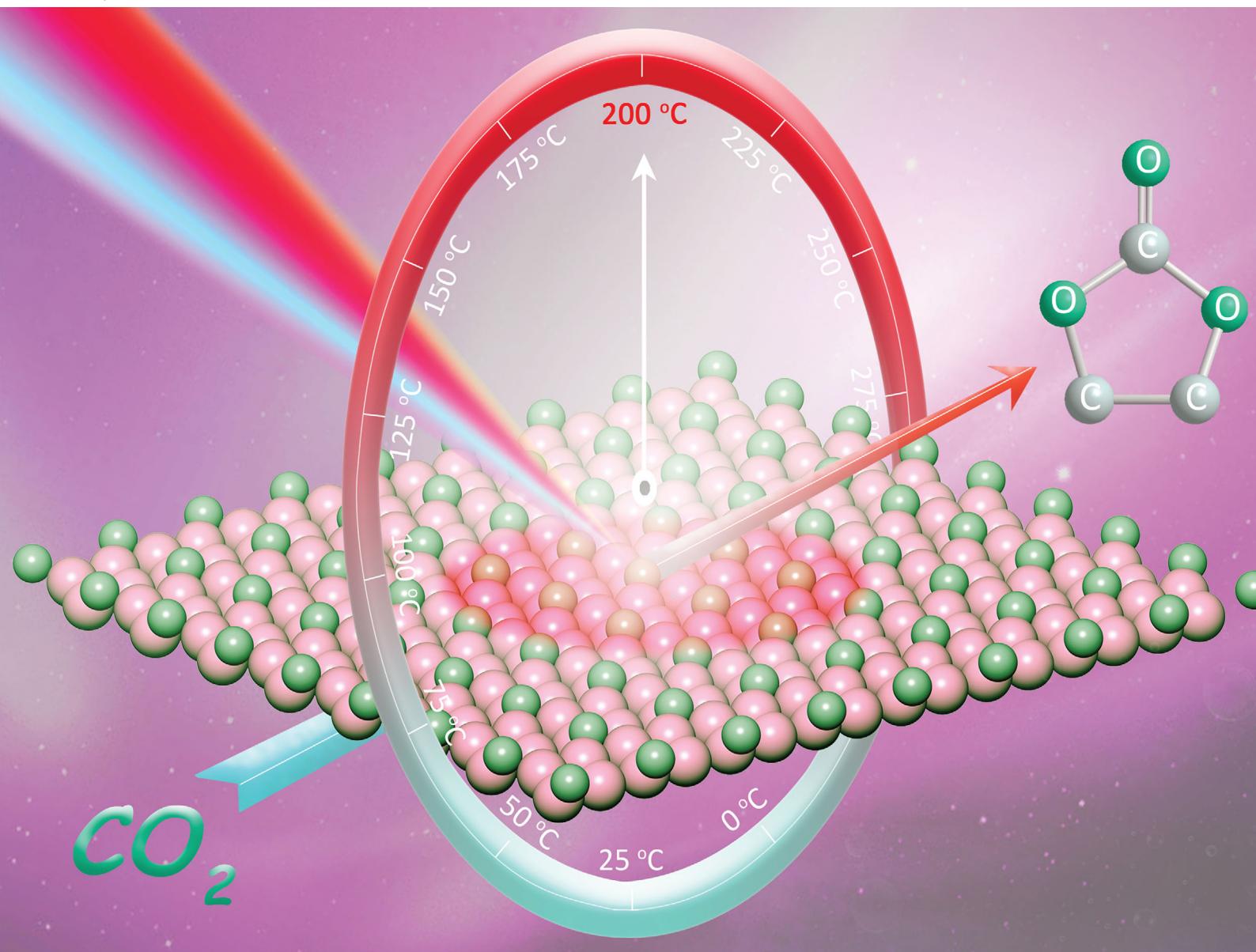


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**Catalytic conversion of carbon dioxide ( $\text{CO}_2$ ) to value-added chemicals under mild conditions is highly desired, albeit with significant challenges. Here, in terms of exposure of abundant active sites and excellent photo-to-thermal conversion properties, flower-like  $\text{Co}_2\text{C}$  has been firstly used for effectively catalysing the cycloaddition of  $\text{CO}_2$  with epoxides to produce cyclic carbonates with yields of up to 95% under solar light. Density functional theory (DFT) calculations reveal that Lewis acid sites of the surface Co atoms can activate both  $\text{CO}_2$  and epoxide, thus opening up the possibility of a  $\text{CO}_2$ -epoxide cycloaddition reaction.**

