient photocatalysts may be an effective strategy with the help of solar energy, which is likely to resolve global warming. So, the development of outstanding photocatalysts for the

photocatalytic reduction of CO₂ has become an active field of research.

In the past few decades, various kinds of photocatalysts have been designed and synthesized, and contain molecular compounds, semiconductors, and others.^{11–30} Common problems of these photocatalysts are listed below: a high recombination of electron–hole pairs, poor CO₂ adsorption ability, and others.

It is urgent to prepare new photocatalysts with improved separation of electron–hole pairs, and enhanced CO₂ adsorption ability. Metal–organic frameworks (MOFs), as a new class of porous crystalline materials, are constructed from numerous metal ions and various organic linkers.^{31–35} This kind of porous materials possesses following advantages: structural tunability, ordered porous structures and large surface area. These excellent characteristics make MOFs widely explored in various fields, such as sensors, energy storage and catalysis.^{36–42} However, it is in early stages that MOFs are employed as photocatalysts for reducing CO₂. A limited number of MOFs, such as UiOs^{43–45} and MILs has made an attempt in this field. For example, a light-harvesting MOF, MIL-125-NH₂ (Ti), serves as a photocatalyst and can convert CO₂ into HCOOH.⁴⁴ These covered examples reveal that the photocatalytic activity of the

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individual MOF is usually not very good. Recently, pioneering examples have demonstrated that the combination of semiconductors with MOFs may be a good choice to enhance the CO₂ photoreduction efficiency. The resulting composite photocatalysts possess the advantages of each component (*e.g.*, strong CO₂ adsorption capacity of MOFs and good photocatalytic ability of semiconductors).⁴⁶ For instance, Wang *et al.*⁴⁷ covered a composite photocatalyst Co-ZIF-9/CdS with an enhanced CO₂ photoreduction performance. Naturally, it is necessary to develop more composite photocatalysts based on MOFs and semiconductors with great performance. As far as we know, most of the photocatalysts based on MOFs and semiconductors have been prepared with the help of conventional solvothermal or hydrothermal or bulk solution or wet-chemistry methods,⁴⁸ which require a multi-step process, long reaction time and large amount of solvents. In order to overcome the above problem, it could be very interesting to explore a simple and scalable synthetic approach to prepare MOF/semiconductor composite photocatalysts with improved photocatalytic performances. Directed by this idea, a facile synthetic method (the grinding method) is selected to fabricate TiO₂/ZIF-8 composite photocatalysts within a few minutes. ZIF-8 is chosen because of its high surface area and good stability towards water, which can guarantee the simultaneous absorption of water and CO₂, critical for the process of photoreducing CO₂. Finally, a variety of composite photocatalysts based on ZIF-8 and TiO₂ have been synthesized through this simple and efficient manner.

Up to now, most of the photocatalysts have been employed for the photoreduction of CO₂ *via* a solid-liquid mode in the presence of sacrificial agents (*e.g.*, triethanolamine) as electron donors, which are toxic and high-cost. Recently, another reaction mode (solid-gas mode) was developed to overcome this problem because this reaction mode does not need photosensitizers and sacrificial agents. In this reaction mode, CO₂ and H₂O molecules directly surround the photocatalyst. Meanwhile, H₂O offers protons and acts as a sacrificial agent. For example, Xiong *et al.*⁴⁹ employed this mode to evaluate the activity of Cu₃(BTC)₂@TiO₂ in the photoreduction of CO₂, which can selectively convert CO₂ into CH₄. Based on the above considerations, herein, a series of composite photocatalysts based on ZIF-8 and TiO₂ have been synthesized with the help of the grinding method. In this method, ZIF-8 particles are located at the surface of the TiO₂ spheres, which avoids the accumulation of TiO₂ spheres, and are responsible for storing CO₂. The obtained composite photocatalysts are evaluated for their CO₂ photoreduction performance *via* solid-gas mode without photosensitizers and sacrificial agents. The results show that the well-integrated structures prefer to enhance the CO₂ photoreduction performance. As a result, an enhanced CO formation rate of 21.74 μmol g⁻¹ h⁻¹ with a great selectivity of 99% was obtained. In order to verify the influence of the synthesis method on the photocatalytic reduction of CO₂, another series of composite photocatalysts have been synthesized *via* the solid-synthesis method. This series of photocatalysts possess a similar structure compared to ZIF-8, where TiO₂ is encapsulated into the framework of ZIF-8. These

structures are different from those of the photocatalysts obtained *via* the grinding method, and this structural feature hinders their CO₂ photoreduction performances, leading to lower activities. In summary, the experimental results reveal that different synthetic approaches generate varied structures and photocatalytic performances, possibly due to their different structural characteristics. Furthermore, the possible mechanism of the CO₂ photocatalytic reduction is also proposed.

2. Experimental section

2.1 Materials and instruments

All used reagents and solvents are commercially available and directly used. The used reagents are listed below: 2-methyl imidazole (2-IM), titanium tetraisopropanolate (Ti(OiPr)₄), ethanol, 5% Nafion solution, zinc acetate dehydrate (Zn(OAc)₂), sodium sulphate and terephthalic acid (TA). All reagents were purchased from Shanghai Macklin Biochemical Co., Ltd.

