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Tailoring the electronic structure of In₂O₃/C photocatalysts for enhanced CO₂ reduction†

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Photoreduction of CO₂ into value-added fuels under mild conditions is a promising route to relieve the pressure from extensive CO₂ emission and energy consumption, but the rational design of novel photocatalysts for efficient CO₂ reduction remains a big challenge. Herein, a series of transition metal doped In₂O₃/C (M = Fe, Cu, and Zn) photocatalysts are prepared based on a bimetallic metal–organic framework template, where the rearrangement of electron density distribution is facilely achieved via doping metal atoms. Correspondingly, the broadened light-harvesting scope, charge transfer rate, and produced intermediates in photocatalytic CO₂ reduction can be optimized. In particular, Cu–In₂O₃/C exhibits a largely improved CO yield with a high selectivity, which is superior to that of most of the previously reported photocatalysts derived from MOFs. This work thus provides an efficient approach for tailoring the electronic structure of photocatalysts, which shows promising applications in carbon cycling.

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10th Anniversary statement

Ten years of *Journal of Materials Chemistry A* have seen many fascinating topics on materials for energy and sustainability arise, mature and succeed into practical application. This manuscript is dedicated to celebrating the 10th anniversary of the journal. Considering the challenge of exploring efficient catalysts for photocatalytic reduction of CO₂ to valuable chemical feedstocks, we reported a general strategy for synthesizing various transition metal-doped In₂O₃/C nanotube (M–In₂O₃/C, M = Fe, Cu, and Zn) photocatalysts. The experimental results and theoretical simulation demonstrate that transition metals can affect photocatalytic activity and selectivity by modifying the doping state and electronic structure. The light-harvesting scope, charge transfer rate, and adsorption/desorption of intermediates are thus optimized. The present work involves a hot topic of functional materials used for solar-to-chemical energy conversion, which is very close to the theme of *Journal of Materials Chemistry A*.

1 Introduction

The energy crisis and climate change are regarded as two major issues in the foreseeable future.^{1–3} In addition to the traditional technologies to achieve energy conservation and emission reduction, renewable energy and related development strategies are highly desirable.^{4–6} As an efficient way of utilizing carbon dioxide (CO₂) to produce various chemical fuels, solar-driven CO₂ reduction has gained a lot of attention.^{7–10} However, the photocatalytic efficiency remains unsatisfactory because the stubborn C=O double bond in a nonpolar CO₂ molecule requires high energy for activation, leading to sluggish kinetics issues.^{11–13} In light of this, great efforts have been devoted to optimizing the structure of photocatalysts so as to improve the

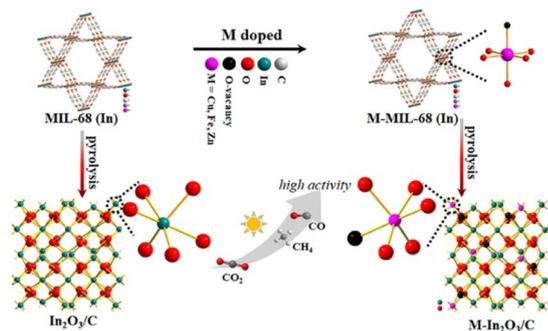
conversion and selectivity of CO₂ reduction.^{14–17} Up to now, a variety of photocatalysts with tailorable band structures have been explored, especially semiconductors (such as TiO₂, Zn₂CeO₄, and C₃N₄).^{18–22} Despite great endeavours, the photocatalytic performance of conventional photocatalysts is still limited by their solar light harvesting ability, unsuitable band gaps, weak CO₂ adsorption capacity, and/or low density of active sites. Thus, it is urgent to rationally design and modify the structure of photocatalysts to achieve efficient CO₂ reduction.^{23–28}

Up to now, various impressive strategies have been proposed and implemented to improve photocatalytic activity. For instance, heterojunction construction, surface modification, doping and vacancy creation, and interface engineering strategies are widely investigated to improve the activity of photocatalysts.^{29–37} Specifically, the doping engineering strategy is capable of adjusting the band gap or electronic structure of photocatalysts. Correspondingly, the light absorption scope, electron–hole separation efficiency, and adsorption of CO₂ and intermediates would be optimized.^{38–40} A recent investigation has reported that transition metal doped photocatalysts can significantly improve photocatalytic activity owing to their

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Scheme 1 Schematic illustration of M-In₂O₃/C (M = Fe, Cu, and Zn) showed enhanced performance for solar light-driven CO₂ reduction, compared with an In₂O₃/C photocatalyst.

special d-band.^{41–45} It is well known that doping of transition metal ions into photocatalysts can introduce electron capture centers, resulting in defect formation and inhibition of electron/hole recombination to enhance catalytic performance. Moreover, transition metal atoms are highly effective as active catalytic species for the conversion of small molecule CO₂. Previous studies have doped various transition metals in semiconductors for accelerating kinetics and profiling catalytic mechanisms in multi-electron CO₂ reduction.^{44,45} However, it remains ambiguous whether any kind of transition metal doping is conducive to photocatalytic CO₂ reduction.