The increasing atmospheric concentration of carbon dioxide ( $\text{CO}_2$ ), which is regarded as the main greenhouse gas, has caused serious environmental concerns (e.g., global warming, abnormal climate change and sea level rise).<sup>1–4</sup> To address the anthropogenic  $\text{CO}_2$  emission issues,<sup>5–11</sup> the approaches of physical  $\text{CO}_2$  capture and storage,<sup>12,13</sup> and chemical conversion of  $\text{CO}_2$  into usable fuels and/or value-added chemicals<sup>14,15</sup> have been widely investigated. From a chemical point of view, cycloaddition of  $\text{CO}_2$  with epoxides represents one of the most promising strategies to generate valuable chemicals.<sup>16–18</sup> By using  $\text{CO}_2$  as the renewable and nontoxic one-carbon ( $\text{C}_1$ ) feedstock,<sup>19</sup> cyclic carbonates are produced with 100% atom-economy efficiency.<sup>20</sup> Cyclic carbonates can be directly employed in industry as solvents or intermediates, such as carbamates,<sup>21</sup> polycarbonates<sup>22</sup> and spiro compounds.<sup>23</sup> Numerous advances in homogeneous (e.g.,  $\text{Co}$ ,<sup>24,25</sup>  $\text{Ni}$ ,<sup>26</sup>  $\text{Al}$ <sup>27</sup> and  $\text{Cu}$ -based<sup>28</sup> monometallic or bimetallic complexes) and heterogeneous (e.g., metal-organic-frameworks (MOFs),<sup>29–31</sup> mesoporous

polymers,<sup>32</sup> and zeolites<sup>33</sup>) catalysts have been made for the cycloaddition of  $\text{CO}_2$  with epoxides. However, most of the state-of-the-art catalysts can work fairly well to yield cyclic carbonates only at an elevated temperature, thus leading to an increase of the energy cost.

Transition-metal carbides (TMCs) show great potential in the field of catalysis owing to their outstanding electronic conductivity, good chemical stability, abundant surface active sites and high photo-to-thermal conversion efficiency.<sup>34–36</sup> Cobalt carbide ( $\text{Co}_2\text{C}$ ), for example, has been demonstrated to be an effective catalyst in various transformations (e.g., hydrogen evolution and Fischer-Tropsch synthesis).<sup>37,38</sup> However, the application of cobalt carbide in cycloaddition of  $\text{CO}_2$  with epoxides is still elusive. Considering these attributes, we are inspired to explore  $\text{Co}_2\text{C}$  as a novel catalyst for cycloaddition of  $\text{CO}_2$  with epoxides by using solar energy to replace external thermal energy input for following reasons: (i) the high specific surface area and tuneable chemical composition provide abundant surface active sites to activate  $\text{CO}_2$  and/or epoxides; (ii) the effective  $\text{CO}_2$  adsorption ability on TMCs favours the very first step of  $\text{CO}_2$  conversion;<sup>39</sup> (iii) the huge amount of heat released during the excellent photo-to-thermal conversion process would promote the endothermic reaction (high  $\text{C}=\text{O}$  bond energy of  $750\text{ kJ mol}^{-1}$ );<sup>40</sup> and (iv) the feasible separation and reusability of the heterogeneous catalysts is beneficial for large-scale applications.<sup>41</sup> To our delight, flower-like  $\text{Co}_2\text{C}$  facilitates the catalysis of  $\text{CO}_2$ -epoxide cycloaddition with yields of up to  $\sim 95\%$  under visible light (Scheme 1), showing the first example of using TMCs for photothermal-driven  $\text{CO}_2$  conversion.