Fourier transform infrared spectroscopy (FT-IR) spectra were recorded with a Thermo Nicolet 5700 using KBr pellets for the sample. X-ray powder diffraction patterns of the samples were recorded on a Bruker D8 Advance diffractometer with Cu Kα (λ = 1.5418 Å) radiation in the range of 5–70°. The morphology analysis of the synthesized samples was collected on a scanning electron microscope (SEM, Sirion 200) at an acceleration voltage of 10 kV. X-ray photoelectron spectroscopy (XPS) measurements were carried out on a scanning X-ray microprobe (K-Alpha, Thermo Scientific) with Al α radiation and the C 1s peak at 284.8 eV as the internal standard. The UV-Vis absorption spectrum was obtained on a UV-2550 spectrophotometer (Shimadzu, Japan). The CO₂ adsorption/desorption measurements were conducted under the ambient condition of 298 K (ASAP 2020). Nitrogen adsorption-desorption isotherms were measured at 298 K on an ASAP 2460 instrument. Transmission electron microscopy (TEM) on a JEM-200CX apparatus was performed at an accelerating voltage of 200 kV.

2.2 Synthesis and preparations

2.2.1 Synthesis of TiO₂. Titanium tetraisopropanolate (400 μL) was added to the mortar, and grinded for 30 min. Then, the obtained powder was transferred to a 25 mL Teflon-sealed autoclave and heated at 120 °C for 12 hours.

2.2.2 Synthesis of ZIF-8. 2-Methyl imidazole (0.071 g) and zinc acetate dehydrate (0.071 g) were added to the mortar, and evenly mixed. Then, the mixture was grinded for 30 min, and transferred to a 25 mL Teflon-sealed autoclave and heated at 120 °C for 12 hours.

2.2.3 Synthesis of TiO₂/ZIF-8-GX. 2-Methyl imidazole (0.071 g) and zinc acetate dehydrate (0.071 g) were added to the mortar, and evenly mixed. Then, ethanol (200 μL) and a certain amount of titanium tetraisopropanolate (200, 300, 400 μL) were put into this mortar, and grinded for 30 min. Finally, the obtained mixture was transferred to a 25 mL Teflon-sealed autoclave and heated at 120 °C for 12 hours. The resulting samples were defined as **TiO₂/ZIF-8-GX** (X = 1, 2, and 3, respectively,



corresponding to 200, 300 and 400 μL titanium tetraisopropanolate).

2.2.4 Synthesis of $\text{TiO}_2/\text{ZIF-8-SX}$. The synthetic process was modified according to the reported literature.⁵⁰ 2-Methyl imidazole (0.71 g) and zinc acetate dehydrate (0.71 g) were added to a 25 mL Teflon-sealed autoclave, and evenly mixed. Then, titanium tetraisopropanolate (2, 3, 4 mL) was added, and the obtained mixture was transferred to a 25 mL Teflon-sealed autoclave and heated at 180 $^\circ\text{C}$ for 24 hours. Finally, the resulting powders were hydrolysed in the presence of water with $\text{pH} = 11$. The obtained samples were defined as $\text{TiO}_2/\text{ZIF-8-SX}$ ($X = 1, 2$, and 3 respectively, corresponding to 2, 3, and 4 mL titanium tetraisopropanolate).

2.3 General catalytic reduction

2.3.1 Photocatalytic CO_2 reduction. The photocatalyst (1 mg) was dispersed in 1 mL ethanol, and then coated on 1 cm \times 3 cm ITO glass. The cover range is 1 cm \times 3 cm. The prepared samples were placed in a self-made photocatalytic reactor, and 150 μL distilled water was added at the bottom as the reducing agent. CO_2 was introduced into the reactor to replace the air and ensured that the reactor was full of CO_2 . A LED lamp was used as the light source. After irradiation for 2 hours, 0.5 mL and 1.0 mL gas were taken and placed in a gas chromatography (GC 1120) instrument to determine the content of CO and H_2 .

2.3.2 CO_2 photoreduction analysis. The electrochemical analyzer (CHI 760E) was used for the photoelectrochemical test and Mott–Schottky test with the standard three-electrode system. A sodium sulfate solution (0.2 mol L^{-1}) served as the electrolyte. The sample (1 mg) and 5% Nafion solution were added to 2 mL ethanol and mixed for 1 h, and then evenly dropped on a 1 cm \times 2 cm ITO conductive glass as the working electrode. The reference electrode was the Ag/AgCl electrode, and the counter electrode was the platinum electrode.

2.3.3 Detection of hydroxyl radicals (OH^\cdot). The experimental condition is similar to that of the CO_2 photoreduction. The difference exists in that $\text{TiO}_2/\text{ZIF-8-G2}$ is uniformly mixed with terephthalic acid (TA) (mass ratio = 5 : 1). The photo-generated OH^\cdot would react with TA to generate 2-hydroxyterephthalic acid (TAOH), which could be used to detect the generated OH^\cdot . After irradiation, the obtained sample is used for fluorescence measurements.

3. Results and discussion

3.1 Structure and morphology

One family of $\text{TiO}_2/\text{ZIF-8}$ composite photocatalysts has been prepared by the grinding method using an *in situ* synthetic process (experiment details in Experimental section), and is defined as $\text{TiO}_2/\text{ZIF-8-GX}$ ($X = 1, 2$ and 3, corresponding to the different volumes of used $\text{Ti}(\text{OiPr})_4$). For comparison, another family of $\text{TiO}_2/\text{ZIF-8}$ composite photocatalysts was also prepared using the same reaction substrates with the help of the solid-synthesis method, namely $\text{ZIF-8}/\text{TiO}_2\text{-SX}$ ($X = 1, 2$ and 3, corresponding to the different volumes of used $\text{Ti}(\text{OiPr})_4$). In order to confirm the successful formation of ZIF-8 and TiO_2 , all