Herein, we intend to demonstrate the effect of transition metal doping on CO₂ reduction performance for semiconductor photocatalysts. As a proof of concept, various transition metal-doped In₂O₃/C photocatalysts are utilized to study the doping effects of metal species on the activity and selectivity of CO₂ photoreduction (Scheme 1). To exclude other interference factors such as morphology structure and surface properties, transition metal-doped metal-organic frameworks (MOFs) were used as templates to fabricate various transition metal-doped In₂O₃/C nanotubes (M-In₂O₃/C, M = Fe, Cu, and Zn). The MOF-derived hollow structure is favorable for harvesting solar light and exposing the surface-active sites. Compared with unmodified In₂O₃, Cu-In₂O₃/C, Fe-In₂O₃/C, and Zn-In₂O₃/C exhibit an expanded photo-response range for light harvesting, and provide a strong driving force for the occurrence of CO₂ activation. In particular, Cu-In₂O₃/C presents a largely improved CO yield (43.7 μmol g⁻¹ h⁻¹) with a high selectivity (78%), which is 11 times higher than that of pristine In₂O₃. The experimental results and theoretical calculation verify that the narrowed band gap generated by Cu doping causes the d-band center upshift, which facilitates the adsorption/activation of CO₂ molecules and charge migration in photocatalysis.

2 Results and discussion

2.1 Synthesis and structural characterization

A series of transition M-In₂O₃/C (M = Fe, Cu, and Zn) photocatalysts were prepared based on a bimetallic MOF template. First, the hexagonal M-MIL-68(In) (M = Fe, Cu, and Zn) were synthesized *via* a solvothermal method.^{46,47} The powder X-ray

diffraction (XRD) analysis shows that the resulting M-MIL-68(In) is in good agreement with the bulk phase of MIL-68(In) without any additional phase.^{48,49} As shown in Fig. 1A and B, the scanning electron microscopy (SEM) images illustrate that the Cu-MIL-68(In) presents a uniform hexagonal prism-shaped morphology, similar to pristine MIL-68(In). The combination of the XRD patterns (Fig. S1†) and SEM (Fig. S2 and S3†) analysis demonstrates that the M-MIL-68(In) maintains the original structure, which is suitable as a template for synthesizing derivatives M-In₂O₃/C. As expected, the M-In₂O₃/C derived from M-MIL-68(In) inherits the skeleton of M-MIL-68(In) after pyrolysis. As shown in Fig. 1D, the SEM image displays the well-defined hexagonal Cu-In₂O₃/C nanotube, which is consistent with In₂O₃/C (Fig. 1C). Besides, the obvious contrast between the dark parts and the relatively bright parts in the transmission electron microscope (TEM) images (Fig. 1E and F) confirms the inherited hollow feature. The high-resolution TEM (HR-TEM) analysis further shows that the shell of In₂O₃/C nanotubes is assembled with small nanocrystals that are firmly interconnected with each other (Fig. S4†), and exhibits porous characteristics. As for the HR-TEM image (Fig. 1F, inset), the lattice fringe with an interlayer distance of 0.289 nm is assigned to the (222) crystal plane of cubic In₂O₃ (Fig. S4B†).⁴⁷ The chemical composition and distribution of the Cu-In₂O₃/C nanotubes were also examined by elemental mappings (Fig. 1G) and energy dispersive X-ray (EDX) spectroscopy. The elemental mappings of a single Cu-In₂O₃/C nanotube show a high distribution of Cu, In, O, and C elements. Similarly, Zn-In₂O₃/C and Fe-In₂O₃/C (Fig. S5–S8†) nanotubes can be feasibly obtained by pyrolysis of the precursor Zn-MIL-68(In) and Fe-MIL-68(In), respectively.

Then, the chemical structure of the obtained photocatalysts was investigated. As shown in Fig. 2A, the XRD diffraction peaks of the Cu-In₂O₃/C, Zn-In₂O₃/C, and Fe-In₂O₃/C derived from M-MIL-68(In) are in good agreement with the cubic phase of In₂O₃ (JCPDS card No. 060416).^{50,51} No other additional phase in XRD is observed, which confirms the high purity of the photocatalysts. As for the M-In₂O₃/C nanotubes, the peaks slightly shift to higher 2θ values relative to In₂O₃/C (Fig. 2A, inset)

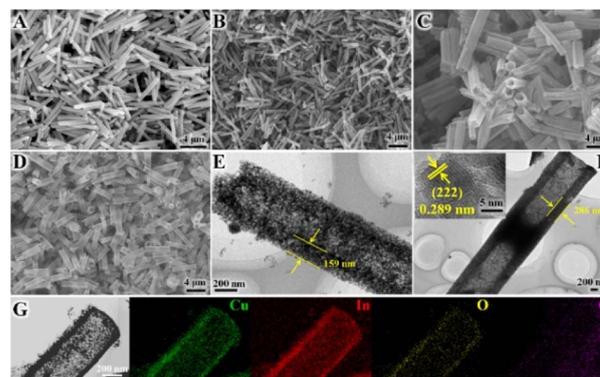


Fig. 1 SEM images of (A) MIL-68(In), (B) Cu-MIL-68(In), (C) In₂O₃/C, and (D) Cu-In₂O₃/C. TEM images of (E) In₂O₃/C, and (F) Cu-In₂O₃/C. (G) TEM and EDX elemental mapping images of Cu-In₂O₃/C.

