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## Computer-aided design of Pt/In<sub>2</sub>O<sub>3</sub> single-atom catalysts for CO<sub>2</sub> hydrogenation to methanol†

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Methanol (CH<sub>3</sub>OH) synthesis from carbon dioxide (CO<sub>2</sub>) hydrogenation is an industrially viable approach to CO<sub>2</sub> utilization. For the recently developed indium oxide (In<sub>2</sub>O<sub>3</sub>) catalyst, higher performance may be achieved by introducing transition metal promoters, although recent studies suggest that single atom sites favour CO formation. Here, by density functional theory-based microkinetic simulations, bulk-doped Pt/In<sub>2</sub>O<sub>3</sub> single atom catalysts (SACs) with much higher CO<sub>2</sub> reactivity than the In<sub>2</sub>O<sub>3</sub> catalyst while maintaining CH<sub>3</sub>OH selectivity were designed. Several Pt/In<sub>2</sub>O<sub>3</sub> SACs were synthesized to confirm our theoretical predictions. The synthesized Pt/In<sub>2</sub>O<sub>3</sub> SAC in the predominantly bulk-doped form exhibits much higher CO<sub>2</sub> reactivity than the In<sub>2</sub>O<sub>3</sub> catalyst with high stability and similar CH<sub>3</sub>OH selectivity, yielding a CH<sub>3</sub>OH productivity of 1.25 g<sub>cat</sub><sup>-1</sup> h<sup>-1</sup>. This study demonstrates the power of computational methods in designing oxide-based catalysts for industrial reactions and reveals a bulk-doped SAC with high performance.

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### Broader context

Rapid increase in the amount of CO<sub>2</sub> emission from fossil fuel consumption accelerates the approaching of climate change, and efficient and sustainable technologies must be swiftly developed and widely deployed to mitigate such severe consequence. Central to CO<sub>2</sub> capture and utilization for reducing CO<sub>2</sub> emission, CO<sub>2</sub> hydrogenation to valuable chemicals such as methanol using renewable hydrogen is economically and technologically viable for applications at industrial scale. However, presently known catalysts for methanol synthesis from CO<sub>2</sub> hydrogenation have suboptimal catalytic performance due to poor activity, low stability, or limited selectivity. For rapid development of more efficient catalysts for this important reaction, first principles-based simulations were employed to rationally design a Pt/In<sub>2</sub>O<sub>3</sub> single atom catalyst in the unusual bulk-doped form, which was shown by our experiments to enable unprecedented methanol productivity of 1.25 g<sub>cat</sub><sup>-1</sup> h<sup>-1</sup> under reaction conditions of 5.0 MPa, 573 K and 54 000 mL<sub>cat</sub><sup>-1</sup> h<sup>-1</sup>, far exceeding the current reported maximum methanol productivity of less than 1.0 g<sub>cat</sub><sup>-1</sup> h<sup>-1</sup>.

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## Introduction

Global warming and climate change induced by the excessive combustion of fossil fuels leading to growing carbon dioxide (CO<sub>2</sub>) emissions from the chemical and energy industries endanger the sustainable development of our society, so effective means for their mitigation must be sought. CO<sub>2</sub> capture and utilization (CCU) is widely recognized as a viable approach for reducing emissions while providing carbon-based chemicals and fuels that are widely used in our society. With renewable hydrogen, CO<sub>2</sub> hydrogenation over heterogeneous catalysts allows for sustainable production of fuels and chemicals including methanol (CH<sub>3</sub>OH) with the key advantages of potential large-scale industrial applications using existing technologies and facilities.<sup>1,2</sup>



Cu-based catalysts are the most widely studied catalysts for methanol synthesis from syngas (carbon monoxide and dihydrogen, CO and H<sub>2</sub>) and also from CO<sub>2</sub> hydrogenation, but poor catalyst stability and CH<sub>3</sub>OH selectivity limit the latter applications.<sup>3–10</sup> In the past decade, a promising family of oxide-based catalysts, such as indium oxide (In<sub>2</sub>O<sub>3</sub>), which exhibit great catalyst stability, high catalytic activity, and excellent CH<sub>3</sub>OH selectivity, especially when supported by an oxide support, such as zirconium oxide or optimized for the crystalline phase and exposed facets, has emerged.<sup>11–14</sup> Nevertheless, there is significant interest in further improving the CO<sub>2</sub> reactivity of In<sub>2</sub>O<sub>3</sub>-based catalysts, for example, *via* transition metal promotion,<sup>15,16</sup> in which CO formation *via* the reverse water gas shift (RWGS) reaction must be inhibited to maintain CH<sub>3</sub>OH selectivity.