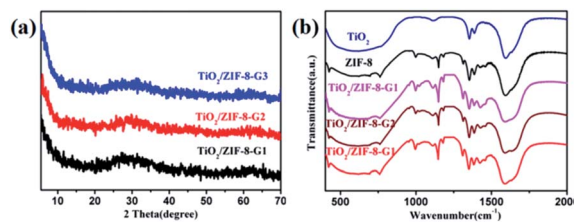


Fig. 1 (a) PXRD patterns and (b) FT-IR spectra of $\text{TiO}_2/\text{ZIF-8-GX}$, ZIF-8 and TiO_2 .

as-synthesized powders have been identified *via* the powder X-ray diffraction (PXRD) patterns. The crystallinities of $\text{TiO}_2/\text{ZIF-8-GX}$ are not well-defined. Only several weak peaks (around 10.4° , 12.5° and 18.5°) are observed, which are consistent with the simulated PXRD pattern of ZIF-8 (Fig. 1a and S3 \dagger). In addition, there is a broad peak between 20° and 40° relative to TiO_2 , which can be attributed to the anatase TiO_2 (JCPDS no. 21-1272).⁵¹ Additionally, the PXRD patterns of $\text{TiO}_2/\text{ZIF-8-SX}$ were performed. Their patterns exhibit good diffraction peaks, and match well with that of ZIF-8, implying that the good crystallinity of ZIF-8 is well maintained (Fig. S2 \dagger). It should be mentioned that a weak diffraction peak at 25.7° is responsible for the (101) plane of TiO_2 .

In addition, the Fourier transform infrared (FT-IR) spectra were used to analyze the surface chemistry of the prepared $\text{TiO}_2/\text{ZIF-8}$ composite photocatalysts. As shown in Fig. 1b and S1, \dagger the spectra of $\text{TiO}_2/\text{ZIF-8-GX}$ and $\text{TiO}_2/\text{ZIF-8-SX}$ composite photocatalysts constructed by different approaches are similar. In Fig. 1b, their characteristic peaks are clearly found in the FTIR spectra. The peaks around 996, 1423 and 1578 cm^{-1} are attributed to the C–N and C=N stretching vibrations from 2-IM,

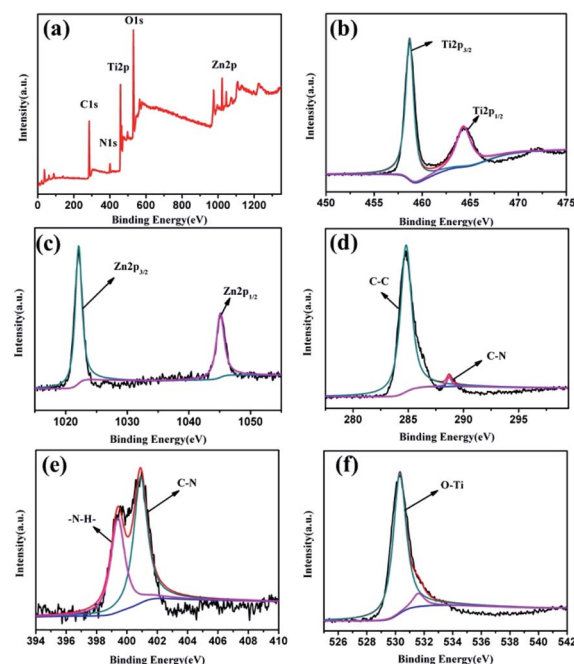


Fig. 2 (a) XPS survey of $\text{TiO}_2/\text{ZIF-8-G2}$, (b) Ti 2p, (c) Zn 2p, (d) C 1s, (e) N 1s and (f) O 1s spectra.



and the signals of the C–N bending vibration are demonstrated by the peaks located at around 1148 and 1308 cm^{-1} . Besides, the peak at 420 cm^{-1} in the spectra belongs to the stretching vibrations of the Zn–N bonds.^{52,53} Additionally, the broad peaks from 500 to 800 cm^{-1} are ascribed to the stretching vibrations of the Ti–O bonds.^{54,55} As shown in Fig. S1,† similar peaks are found in the spectra of $\text{TiO}_2/\text{ZIF-8-SX}$. The signals of the C–N and C=N stretching vibrations and the C–N bending vibrations are demonstrated by the peaks at around 998, 1421, 1582, 1145 and 1304 cm^{-1} . The peak located at 424 cm^{-1} corresponds to the Zn–N bonds. The broad peaks at around 500–790 cm^{-1} belong to the Ti–O bond stretching vibration.

X-ray photoelectron spectroscopy (XPS) has been used to study the chemical states and the composition of the prepared photocatalysts. The survey spectrum of $\text{TiO}_2/\text{ZIF-8-G2}$ proves the presence of the Zn 2p, Ti 2p, N 1s, C 1s and O 1s peaks (Fig. 2a). The XPS spectrum of Ti exhibits two peaks at 458.6 eV and 464.3 eV, which are relative to the binding energies of Ti 2p_{3/2} and Ti 2p_{1/2}, respectively (Fig. 2b). This implies the existence of the oxidation state Ti⁴⁺ in $\text{TiO}_2/\text{ZIF-8-G2}$. As seen in Fig. 2c, the binding energies at 1022.1 eV and 1045.1 eV belong to the Zn 2p_{3/2} and Zn 2p_{1/2}, respectively. Fig. 2d shows that two peaks at around 284.7 eV and 288.5 eV are assigned to the C–C and C–N bonds from the imidazole groups in the C 1s spectrum, respectively. Additionally, in the spectrum of N, two peaks (399.3 and 400.9 eV) can be attributed to –NH– and C–N, respectively (Fig. 2e). In the O 1s spectrum, one main peak at 530.3 eV belongs to the Ti–O bonds, and the other peak with weak intensity at 531.6 eV is attributed to the lattice oxygen atoms in TiO_2 (Fig. 2f).^{56,57} In summary, all characterization results indicate that the successful combination of TiO_2 and ZIF-8 has been realized.