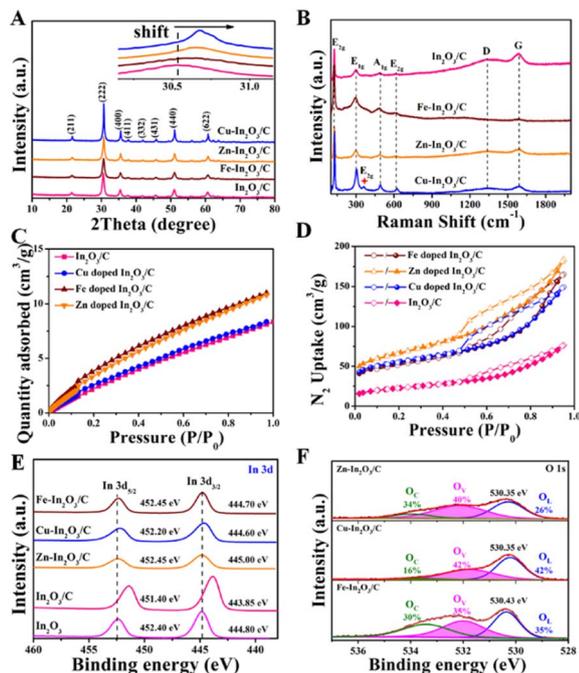


Fig. 2 (A) XRD patterns, (B) Raman spectra, (C) CO₂ adsorption isotherms and (D) N₂ adsorption–desorption isotherms of In₂O₃/C, Cu–In₂O₃/C, Zn–In₂O₃/C, and Fe–In₂O₃/C. (E) High-resolution In 3d XPS spectra of In₂O₃, In₂O₃/C, Cu–In₂O₃/C, Zn–In₂O₃/C, and Fe–In₂O₃/C. (F) High-resolution O 1s XPS spectra of Cu–In₂O₃/C, Zn–In₂O₃/C, and Fe–In₂O₃/C.

because the ionic radii of Fe³⁺ (0.69 Å), Zn²⁺ (0.74 Å), and Cu²⁺ (0.73 Å) are smaller than that of In³⁺ (0.80 Å).^{52–57} The result indicates that metal ions are indeed doped into the In₂O₃ lattice. In addition, the Raman peaks observed at 127, 302, 363, 492, and 621 cm⁻¹ are characteristic peaks of body-centered-cubic (bcc) In₂O₃ (Fig. 2B).⁵⁸ Peak E_{2g} at 363 cm⁻¹ reflects the content of oxygen vacancy (O_v). Under the same pyrolysis treatment, the relative intensity of peak E_{2g} in Cu–In₂O₃/C is higher than those of Fe–In₂O₃/C and Zn–In₂O₃/C. The results illustrate that Cu–In₂O₃/C possesses the highest concentration of surface O_v. Besides, the Raman spectra of M–In₂O₃/C in Fig. 2B show a D band (1340 cm⁻¹) from disordered or defect sp² carbon and a G band (1591 cm⁻¹) from graphitic sp² carbon. Moreover, the low I_D/I_G (the intensity ratio of D to G bands) values manifest a distinct degree of graphitization in M–In₂O₃/C.

After characterization of the morphology and chemical structure of the obtained M–In₂O₃/C, we investigated their porous structure and CO₂ adsorption capacity by gas adsorption/desorption measurements. As shown in Fig. S9,† a type-I isotherm curve is observed for MIL-68 (In), confirming a typical microporous structure for the precursor (Fig. S10†). After pyrolysis of the MIL-68 (In), the N₂ adsorption–desorption measurements show that In₂O₃/C, Cu–In₂O₃/C, Zn–In₂O₃/C, and Fe–In₂O₃/C nanotubes maintain a high Brunauer–Emmet–Teller (BET) surface area (Fig. 2D). The N₂ adsorption–desorption isotherms with a type IV behavior show an H3-type

hysteresis loop, indicating the existence of mesopores in M–In₂O₃/C. The corresponding Barrett–Joyner–Halenda analysis for the In₂O₃/C nanotubes illustrates that the majority of the pores are around 13 nm (Fig. S11†). Moreover, CO₂ adsorption measurements demonstrate the advantages of such porous properties in improving CO₂ adsorption capacity. And In₂O₃/C, Cu–In₂O₃/C, Zn–In₂O₃/C, and Fe–In₂O₃/C nanotubes exhibit a high CO₂ uptake at 25 °C (Fig. 2C), respectively, which is probably inherited from the high CO₂ adsorption properties of MIL-68 (In) (Fig. S12†). The above results thus confirm that M–In₂O₃/C derived from M–MIL-68 (In) retains the MOF skeleton and porous structure, which is conducive to the exposure of surface sites for the adsorption of CO₂.