Flower-like  $\text{Co}_2\text{C}$  was synthesized through a modified method of solution pyrolysis at high temperature (Fig. 1a),<sup>42–44</sup> see experimental details in the ESI.† Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) clearly showed the flower-like morphology of the synthesized material (Fig. 1b and c). The average diameter of the nanoflowers was determined to be  $\sim 500\text{ nm}$  by TEM characterization (Fig. 1c). The nearly apparent nanosheet on the outside of the nanoflowers indicated that the obtained nanoflower was a result of self-assembly of

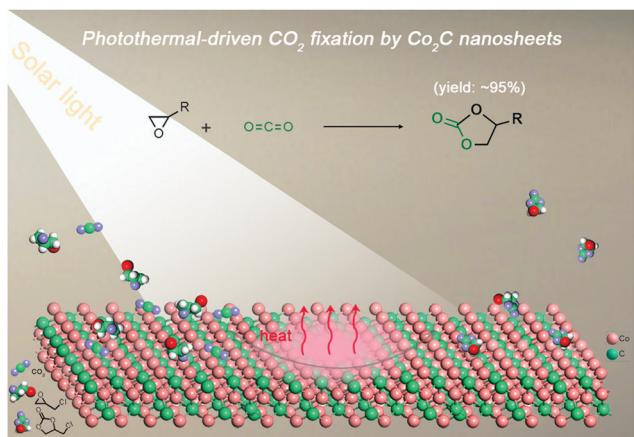
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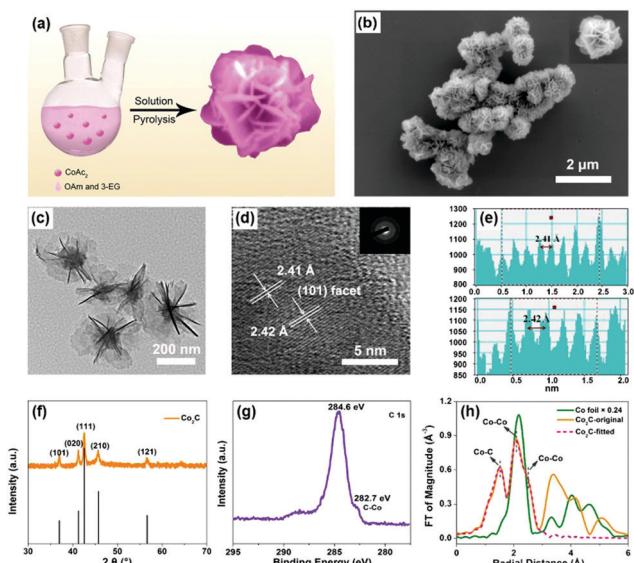
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**Scheme 1** Illustration of the photothermal-driven cycloaddition of  $\text{CO}_2$  with epoxides catalyzed by  $\text{Co}_2\text{C}$  nanosheets of the nanoflower.



**Fig. 1** (a) Synthetic process of flower-like  $\text{Co}_2\text{C}$ . (b) SEM image (the inset panel is the high-resolution SEM image) and (c) TEM image of  $\text{Co}_2\text{C}$  nanoflowers. (d) High-resolution TEM image of  $\text{Co}_2\text{C}$  (the inset panel is the corresponding SAED pattern). (e) The corresponding lattice distances of the exposed (101) plane of  $\text{Co}_2\text{C}$ . (f) XRD pattern and (g) C 1s XPS spectrum of  $\text{Co}_2\text{C}$  nanoflowers. (h) Magnitude of  $k^2$ -weighted Fourier transform of the Co K-edge EXAFS spectra of Co foil and the obtained  $\text{Co}_2\text{C}$  nanoflowers with corresponding curve-fitting results.

individual nanosheets. The thickness of individual nanosheet was determined to be  $\sim 2.4$  nm by atomic force microscopy (AFM) (Fig. S1, ESI<sup>†</sup>). In the high-resolution TEM image, a lattice distance of  $\sim 2.41$  Å was observed, indicating the exposure of the (101) facet of  $\text{Co}_2\text{C}$  (Fig. 1d and e). Moreover, selective area electron diffraction (SAED) patterns in Fig. 1d confirmed the polycrystalline nature of the synthesized materials. In addition, elemental mapping analysis indicated the coexistence of Co, C and O elements (Fig. S2, ESI<sup>†</sup>), which matched well with the X-ray photoelectron spectroscopy (XPS) results (see below).