The obtained photocatalysts have been used to evaluate their surface morphology with the help of scanning electron microscopy (SEM) images. The morphologies of ZIF-8, TiO_2 and $\text{TiO}_2/\text{ZIF-8-GX}$ are found to be different by SEM images. The SEM images show that the particles of ZIF-8 possess the smooth surface and exhibit angular shapes (Fig. 3a and b). Fig. 3b shows that the as-synthesized TiO_2 particles are spherical with rough surfaces. In addition, the pure TiO_2 spheres can agglomerate

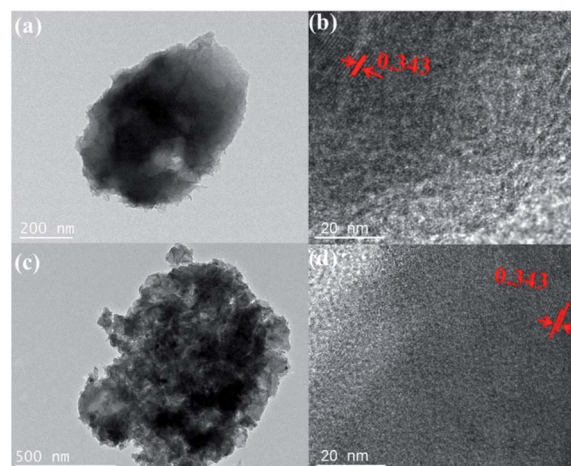


Fig. 4 TEM images of (a) $\text{TiO}_2/\text{ZIF-8-G2}$, (c) $\text{TiO}_2/\text{ZIF-8-S2}$, and high-resolution transmission electron microscope (HRTEM) images of (b) $\text{TiO}_2/\text{ZIF-8-G2}$, (d) $\text{TiO}_2/\text{ZIF-8-G2}$.

together. As shown in Fig. 3c–e, most of the particles also maintain the sphere shape, but possess rougher surfaces, compared with that of the pure TiO_2 spheres, indicating that the ZIF-8 particles have successfully coated the surfaces of the TiO_2 spheres. The coating of ZIF-8 make $\text{TiO}_2/\text{ZIF-8-GX}$ greatly avoid the agglomeration of TiO_2 , which may enhance their catalytic activity. The elemental distribution of $\text{TiO}_2/\text{ZIF-8-GX}$ has been carried out with the help of element mapping. Fig. 3f clearly displays the element distribution of $\text{TiO}_2/\text{ZIF-8-G2}$, where the cyan, red, grey, green and yellow colours represent the distributions of each element C, N, O, Ti and Zn, respectively. With the help of the element mapping, we can confirm that ZIF-8 was successfully located on the surface of the TiO_2 spheres. Summarily, in $\text{TiO}_2/\text{ZIF-8-GX}$, ZIF-8 is located at the surface of the TiO_2 spheres. In order to justify our hypothesis, taking $\text{TiO}_2/\text{ZIF-8-G2}$ as an example, transmission electron microscope (TEM) images have been used to prove this result. As shown in Fig. 4a and b, the generated TiO_2 nanoparticles are surrounded by ZIF-8, and the peripheral surface is terminated by ZIF-8. The generated TiO_2 presents a plane spacing with the value of approximately 0.343 nm (Fig. 4b), which is relative to the (101) lattice plane of the generated TiO_2 . Meanwhile, the SEM images (Fig. S4†) show that the particles of $\text{TiO}_2/\text{ZIF-8-SX}$ are held together and $\text{TiO}_2/\text{ZIF-8-SX}$ exhibits similar morphology, compared to that of ZIF-8. Moreover, the TEM images (Fig. 4c and d) of $\text{TiO}_2/\text{ZIF-8-S2}$ are provided, demonstrating the existence of TiO_2 , and indicate that TiO_2 may be embedded into the framework of ZIF-8 together with its SEM image.⁴⁸ The photocatalysts prepared by different methods possess different structures. The above results show that the synthetic method employed for preparing the composite photocatalyst has an important influence on the structure and morphology of the samples.

3.2 Photocatalytic activity

The photoreduction of CO_2 has been carried out through a solid–gas reaction mode by placing TiO_2 , ZIF-8 and $\text{TiO}_2/\text{ZIF-8}$

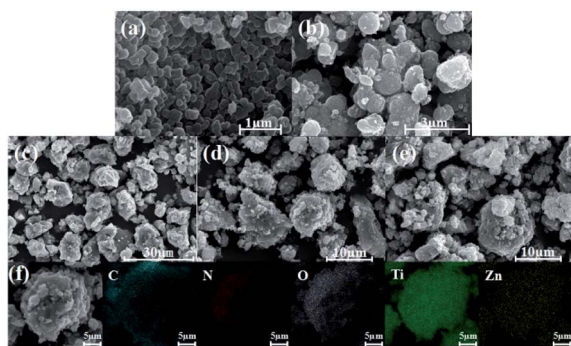


Fig. 3 SEM images of (a) ZIF-8, (b) TiO_2 , (c) $\text{TiO}_2/\text{ZIF-8-G1}$, (d) $\text{TiO}_2/\text{ZIF-8-G2}$, (e) $\text{TiO}_2/\text{ZIF-8-G3}$, and (f) EDS elemental mapping images of $\text{TiO}_2/\text{ZIF-8-G2}$.