To further demonstrate the influence of M doping on the electronic structure of M–In₂O₃/C, X-ray photoelectron spectroscopy (XPS) characterization was conducted. The C 1s spectrum of In₂O₃/C is coherently fitted by four peaks centered at 284.8, 285.5, 286.7, and 288.9 eV (Fig. S13†), which are ascribed to C=C, C–C, C–O, and C=O bonds, respectively. High-resolution XPS of In 3d exhibits two prominent bands of In 3d_{3/2} and In 3d_{5/2} at 444.8 and 452.4 eV, respectively (Fig. 2E). After the introduction of carbon, the two In 3d peaks of In₂O₃/C decrease to 443.85 and 451.4 eV, confirming the electronic coupling interaction between In₂O₃ and C. As shown in Fig. S14–S16,† the obtained high-resolution XPS spectra of Cu, Zn and Fe illustrate that the transition metals have been introduced into M–In₂O₃/C. Most importantly, the In 3d_{5/2} and In 3d_{3/2} peaks in the M–In₂O₃/C nanotubes show an obvious positive shift. The results thus confirm that M doping could modify the electronic structure of In₂O₃/C. In addition, the high-resolution XPS spectrum of O 1s (Fig. 2F and S17†) displays a broad asymmetric curve, which is deconvoluted into three contributions including a distinct peak and two shoulder peaks. The distinct peak is attributed to the typical lattice oxygen (O_l). The two shoulder peaks are assigned to O_v and dissociated/chemisorbed oxygen (O_c), respectively. The ratios of O_v for In₂O₃/C, Cu–In₂O₃/C, Zn–In₂O₃/C and Fe–In₂O₃/C are about 26%, 42%, 40% and 35%, respectively. Moreover, the ratio of O_v for Fe–In₂O₃/C is lower than that for Cu–In₂O₃/C. Compared with high valent Fe³⁺/Fe²⁺ in Fe–In₂O₃/C, the low valent Cu²⁺/Cu⁺ in Cu–In₂O₃/C can elongate and weaken the M–O bonds, hence facilitating the generation of more O_v. This comparison thus illustrates that the ratio of the generated O_v is highly dependent on the doped element M.

2.2 Evaluation of photocatalytic CO₂ reduction performance

Encouraged by the above characterization results, the photocatalytic CO₂ reduction performance of M–In₂O₃/C was evaluated. As shown in Fig. 3A and B, the production rates of CO and CH₄ for M–In₂O₃/C are following the sequence Cu–In₂O₃/C (43.7 and 15.9 μmol g⁻¹ h⁻¹) > Zn–In₂O₃/C (32.1 and 11.4 μmol g⁻¹ h⁻¹) > Fe–In₂O₃/C (21.9 and 6.3 μmol g⁻¹ h⁻¹), which are all higher than that of pristine In₂O₃ (3.9 and 1.4 μmol g⁻¹ h⁻¹) and In₂O₃/C (9.1 and 2.4 μmol g⁻¹ h⁻¹). As for the CO and CH₄ production rates, Cu–In₂O₃/C exhibits a ~11-fold and 7-fold higher rate than that of pristine In₂O₃. The comparison

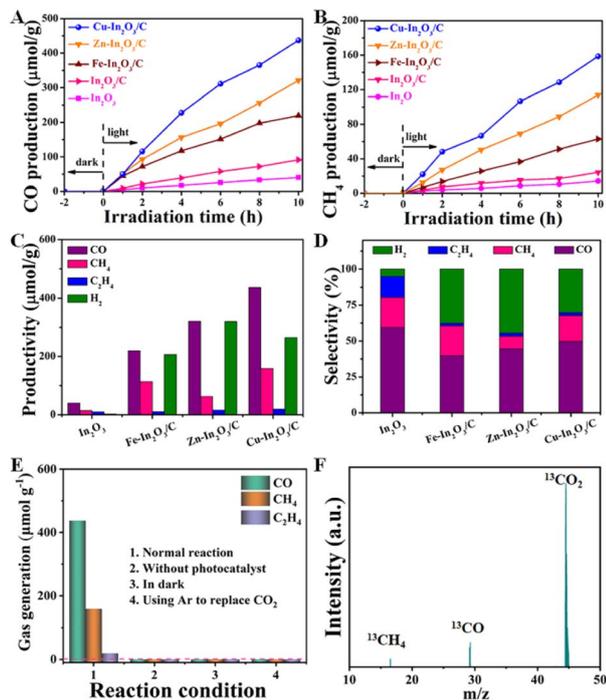


Fig. 3 Time-production plots of (A) CO and of (B) CH₄ over In₂O₃/C, Cu–In₂O₃/C, Zn–In₂O₃/C, and Fe–In₂O₃/C nanotubes. (C) Productivity and (D) selectivity of different products over In₂O₃/C, Cu–In₂O₃/C, Zn–In₂O₃/C, and Fe–In₂O₃/C nanotubes. (E) Photocatalytic CO₂ reduction performance of Cu–In₂O₃/C under different conditions. (F) Result of mass spectra analysis from the ¹³CO₂ isotope-labeling experiment for Cu–In₂O₃/C.