The powder X-ray diffraction (XRD) (Fig. 1f) pattern of the as-prepared sample was in good agreement with the standard pattern of  $\text{Co}_2\text{C}$  (Joint Committee on Powder Diffraction Standards (JCPDS) Powder Diffraction File (PDF) No. 65-1457),<sup>42</sup> indicating the successful formation of  $\text{Co}_2\text{C}$ . The peaks at 1630, 1420 and 1050  $\text{cm}^{-1}$  corresponding to C=C, C-H, and C-N bonds, respectively, in the Fourier transform infrared (FTIR) spectra (Fig. S3, ESI<sup>†</sup>) almost disappeared after calcination, suggesting the removal of surface organic ligands. Full XPS survey confirmed the coexistence of Co, C and O elements in the obtained sample (Fig. S4, ESI<sup>†</sup>). High-resolution XPS spectra of C 1s (Fig. 1g) and Co 2p (Fig. S5, ESI<sup>†</sup>) show the characteristic peaks of carbide and carbidic Co at 282.7 and 778.1 eV,<sup>36,45,46</sup> respectively. Combined with the peak at 531.6 eV in the O 1s XPS spectrum (Fig. S6, ESI<sup>†</sup>), the peak at 781.0 eV in the Co 2p XPS spectrum was attributed to the  $\text{Co}(\text{OH})_2$  species formed in the process of  $\text{Co}_2\text{C}$  preparation, proving the fact that solution pyrolysis under high temperature inevitably leads to the formation of trace amounts of the hydroxide impurity.<sup>46,47</sup> Fig. 1h shows the X-ray absorption spectra (XAS) of the obtained sample. The Co K-edge extended X-ray absorption fine structure (EXAFS) of the synthesized sample exhibits two peaks in the *R*-space, which could be assigned to the first Co–C shell (1.89 Å) and the second Co–Co shell (2.54 Å) of  $\text{Co}_2\text{C}$ , see the fitting details in Table S1, ESI<sup>†</sup>.

Then, photo-to-thermal conversion effects of  $\text{Co}_2\text{C}$  nanoflowers were experimentally examined. UV-vis-NIR diffuse reflectance spectroscopy (DRS) measurement indicated that the synthesized  $\text{Co}_2\text{C}$  nanoflowers showed strong absorption in the range of 300 to 1200 nm (Fig. S7, ESI<sup>†</sup>), directly confirming its excellent light-harvesting properties. When the water suspension of  $\text{Co}_2\text{C}$  nanoflowers ( $0.6 \text{ mg mL}^{-1}$ ) was exposed to a 635 nm laser at varied power densities ( $0.1, 0.5, 1.0$  and  $2.0 \text{ W cm}^{-2}$ ), the solution displayed apparent temperature elevation (Fig. 2a). For instance, under 635 nm laser irradiation ( $0.5 \text{ W cm}^{-2}$ ), the temperature of the  $\text{Co}_2\text{C}$  nanoflowers water suspension reached  $42.8^\circ\text{C}$  in 13 minutes, while the temperature of pure water only increased to  $24^\circ\text{C}$  under the same conditions (Fig. S8, ESI<sup>†</sup>). Huge amount of heat released from  $\text{Co}_2\text{C}$  nanoflowers was also monitored by an IR camera in the solid state. As shown in the inset panel of Fig. 2b, the local temperature of the powder  $\text{Co}_2\text{C}$  sample quickly increased to  $116.8^\circ\text{C}$  upon exposure to a 635 nm laser ( $0.5 \text{ W cm}^{-2}$ ) for 4.0 min, further confirming the *in situ* conversion of solar light into heat.