photocatalysts in a homemade reactor full of CO₂ and several drops of water. This reaction mode is chosen due to its relative high product selectivity, and inhibited comparative H₂ generation reaction. The detailed experimental results of various photocatalysts on the CO₂ photoreduction are present and given in Fig. 6. It is obvious that CO and trace H₂ have been observed for all samples. It should be mentioned that TiO₂/ZIF-8-GX creates a high selectivity for CO₂ photoreduction. The formation rate of CO increases from 14.63 to 21.74 μmol g⁻¹ h⁻¹, and then decreases to 15.9 μmol g⁻¹ h⁻¹ after irradiation for 2 h. Conversely, the as-synthesized TiO₂ and ZIF-8 exhibited CO formation rates of 7.53 and 1.87 μmol g⁻¹ h⁻¹, respectively, under the same experimental conditions, revealing their much lower CO₂ photoreduction efficiencies.

In order to investigate the influence of the synthetic method on the photocatalytic performances, the solid synthesis method was used to prepare this type of photocatalyst. Then, the composite photocatalysts prepared *via* the solid synthesis method were employed to evaluate their ability for reducing CO₂. These photocatalysts possess similar photocatalytic behaviours. Three samples have similar formation rates of CO after irradiation for 2 h (9.82, 10.67 and 9.80 μmol g⁻¹ h⁻¹ for TiO₂/ZIF-8-S1, TiO₂/ZIF-8-S2 and TiO₂/ZIF-8-S3, respectively). Naturally, TiO₂/ZIF-8-S2 exhibits the best performance. Obviously, the CO formation rates of TiO₂/ZIF-8-SX are lower than those of TiO₂/ZIF-8-GX. Summarily, TiO₂/ZIF-8-SX exhibited inferior activities compared to the performances of TiO₂/ZIF-8-GX. The different photocatalytic performances of two kinds of photocatalysts may probably result from their different structures. In order to excavate the influence of the structure on the photocatalytic performance, TiO₂ from the etching of TiO₂/ZIF-8-G2 and TiO₂/ZIF-8-S2 was collected and employed to evaluate their photocatalytic performances. It should be mentioned that the crystallinity of TiO₂ resulting from TiO₂/ZIF-8-G2 is lower than that of TiO₂ obtained from TiO₂/ZIF-8-S2, confirmed by their PXRD patterns (Fig. S5†). The formation rates of CO are 7.50 and 5.88 μmol g⁻¹ h⁻¹, respectively (Fig. S6†), and TiO₂ derived from TiO₂/ZIF-8-G2 exhibited better photocatalytic

performances than that of TiO₂ from TiO₂/ZIF-8-S2. The experimental results reveal that TiO₂ with low crystallinity is beneficial for CO₂ reduction.⁵⁸ Exposed defects induced by the low crystallinity of TiO₂ in TiO₂/ZIF-8-GX can facilitate the separation of photogenerated electrons and holes, which favours the improvement of photocatalytic activities. ICP measurements have also been performed. The calculated results display that two types of photocatalysts possess different molar ratios of Ti to Zn, and the molar ratios of Ti to Zn in TiO₂/ZIF-8-GX are higher (Tables S1 and S2†), indicating that TiO₂/ZIF-8-GX could provide more reaction active sites. Besides, the distribution of ZIF-8 at the surface of TiO₂ in TiO₂/ZIF-8-GX not only enriches CO₂, but also prevents the aggregation of TiO₂. In a word, the structural features of TiO₂/ZIF-8-GX prefer to reduce CO₂ under the irradiation of light. Conversely, the structures of TiO₂/ZIF-8-SX are unfavourable to reduce CO₂ because TiO₂ with good crystallinity cannot suppress the separation of photogenerated electrons and holes effectively, and the photocatalytic active sites of TiO₂ are difficult to form contacts with CO₂ because they are trapped in the skeleton of ZIF-8.

The experimental phenomena show that the introduction of ZIF-8 indeed improves the CO₂ photoreduction performances of the composite photocatalysts. The optimized performance comes from TiO₂/ZIF-8-G2, and its photocatalytic production yields at the given times are 5.04, 13.38, 31.85 and 43.49 μmol g⁻¹ (Fig. 6c). Compared to the original TiO₂ and ZIF-8, as well as TiO₂ derived from TiO₂/ZIF-8-G2 and TiO₂/ZIF-8-S2, the photocatalytic efficiency of TiO₂/ZIF-8-G2 increases by two, eleven and two times, respectively. For composite photocatalysts with varied amounts of TiO₂, the experimental results reveal that the photocatalytic performances improve first, and then decrease along with the increased amount of TiO₂. We speculate that the increased mass ratio of TiO₂ could provide more reactive sites. However, too much TiO₂ hinders the CO₂ absorption ability of the composite photocatalysts, suppressing the benefits of the increased active sites. The enhanced photocatalytic performance of TiO₂/ZIF-8-GX is mainly due to the well-integrated

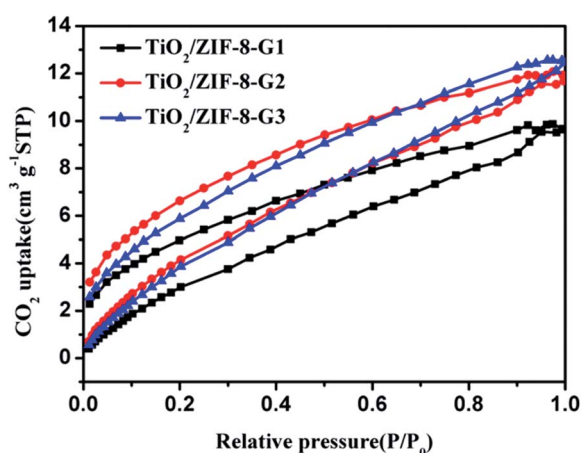


Fig. 5 CO₂ adsorption and desorption isotherm curves of TiO₂/ZIF-8-GX.