illustrates that Cu doping in the structure of In₂O₃ enables facilitation of the improvement of CO₂ activation. Besides the products of CO and CH₄, other by-products including C₂H₄ and H₂ are also detected (Fig. 3C). The comparison illustrates that CO is the main carbonous product. It should be noted that the selectivity is highly dependent on the doping elements in In₂O₃/C (Fig. 3D). The comparison displays that Cu doping contributes higher selectivity of CO than Fe or Zn doping. The obtained Cu–In₂O₃/C exhibits a high selectivity of 78% for CO₂ reduction towards CO relative to the main carbon product (CO, C₂H₄, and CH₄). In addition, the obtained Cu–In₂O₃/C and In₂O₃/C exhibit a CO selectivity of ~50% and ~59%, respectively. Of note, the CO yield of Cu–In₂O₃/C is ~4.8 times higher than that of pristine In₂O₃/C. Compared with the high catalytic efficiency, the difference in catalytic selectivity between Cu–In₂O₃/C and In₂O₃/C is not more obvious. Of note, the apparent quantum efficiency (AQE) of Cu–In₂O₃/C, Zn–In₂O₃/C, and Fe–In₂O₃/C for CO production is about $2 \times 10^{-3}\%$, $1 \times 10^{-3}\%$ and $1 \times 10^{-3}\%$ at 380 nm, respectively. The photocatalytic results thus confirm that In₂O₃ doped with transition metals can enhance the photocatalytic performance for CO₂ reduction by regulating the internal electronic structure. Most importantly, the activation of CO₂ is highly dependent on the doped metal. And, Cu is confirmed as an optimized candidate doped into In₂O₃ because of the best photocatalytic CO₂ reduction performance (Fig. 3A and B). Compared with previously reported MOF derivative-

based photocatalysts, Cu–In₂O₃/C displays higher efficiency in photocatalytic CO₂ reduction (Table S1†).

In addition, a series of control experiments were conducted to investigate the source of CO and CH₄ over Cu–In₂O₃/C (Fig. 3E). There is no detectable product when the photocatalytic CO₂ reduction reaction is carried out in an Ar atmosphere, under dark conditions, or without catalysts (Fig. 3E). To further verify the origin of the as-produced CH₄ and CO, isotopic ¹³CO₂ is used as a reactant for CO₂ photoreduction. The obtained products were examined by using the mass spectrum (Fig. 3F). The corresponding signal at *m/z* = 29 and 17 can be ascribed to ¹³CO and ¹³CH₄, respectively, which confirms that the products CH₄ and CO originate from the photocatalytic reduction of CO₂. In addition, the cycling experiment (Fig. S18†) and the corresponding SEM image (Fig. S19†) after 30 h for the CO₂ reduction reaction were recorded. The results show that the morphology and photoactivity of Cu–In₂O₃/C do not change significantly, hence exhibiting high photocatalytic stability.

2.3 Investigation of photocatalytic properties

To illustrate the effect of M doping on enhancement of photocatalytic CO₂ reduction, the photocatalytic properties of M–In₂O₃/C photocatalysts are investigated. The optical absorption of the as-obtained M–In₂O₃/C nanotubes was measured by UV-vis diffuse reflectance spectroscopy (UV-DRS). It is observed that all samples M–In₂O₃/C have strong absorption in the UV-vis range (Fig. 4A). Compared with the M-MIL-68 (In) (200 nm–