On the basis of the time constant for heat transfer and the maximal steady-state temperature, photo-to-thermal conversion efficiency ( $\eta$ ), regarded as a major parameter in evaluating the performance in converting light to heat of a given material,<sup>48</sup> of the flower-like  $\text{Co}_2\text{C}$  was calculated to be as high as  $\sim 63.1\%$  at 635 nm (Fig. 2b and c, see details in the ESI<sup>†</sup>). The exceptional photo-to-thermal conversion performance of  $\text{Co}_2\text{C}$  nanoflowers obtained here was comparable with those of the reported materials (Table S2, ESI<sup>†</sup>). To further evaluate its photothermal stability, temperature variations of  $\text{Co}_2\text{C}$  nanoflowers suspension were recorded under light irradiation (laser on) followed by natural cooling to room temperature (laser off). As shown in Fig. 2d,

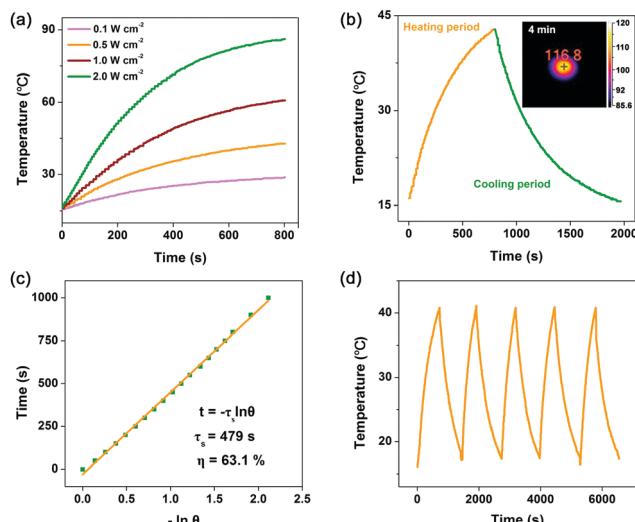


Fig. 2 (a) Photothermal heating curves of  $\text{Co}_2\text{C}$  nanoflowers dispersed in water under  $635\text{ nm}$  laser irradiation at varied power densities ( $0.1, 0.5, 1.0$  and  $2.0\text{ W cm}^{-2}$ ). (b) Photothermal effect of  $\text{Co}_2\text{C}$  aqueous dispersion under  $635\text{ nm}$  laser irradiation ( $0.5\text{ W cm}^{-2}$ ) and the cooling process after laser off. The inset panel in (b) is the IR image of  $\text{Co}_2\text{C}$  powder under  $635\text{ nm}$  laser irradiation ( $0.5\text{ W cm}^{-2}$ ) for  $4.0\text{ min}$ . (c) The corresponding time constant ( $\tau_s$ ) for the heat transfer from the system determined by applying the linear time data from cooling period. (d) Recycling-heating curves of the  $\text{Co}_2\text{C}$  aqueous suspension with  $635\text{ nm}$  laser irradiation at  $0.5\text{ W cm}^{-2}$  for five laser on/off cycles.

negligible changes in temperature elevation were observed during 5 cycles, which highlighted the potential application of  $\text{Co}_2\text{C}$  nanoflowers as durable photothermal materials.

To investigate the catalytic performance of  $\text{Co}_2\text{C}$  nanoflowers, 3-chloropropylene oxide was chosen as the model substrate under visible light (Table 1). A water/fan-cooling system was employed to maintain the outside temperature of the reactor at room temperature, see experimental details in the ESI.† Increase of  $\text{Co}_2\text{C}$  nanoflowers from 0 to 25 mg obviously improved the yields up to  $\sim 93.5\%$  (entries 1–4; Table 1). Control experiments showed that all components were essential for the conversion. Trace or negligible amount of the product was detected without light, tetrabutylammonium bromide (TBAB) or  $\text{CO}_2$  (entries 5–7; Table 1). When tetrabutylammonium chloride (TBAC) was employed as the co-catalyst, a significantly declined yield of  $\sim 27\%$  was observed (entry 8; Table 1). This result showed that easier dissociation and stronger nucleophilicity of  $\text{Br}^-$  compared to  $\text{Cl}^-$  dramatically benefited the ring-opening reaction of epoxides.<sup>29</sup> To verify the photothermal effects of  $\text{Co}_2\text{C}$  nanoflowers, we monitored the temperature variation of the reaction solution by using a thermometer. Upon light irradiation, the temperature of the solution was significantly elevated to  $\sim 60\text{ }^\circ\text{C}$  in a period of 35 min (Fig. S9, ESI†), indicating the conversion of light into heat. Moreover, very similar yields were observed under either visible-light irradiation or external heating ( $60\text{ }^\circ\text{C}$ ), implying that the photothermal effects could promote the cycloaddition reaction between  $\text{CO}_2$  and epoxide (Fig. S10, ESI†).