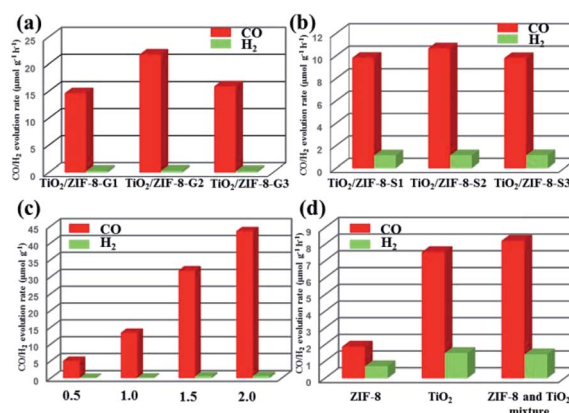


Fig. 6 (a) CO and H₂ yields of TiO₂/ZIF-8-GX and (b) TiO₂/ZIF-8-SX. (c) Time–yield plots of CO and H₂ over TiO₂/ZIF-8-G2 composites under light illumination. (d) CO and H₂ yields of ZIF-8, TiO₂, and ZIF-8 and the TiO₂ mixture.



Table 1 Comparisons between TiO₂/ZIF-8-G2 and other photocatalysts based on MOFs and semiconductors

Photocatalyst	Product and its formation rate ($\mu\text{mol g}^{-1} \text{h}^{-1}$)	Reaction agent	Light source	Ref.
TiO ₂ -Co-ZIF-9	CO 8.80, CH ₄ 2.00, H ₂ 2.60	H ₂ O vapor, 50 mg catalyst	300 W Xe lamp	61
TiO ₂ -Mg-CPO-27	CO 4.09, CH ₄ 2.35	H ₂ O vapor, 10 mg catalyst	4 W LED lamp	62
CsPbBr ₃ QDs/UiO-66(NH ₂)	CO 8.21	10 mg	300 W Xe lamp	63
G-CNQDs/PMOF	CO 16.10, CH ₄ 6.86	MeCN/TEOA (4 : 1)	300 W Xe lamp	64
CNNS-UiO66(Zr)	CO 9.90	MeCN/TEOA (4 : 1)	300 W Xe lamp	65
CsPbBr ₃ @ZIF-67	CH ₄ 29.63	Films (mass of about 4.5 mg)	100 W Xe lamp	66
Cu ₃ (BTC) ₂ @TiO ₂	CH ₄ 2.64	CO ₂ /H ₂ O vapor	300 W xenon arc lamp	67
TiO₂/ZIF-8-G2	CO 21.74	H ₂ O vapor, 1 mg catalyst	40 W LED lamp	This work

structure, and could result from the following issues: (i) ZIF-8 in the composites owns a large surface area, and is favourable for capturing CO₂; (ii) the distribution of ZIF-8 in the TiO₂ matrix can effectively avoid the aggregation of TiO₂ and make TiO₂ expose more reaction active sites; (iii) the low crystallinity of TiO₂/ZIF-8-GX can create more defects at the surface, which can accelerate the separation of the photogenerated electrons and holes. Naturally, the above factors make TiO₂/ZIF-8-GX possess high photocatalytic activity.

Previous achievements have demonstrated that the great CO₂ adsorption capability can benefit from enhancing the photocatalytic performance.^{59–62} Naturally, the CO₂ adsorption capacities of all samples have been evaluated at room temperature. The experimental findings exhibit TiO₂/ZIF-8-GX with CO₂ uptakes of 9.9, 12.1 and 12.6 cm³ g⁻¹ (Fig. 5) at 298 K, respectively. TiO₂/ZIF-8-SX exhibited CO₂ uptakes of 9.84, 9.87 and 11.59 cm³ g⁻¹ (Fig. S7[†]) at 298 K, which are lower than those of the corresponding TiO₂/ZIF-8-GX. ZIF-8 shows a CO₂ uptake of 17.0 cm³ g⁻¹,⁶³ while TiO₂ exhibits nearly no adsorption of CO₂.

To demonstrate that the product actually comes from the photoreduction of CO₂, the control experiments were performed. First, the homemade reactor in the absence of photocatalysts does not respond to light irradiation. Second, TiO₂/ZIF-8-G2 shows no photocatalytic responses in N₂ and H₂O vapours. When CO₂ is used to replace N₂, a remarkable photocatalytic response is observed. Similar experimental findings can also be achieved for TiO₂ and TiO₂/ZIF-8-S2. In addition, the control experiment employing a physical mixture of TiO₂ and ZIF-8 as photocatalysts exhibits lower activity than those of TiO₂/ZIF-8-GX, and its formation rate of CO is 8.21 $\mu\text{mol g}^{-1} \text{h}^{-1}$.