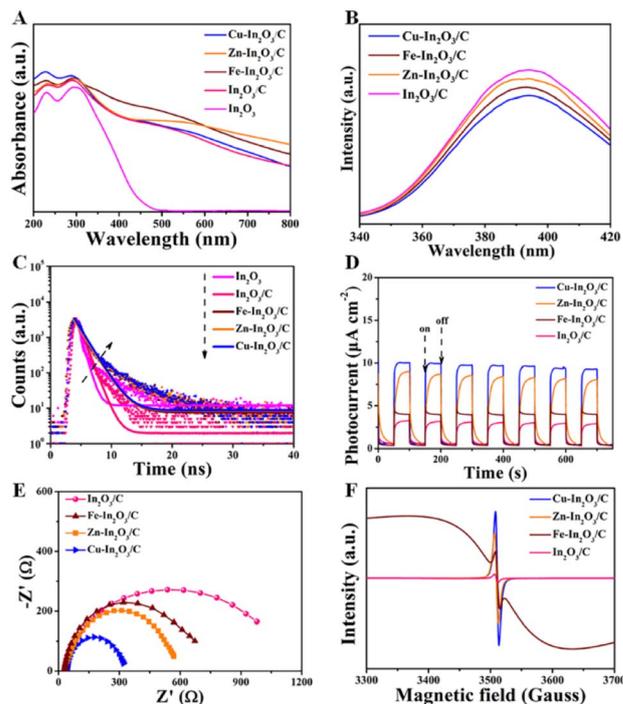


Fig. 4 (A) UV-DRS of In₂O₃, In₂O₃/C, Cu–In₂O₃/C, Zn–In₂O₃/C, and Fe–In₂O₃/C nanotubes. (B) Steady-state PL spectra, (C) time-resolved PL decay spectra, (D) transient photocurrent responses, (E) EIS Nyquist plots, and (F) EPR spectra of In₂O₃/C, Cu–In₂O₃/C, Zn–In₂O₃/C, and Fe–In₂O₃/C nanotubes.

320 nm) and M-In₂O₃ (200 nm–500 nm) (Fig. S20 and S21†), M-In₂O₃/C presents a broad light absorption region towards visible light due to the existence of abundant O_v and graphitic carbon. According to the obtained spectra, the band gap (E_g) is calculated by using the Kubelka–Munk theorem. Compared with the E_g of In₂O₃ (3.2 eV), narrow E_g values of Cu-In₂O₃ (3.0 eV), Fe-In₂O₃ (3.1 eV), and Zn-In₂O₃ (3.1 eV) are observed (Fig. S22–S25†). Based on the Mott–Schottky analysis (Fig. S26–S29†), the E_{CB} values of In₂O₃/C, Cu-In₂O₃/C, Zn-In₂O₃/C and Fe-In₂O₃/C are calculated to be -0.75 , -0.66 , -0.70 and -0.69 eV vs. the normal hydrogen electrode (NHE), respectively. According to the formula: $E_{VB} = E_{CB} + E_g$, the E_{VB} of In₂O₃/C, Cu-In₂O₃/C, Zn-In₂O₃/C and Fe-In₂O₃/C is calculated to be 2.55, 2.44, 2.40 and 2.31 eV vs. NHE (Fig. S30†), respectively. The reason is that M doping and O_v in M-In₂O₃/C are capable of modifying the electronic structure, resulting in a reduced E_g . It should be noted that Cu doping largely narrows the E_g from 3.2 to 3.0 eV. The result thus indicates that doping of transition metals can tailor the band structure, hence promoting solar light harvesting and electron–hole separation capability of the photocatalysts. Besides, it is proved that M doping can affect the lifetime of charge migration for various M-In₂O₃/C. As shown in Fig. 4B, a weaker photoluminescence (PL) emission of Cu-In₂O₃/C than that of In₂O₃/C or In₂O₃ is observed. Meanwhile, Cu-In₂O₃/C has longer average decay times (~ 1.5 ns), compared with In₂O₃/C (~ 0.6 ns) or In₂O₃ (~ 0.5 ns) (Fig. 4C). The result illustrates that doping of M acts as a trapping site for photo-generated electrons, which can increase the lifetime of charge carriers.

To evaluate the charge transfer efficiency, the photocurrent density of In₂O₃/C and various M-In₂O₃/C nanotubes was measured under light and in the dark with 50 s intervals. As shown in Fig. 4D, the sequence of average photocurrent densities follows the order Cu-In₂O₃/C > Zn-In₂O₃/C > Fe-In₂O₃/C > In₂O₃/C. Meanwhile, the recorded electrochemical impedance spectrum (EIS) of Cu-In₂O₃/C shows a smaller semicircle in the Nyquist plot than those of In₂O₃/C, Zn-In₂O₃/C, and Fe-In₂O₃/C (Fig. 4E). These results thus confirm a higher separation efficiency of photogenerated electron–hole pairs and that a faster interfacial charge transfer rate occurred on Cu-In₂O₃/C. In addition, the electron paramagnetic resonance (EPR) spectra normally used for detecting unpaired electrons was obtained for In₂O₃/C and various M-In₂O₃/C nanotubes. According to previously reported work,³³ the symmetry EPR signals at $g = 2.003$ are ascribed to the unpaired electrons trapped on the surface O_v. As shown in Fig. 4F, the EPR signals are significantly increased after M-doping, demonstrating an increased O_v concentration. Owing to the existence of abundant O_v for Cu-In₂O₃/C, more electrons can be captured at the surface, which can effectively modify the surface electronic state for accelerating charge transfer. Besides, the broadness of the EPR resonance signal for Fe-In₂O₃/C is generated by the random orientation of the ferromagnetic Fe, which scatters in the directions of the anisotropic field. As a result, the shape of the EPR curve would change. The above results therefore illustrate that the photocatalytic properties including light harvesting capacity, electro-hole separation efficiency and the surface

charge transfer rate of Cu-In₂O₃/C are obviously higher than those of other M-In₂O₃/C and In₂O₃/C.