Furthermore, the obtained  $\text{Co}_2\text{C}$  sample was treated with hydrochloric acid ( $\text{HCl}$ ;  $6\text{ mol L}^{-1}$ ) to exclude the contribution

Table 1 Optimization of the reaction conditions<sup>a</sup>

Entry	Catalyst	Additive	Yield <sup>b</sup> (%)	Cl	$\text{O}$	$+$	$\text{CO}_2$	$\xrightarrow[\text{Visible light}]{\text{Catalyst}}$	Cl	$\text{O}$
				$\text{O}$	$\text{O}$	$\text{O}$	$\text{O}$		$\text{O}$	$\text{O}$
1	$\text{Co}_2\text{C}$ (0 mg)	TBAB	< 5							
2	$\text{Co}_2\text{C}$ (15 mg) <sup>c</sup>	TBAB	54							
3	$\text{Co}_2\text{C}$ (15 mg)	TBAB	73.3							
4	$\text{Co}_2\text{C}$ (25 mg)	TBAB	93.5							
5	$\text{Co}_2\text{C}$ (25 mg) <sup>d</sup>	TBAB	< 5							
6	$\text{Co}_2\text{C}$ (25 mg)	—	0							
7	$\text{Co}_2\text{C}$ (25 mg) <sup>e</sup>	TBAB	0							
8	$\text{Co}_2\text{C}$ (15 mg) <sup>f</sup>	TBAC	26.7							
9	$\text{Co}_2\text{C}$ (25 mg) <sup>g</sup>	TBAB	81.9							
10	$\text{Co(OH)}_2$ (25 mg)	TBAB	64							
11	$\text{CoO}$ (25 mg)	TBAB	63.6							
12	$\text{Co}_3\text{O}_4$ (25 mg)	TBAB	48.6							
13	$\text{Co}_2\text{C}$ (50 mg) <sup>h</sup>	TBAB	66.4							

<sup>a</sup> Reaction conditions: 0.15 mmol 3-chloropropylene oxide, 0.25 mmol TBAB, 3 mL  $\text{CH}_3\text{CN}$  as the solvent, blue LEDs ( $\lambda = 450\text{ nm}$ ) as the light source, 15 h. <sup>b</sup> The carbonate product was quantified by  $^1\text{H}$  NMR with diphenylmethanol as the internal standard. The yield was calculated by the equation,  $[\eta\text{ }(\%)] = n(\text{carbonate})/n(\text{3-chloropropylene oxide}) \times 100\%$ .

<sup>c</sup> 0.1 mmol TBAB. <sup>d</sup> No light irradiation. <sup>e</sup>  $\text{N}_2$  instead of  $\text{CO}_2$ . <sup>f</sup> 0.1 mmol TBAC. <sup>g</sup>  $\text{Co}_2\text{C}$  nanoflowers treated with  $\text{HCl}$  ( $6\text{ mol L}^{-1}$ ). <sup>h</sup> 0.50 mmol TBAB, AM 1.5 (100 mW  $\text{cm}^{-2}$ ) as the light source, 24 h.