In order to highlight the excellence of our work, the previous covered photocatalysts based on MOF and semiconductors are summarized and listed in Table 1. Naturally, the reported experimental findings are used for comparison with precious experimental results.^{64–70} As shown in Table 1, most of the photocatalysts can only convert CO₂ into CO, and the photocatalytic performance of TiO₂/ZIF-8-G2 is located at a high level compared to other similar photocatalysts. This comparison implies that the structure of TiO₂/ZIF-8-GX is favourable for the photocatalytic reduction of CO₂.

3.3 Optical and electrochemical properties

The UV-Vis diffuse reflectance spectra of ZIF-8, TiO₂ and TiO₂/ZIF-8-GX, as well as TiO₂/ZIF-8-SX have been measured to evaluate their light absorption ability (Fig. 7a and S9[†]). The prepared TiO₂ shows a steep absorption edge situated at about 350 nm. ZIF-8 can only adsorb UV light from 200 nm to 250 nm (Fig. S8[†]). TiO₂/ZIF-8-G1 and TiO₂/ZIF-8-G3 also show steep absorption edges around 350 nm, similar to that of TiO₂. Additionally, for TiO₂/ZIF-8-SX, their adsorption edges are located at about 350 nm, having similar light absorption ability. The spectra clearly reveal that TiO₂/ZIF-8-G2 has a wider absorption band, compared to other photocatalysts, which indicates that it possesses a stronger light absorption capacity. TiO₂/ZIF-8-G2 exhibits an expanded absorption edge at about 400 nm. The band gaps of TiO₂, ZIF-8 and TiO₂/ZIF-8-G1/2/3 are

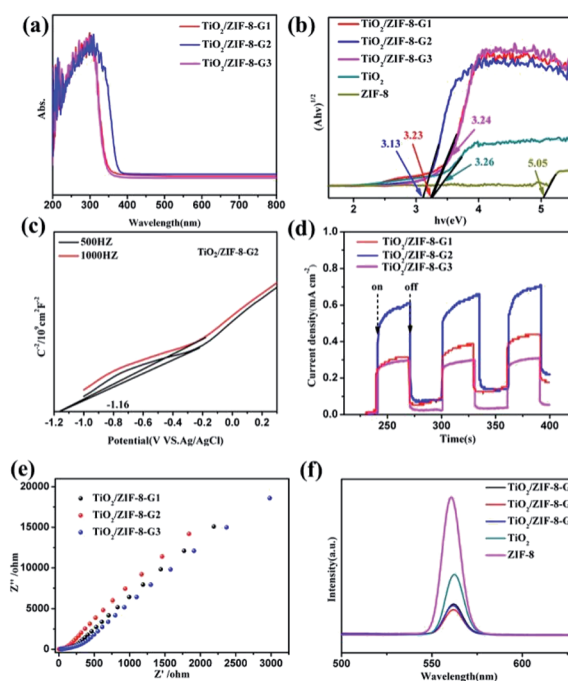


Fig. 7 (a) UV-Vis diffuse reflectance spectra of TiO₂/ZIF-8-GX. (b) Tauc plots of TiO₂/ZIF-8-GX, TiO₂ and ZIF-8. (c) Mott-Schottky plots of TiO₂/ZIF-8-G2. (d) Photocurrents of TiO₂/ZIF-8-GX. (e) Nyquist plots of TiO₂/ZIF-8-GX. (f) Photoluminescence spectra of TiO₂/ZIF-8-GX, TiO₂ and ZIF-8 ($\lambda_{\text{ex}} = 325 \text{ nm}$).



calculated to be 3.26 eV, 5.05 eV, 3.23 eV, 3.13 eV, 3.24 eV by the Kubelka–Munk (KM) method, respectively (Fig. 7b). With the help of the same calculation method, the band gaps of $\text{TiO}_2/\text{ZIF-8-S1}/2/3$ are obtained to be 3.26 eV, 3.25 eV and 3.27 eV, respectively. To reveal their band structures, the Mott–Schottky (MS) measurements of TiO_2 , ZIF-8 and $\text{TiO}_2/\text{ZIF-8-G1}/2/3$, as well as $\text{TiO}_2/\text{ZIF-8-S1}/2/3$, were also carried out (Fig. 7c, S10 and S11†). With the help of the Mott–Schottky equations, the electronic band positions of $\text{TiO}_2/\text{ZIF-8-GX}$ and $\text{TiO}_2/\text{ZIF-8-SX}$ could be found. The conduction band (CB) positions of $\text{TiO}_2/\text{ZIF-8-G1}/2/3$ and $\text{TiO}_2/\text{ZIF-8-S1}/2/3$ were determined to be -1.08 , -1.14 , -1.10 , -1.02 , -1.07 and -1.06 eV (*vs.* Ag/AgCl), respectively. Their valence band (VB) positions were calculated to be 2.13, 1.97, 2.12, 2.24, 2.23 and 2.21 eV, respectively, according to the band gaps coming from the UV-Vis absorption data (Fig. 7b). Naturally, the energy band structures of TiO_2 and ZIF-8 can be established based on this calculation, and is shown in Fig. S10.† Among all photocatalysts, it is clearly shown that the CB position of $\text{TiO}_2/\text{ZIF-8-G2}$ is more negative than the reduction potential of CO_2 converting into CO, which makes it easier to photoreduce CO_2 .