Then, we performed *in situ* diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) measurements to monitor the reaction intermediates in the CO₂ reduction process. DRIFTS of the Cu-In₂O₃/C photocatalyst collected without CO₂ in the dark is selected as the background (Fig. 5). After adsorbing CO₂ gas and H₂O vapor for 25 minutes, monodentate carbonate (m-CO₃²⁻, located at 1537, 1518, 1469, 1178, and 1154 cm⁻¹), bidentate carbonate (b-CO₃²⁻, located at 1502 and 1355 cm⁻¹) and bicarbonate (HCO³⁻, located at 1452 cm⁻¹) are visible. According to previous reports, *HCOO and COO⁻ species, and *COH₃ and CH₃O⁻ groups are intermediate species in CO and CH₄ generation, respectively. It is most interesting that, the peak intensity of intermediate species increases along with the light irradiation time. It suggests that CO₂ is continuously adsorbed and converted into carbon-active species. In the comparison, the intensity of peaks for intermediates on In₂O₃/C (Fig. S31†) is lower than that of Cu-In₂O₃/C. Most importantly, a new infrared peak at 1651 cm⁻¹ in the Cu-In₂O₃/C system appears and it gradually increases with extension of the irradiation time. The peak is ascribed to COOH*, which is generally regarded as the crucial intermediate during CO₂ reduction to CO.^{9,37} In addition, a remarkable signal at 2077 cm⁻¹ ascribed to the CO* absorption band is also detected (Fig. S32†). The intensity gradually increases with extension of the irradiation time, hence accounting for the high CO selectivity of the Cu-In₂O₃/C photocatalyst.

2.4 Investigation of the theoretical mechanism

Density functional theory (DFT) calculations were carried out to elucidate the electronic structure and disclose the catalytic mechanism in the multi-electron CO₂ reduction reaction for Cu-In₂O₃ and In₂O₃. As shown in Fig. 6A and B, the calculated partial density of states (PDOS) curves indicate that both Cu-In₂O₃ and In₂O₃ exhibit typical semiconductor features. As for pure In₂O₃, the E_g is calculated to be ~ 3.1 eV. After introducing

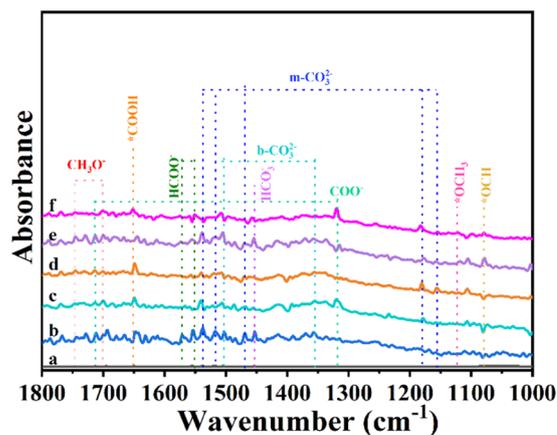


Fig. 5 *In situ* DRIFT spectra of Cu-In₂O₃/C (a) in the dark, and under visible light irradiation for (b) 5, (c) 10, (d) 15, (e) 20, and (f) 25 min in the photocatalytic CO₂ reduction process.