of trace amounts of cobalt hydroxide (*i.e.*,  $\text{Co(OH)}_2$ ) and/or cobalt oxide (*i.e.*,  $\text{CoO}$  and  $\text{Co}_3\text{O}_4$ ) on the surface of  $\text{Co}_2\text{C}$  nanoflowers in  $\text{CO}_2$  fixation. After treating the sample with  $\text{HCl}$ , the slightly declined yield of the target product was still much higher than those of pure  $\text{Co(OH)}_2$ ,  $\text{CoO}$ , or  $\text{Co}_3\text{O}_4$  under the same conditions (entries 9–12; Table 1). These results confirmed that  $\text{Co}_2\text{C}$ , but not the hydroxide or oxide impurities, served as the real active sites for  $\text{CO}_2$  fixation. More importantly, the  $\text{Co}_2\text{C}$  catalysed cycloaddition reaction of  $\text{CO}_2$  and epoxides with electron-donating/withdrawing groups could also give rise to products in good to excellent yields ( $\sim 95\%$ ) (Table S3, ESI†). Even under AM1.5 irradiation (entry 13; Table 1), this reaction proceeded with good yields. The activity was well preserved after three-time recycling (Fig. S11, ESI†), indicating the potential use of sunlight as the energy source for enhanced photothermal catalysis.

Based on the above experimental results, a plausible mechanism of the  $\text{Co}_2\text{C}$  nanoflowers catalysed  $\text{CO}_2$ -epoxide cycloaddition reaction is proposed (Fig. 3). Epoxide molecules adsorb on the surface exposed Co sites *via* Co–O interaction with an adsorption energy of  $-0.53\text{ eV}$  (Fig. S12a, see details of density functional theory (DFT) calculations in the ESI†), thereby

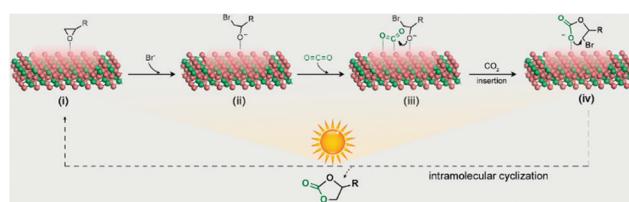


Fig. 3 The proposed mechanism of  $\text{Co}_2\text{C}$  catalysed  $\text{CO}_2$  cycloaddition with epoxides under light irradiation.

leading to the elongation of C–O bond from 1.956 to 2.086 Å. Then, the nucleophilic  $\text{Br}^-$  ion attacks the adsorbed epoxide at the less hindered carbon atom to generate the metal alkoxide intermediate *via* the ring-opening reaction. At the same time,  $\text{CO}_2$  adsorbs on the surface Co atom to give a bent molecular configuration (O1–C–O2 angle 146.99°) with a concerted interaction of C–Co and O–Co coordination (Fig. S12b, ESI†). With the aid of photothermal  $\text{Co}_2\text{C}$  nanoflowers, the oxygen anion of the alkoxide intermediate combines with the adjacent highly activated  $\text{CO}_2$  molecules to yield the cyclic carbonate product, which is eventually released into the solvent to regenerate the catalyst. As a huge amount of heat is released due to the excellent photo-to-thermal conversion effects of  $\text{Co}_2\text{C}$ , the endothermic  $\text{CO}_2$  cycloaddition reaction proceeds with high yields, which is comparable with the reported results (Table S4, ESI†).

In summary, an efficient  $\text{CO}_2$  cycloaddition reaction with epoxides is achieved on low-priced photothermal catalyst of  $\text{Co}_2\text{C}$  nanoflowers. The yield of cyclic carbonates is up to ~95% with visible-light irradiation, owing to the excellent photothermal effects of  $\text{Co}_2\text{C}$  nanoflowers in converting light to heat. Besides, the high specific area as well as efficient  $\text{CO}_2$  adsorption on the exposed Co atoms of the catalysts can simultaneously activate the adsorbed  $\text{CO}_2$  and epoxides, thus promoting the  $\text{CO}_2$  fixation reaction. This work provides new insights into the utilization of TMCs in the field of advanced photothermal-driven catalysis. Moreover, the influence of the morphology, size and thickness of TMCs on the catalytic performance will be further investigated by us.

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## Conflicts of interest

There are no conflicts to declare.

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