The photocurrent density spectra are able to reflect the separation ability of the photo-induced charges. These data of all composite photocatalysts clearly reveal that the photocurrent density increases in the order of $\text{TiO}_2/\text{ZIF-8-S3} < \text{TiO}_2/\text{ZIF-8-S1} < \text{TiO}_2/\text{ZIF-8-S2} < \text{TiO}_2/\text{ZIF-8-G3} < \text{TiO}_2/\text{ZIF-8-G1} < \text{TiO}_2/\text{ZIF-8-G2}$ (Fig. 7d and S9c†). Obviously, the photocurrent responses of $\text{TiO}_2/\text{ZIF-8-GX}$ are stronger than those of $\text{TiO}_2/\text{ZIF-8-SX}$, which are consistent with their photocatalytic results. Among them, $\text{TiO}_2/\text{ZIF-8-G2}$ possesses the maximum photocurrent density under the irradiation of light, and its high photocurrent response can be ascribed to the lower recombination rate of photogenerated electrons and holes pairs. Besides, the electrochemical impedance spectrum (EIS) is demonstrated to be a promising method for investigating the interfacial charge transfer. As shown in Fig. 7e and S9d,† the EIS plots of $\text{TiO}_2/\text{ZIF-8-G2}$ show the smallest radius among all $\text{TiO}_2/\text{ZIF-8-GX}$ photocatalysts. Smaller resistances result in better conductivity and prefer to transfer the photogenerated electrons. It should be mentioned that the smallest radius of $\text{TiO}_2/\text{ZIF-8-G2}$

corresponds to the result of the photocurrent measurements and CO_2 photoreduction performance.

In addition, the photoluminescence (PL) emission spectra of $\text{TiO}_2/\text{ZIF-8-GX}$, ZIF-8 and TiO_2 were performed to study the ability of the photogenerated charge carrier transfer. As shown in Fig. 7f, the PL emissions of $\text{TiO}_2/\text{ZIF-8-GX}$ were quenched significantly compared to those of ZIF-8 and TiO_2 , revealing the inhibited photoinduced charge recombination existing in $\text{TiO}_2/\text{ZIF-8-GX}$. This is because the defects induced by the low crystallinity of $\text{TiO}_2/\text{ZIF-8-GX}$ offer many charge transfer pathways for photogenerated electrons. Additionally, the ZIF-8 shell makes an important contribution to the transfer of photo-generated electrons due to its more positive conduction band. Both of them hinder the recombination of photoelectrons and holes, resulting in enhanced photocatalytic performances.

4. Possible photocatalytic mechanism

The possible CO_2 photoreduction reaction pathways of $\text{TiO}_2/\text{ZIF-8-GX}$ and the corresponding possible mechanism are proposed to explain the synergistic effects between TiO_2 and ZIF-8 on the photocatalytic reduction of CO_2 (Fig. 8). This is because ZIF-8 possesses a large surface area, and is mainly responsible for CO_2 and H_2O uptake. CO_2 and water molecules first enter the pores of ZIF-8, and can subsequently migrate to the surface of TiO_2 through interconnected channels in the framework. Under the irradiation of light, several common intermediates (*e.g.*, CO_3^{2-})⁴⁹ are generated with the help of the chemisorption between CO_2 and the surface of TiO_2 . TiO_2 serves as the photocatalyst, and produces electrons and holes. Naturally, the photogenerated electrons gather together at the interfaces between TiO_2 and ZIF-8, and then take part in the photoreduction of abundant CO_2 and H_2O inside ZIF-8, promoting the progress of the photocatalytic reaction (Fig. 8). Meanwhile, the adsorbed water forms contacts with the holes in TiO_2 , and then produces protons and OH^\cdot .⁷¹ The appearance of this process is demonstrated by the successful detection of OH^\cdot (Fig. S12†). Finally, the intermediates produce the final product of CO with the help of the generated electrons and protons.

5. Conclusions

In summary, various binary semiconductor/ZIF photocatalysts ($\text{TiO}_2/\text{ZIF-8}$) have been fabricated with the help of the grinding method and the solid synthesis method. The photocatalysts prepared by the grinding method exhibit better photocatalytic performances than those of the photocatalysts fabricated by the solid synthesis method. The experimental finding demonstrates that different synthetic methods result in varied photocatalytic performances, caused by their different structural features. The resulting $\text{TiO}_2/\text{ZIF-8-GX}$ exhibits enhanced photocatalytic reduction efficiencies toward CO_2 compared to pure TiO_2 and ZIF-8, as well as $\text{TiO}_2/\text{ZIF-8-SX}$, and $\text{TiO}_2/\text{ZIF-8-G2}$ exhibits the highest CO formation rate of $21.74 \mu\text{mol g}^{-1} \text{h}^{-1}$. The good performance could be attributed to the enhanced CO_2

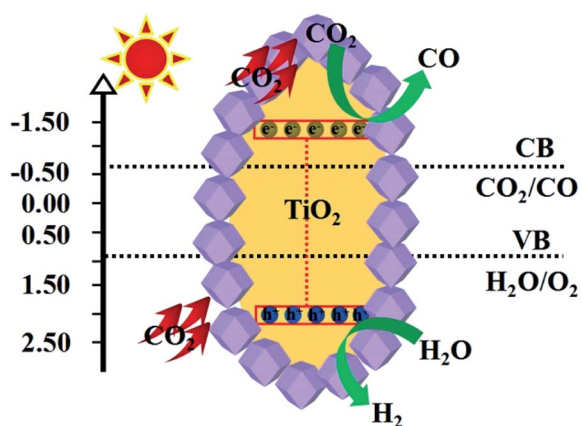


Fig. 8 Possible mechanism of $\text{TiO}_2/\text{ZIF-8-G2}$ for photoreducing CO_2 .



absorption ability and the well-integrated structure, which can expose more active sites and absorb more CO₂. This work may offer some guidance for designing composited photocatalysts with high efficiency.

Conflicts of interest

There are no conflicts to declare.

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