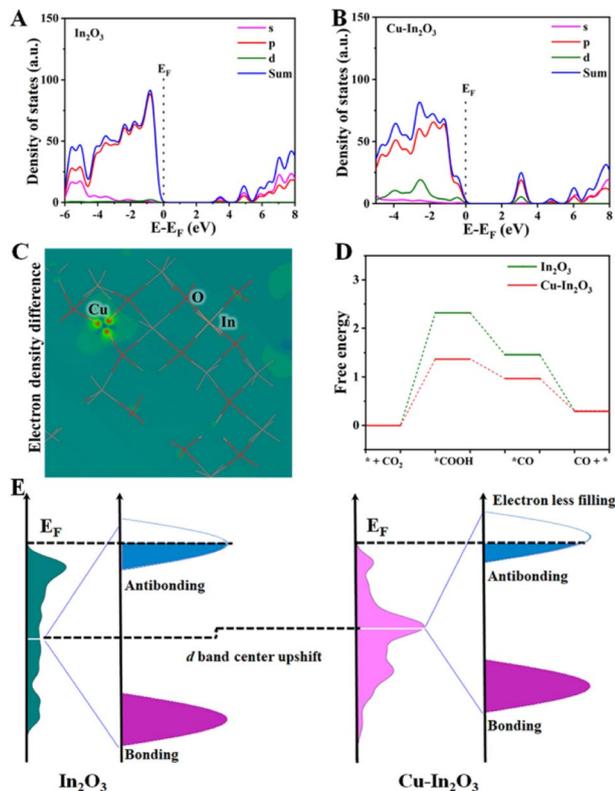


Fig. 6 PDOS curves of (A) In_2O_3 and (B) $\text{Cu-In}_2\text{O}_3$. (C) Model of electronic density difference for $\text{Cu-In}_2\text{O}_3$. (D) Calculated free energy for the photocatalytic CO_2 reduction reaction over $\text{Cu-In}_2\text{O}_3$ and In_2O_3 . (E) d-band center of $\text{Cu-In}_2\text{O}_3$ and In_2O_3 indicated by the white line (upshifted d-band center of $\text{Cu-In}_2\text{O}_3$ compared to that of In_2O_3).

Cu atoms into In_2O_3 , the E_g is narrowed, which is consistent with the experimental result of the UV-vis spectrum (Fig. S23[†]). The result illustrates that doping Cu into In_2O_3 is favorable for enhancing electrical conductivity and facilitating electron-hole separation, which is in good agreement with the photocurrent responsive test and EIS results (Fig. 4D and E). To gain atomic-level insight into the Cu doping effect, the electronic density difference of $\text{Cu-In}_2\text{O}_3$ was calculated. The result shows the obvious charge density difference on Cu sites (Fig. 6C). The reason is that Cu sites can modify the local electronic environment of In and O sites, thereby adjusting the band structure and improving photocatalytic activity of $\text{Cu-In}_2\text{O}_3$.

The thermodynamic mechanisms for photocatalytic CO_2 reduction towards the main product CO are then compared. The corresponding Gibbs free energy change (ΔG) for possible reduction pathways of $\text{CO}_2 \rightarrow * \text{COOH} \rightarrow * \text{CO} \rightarrow \text{CO}$ (* is the reaction site) is shown in Fig. 6D. For both $\text{Cu-In}_2\text{O}_3$ and In_2O_3 , the rate-determining step is the hydrogenation of CO_2 . Compared with In_2O_3 ($\Delta G = 2.3$ eV), CO_2 hydrogenation to $* \text{COOH}$ requires 1.4 eV over $\text{Cu-In}_2\text{O}_3$. In addition, the formation of $* \text{CO}$ is also easier for the $\text{Cu-In}_2\text{O}_3$ system compared with the In_2O_3 system. The results indicate that Cu doping enables tailoring the electronic structure of In_2O_3 . As a result, faster kinetics of $\text{Cu-In}_2\text{O}_3$ is achieved for efficiently driving CO_2 reduction, which is consistent with the photocatalytic

evaluation results (Fig. 3A and B). In addition, the d-band structure affected by Cu sites is further analyzed (Fig. 6E) to demonstrate the improved photocatalytic CO_2 reduction performance. After doping Cu, $\text{Cu-In}_2\text{O}_3$ exhibits an upward shift compared to In_2O_3 . Normally the occupancy of anti-bonding states is highly deepened on the d-band position to the Fermi level (E_F).^{59–61} Based on the d-band center theory, the upward shift of $\text{Cu-In}_2\text{O}_3$ would exhibit a strong binding strength of electrons on CO_2 . Correspondingly, $\text{Cu-In}_2\text{O}_3$ displays less filling and decreased occupation of anti-bonding states, which is favorable for adsorption/activation of CO_2 . Therefore, the above theoretical calculations combined with experiment results illustrates that Cu doping into In_2O_3 can feasibly optimize the electronic structure, thereby contributing to largely improved photocatalytic performance.

3 Conclusions

In summary, a feasible bimetallic MOF template is developed for the synthesis of a series of transition metal-doped $\text{In}_2\text{O}_3/\text{C}$ photocatalysts. The electronic structure can be adjusted by selecting a suitable doping transition metal, which is an effective way to optimize the photocatalytic properties, such as accelerating charge transfer rates, exposing active sites, and enhancing solar light absorption. In the comparison, the resultant $\text{Cu-In}_2\text{O}_3/\text{C}$ exhibits largely improved photocatalytic performance for CO_2 reduction. The experiment results and theoretical calculation verify that the narrow E_g generated by the Cu doping effect is favorable for adsorption/desorption of CO_2 and charge transfer, thereby contributing to efficient CO_2 conversion towards CO. This present work therefore offers a new perspective for modulating the structure of doped photocatalysts by the MOF template strategy, which shows promising applications in solar-to-chemical energy conversion.

Author contributions

A. Zhou performed the experiments and data analysis, and wrote the manuscript. Y. Dou performed the theoretical calculations, and gave specific guidance and revision in the experimental and manuscript preparation stages. J. Zhou and C. Zhao synthesized and characterized the photocatalysts, and tested the photocatalytic performance. J.-R. Li and M. Wei directed and edited the manuscript. All authors read, revised, and approved the submission of the final manuscript.

Conflicts of interest

The authors declare no competing financial interest.

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