Compared with metal nanoparticles modified In<sub>2</sub>O<sub>3</sub>, metal-promoted In<sub>2</sub>O<sub>3</sub> (M/In<sub>2</sub>O<sub>3</sub>) catalysts with highly dispersed metal sites were found more effective for CO<sub>2</sub> hydrogenation to methanol.<sup>17–20</sup> M/In<sub>2</sub>O<sub>3</sub> in the form of single atom catalysts (SACs) has significant advantages such as high metal utilization and large cost reduction, especially for noble metals. However, there are few studies of CO<sub>2</sub> hydrogenation to methanol on M/In<sub>2</sub>O<sub>3</sub> SACs.<sup>16,21,22</sup> Although good CO<sub>2</sub> reactivity and CH<sub>3</sub>OH selectivity have been reported for Rh/In<sub>2</sub>O<sub>3</sub> SACs,<sup>16</sup> a recent theoretical study<sup>23</sup> suggests that introducing atomic metal promoters such as Ni in the form of a surface dopant or an adatom can be detrimental to CH<sub>3</sub>OH selectivity and may lead predominantly to CO formation. This casts doubt on the effectiveness of M/In<sub>2</sub>O<sub>3</sub> SACs in promoting the methanol synthesis reaction and raises questions regarding the nature of the metal-induced promotional effect in these catalysts, which significantly limits targeted catalyst design.

Most SACs reported in the literature involve active atomic metal sites over the support surface, where the supports are mostly inactive,<sup>24–26</sup> whereas atomic metal promoters present in the bulk of the supports are assumed to have no significant reactivity. However, the M/In<sub>2</sub>O<sub>3</sub> SACs for CO<sub>2</sub> hydrogenation are quite unique in that the In<sub>2</sub>O<sub>3</sub> support is catalytically active, and the complex interaction between metal sites and In<sub>2</sub>O<sub>3</sub> can significantly affect catalytic behaviours, so it is a great challenge to design and synthesize highly efficient M/In<sub>2</sub>O<sub>3</sub> SACs for methanol synthesis.

In this work, we performed density functional theory (DFT) calculations and microkinetic simulations to elucidate the role of a platinum (Pt) dopant in Pt/In<sub>2</sub>O<sub>3</sub> SACs for CO<sub>2</sub> hydrogenation. Our simulations show that surface atomic Pt sites are detrimental to CH<sub>3</sub>OH formation, while surprisingly, the presence of bulk atomic Pt dopants greatly enhances CO<sub>2</sub> reactivity while maintaining CH<sub>3</sub>OH selectivity. Our theoretical predictions are confirmed by the synthesis, evaluation, and characterization of several Pt/In<sub>2</sub>O<sub>3</sub> SACs prepared using different methods. This study demonstrates the computer-aided design and experimental realization of highly efficient Pt/In<sub>2</sub>O<sub>3</sub> SACs, and showcases the bulk-doped form of SACs with high performance.

## Experimental

### Density functional theory calculations

Spin-polarized DFT calculations were performed with the Vienna ab initio simulation package (VASP)<sup>27–30</sup> using the Bayesian error estimation functional with van der Waals correlation (BEEF-vdW)<sup>31</sup> and the projector-augmented wave (PAW) method.<sup>32,33</sup> Transition states were optimized using the climbing-image nudged elastic band (CI-NEB)<sup>34</sup> and dimer<sup>35</sup> methods as implemented in the transition state tools for VASP (VTST), and were further verified by numerical frequency calculations. Charge density difference analysis was performed using the VESTA program,<sup>36</sup> whereas all structures were built and visualized using Materials Visualizer from Materials Studio.

The In<sub>2</sub>O<sub>3</sub>(111) surface was modelled with a stoichiometric and symmetric  $p(1 \times 1)$  slab consisting of 72O and 48In atoms distributed in three O–In–O trilayers, where the bottom trilayer was fixed at its bulk position and a vacuum layer of 15 Å was inserted between adjacent slabs. A  $\Gamma$ -centred Monkhorst–Pack  $k$ -point mesh of  $(3 \times 3 \times 1)$ , an energy cutoff of 400 eV, and a force convergence of 0.03 eV Å<sup>-1</sup> were applied in the DFT calculations, similar to our previous works on this system<sup>12,37–41</sup>

Two types of SAC models for Pt/In<sub>2</sub>O<sub>3</sub> were built by substituting one of the surface and bulk In atoms in the above In<sub>2</sub>O<sub>3</sub>(111) slab model. The most probable Pt/In<sub>2</sub>O<sub>3</sub>(111) structure in each case was determined by predicting the energetically most favourable location for the substitution, whose thermal stability was further verified by calculating the adhesive energy ( $\Delta E_{\text{adh}}$ ) of the Pt single atom from eqn (1)

$$\Delta E_{\text{adh}} = E_{\text{Pt/In}_2\text{O}_3(111)} - E_{\text{Pt}} - E_{\text{V}_{\text{In}}/\text{In}_2\text{O}_3(111)} \quad (1)$$

where  $E_{\text{Pt/In}_2\text{O}_3(111)}$ ,  $E_{\text{Pt}}$ , and  $E_{\text{V}_{\text{In}}/\text{In}_2\text{O}_3(111)}$  are energies of the Pt/In<sub>2</sub>O<sub>3</sub>(111) surface, bulk Pt, and the In<sub>2</sub>O<sub>3</sub>(111) surface with an In vacancy (V<sub>In</sub>), respectively, so a more negative  $\Delta E_{\text{adh}}$  value indicates a more stable SAC binding site.

Surface oxygen vacancy (V<sub>O</sub>) sites were considered as the active sites for the In<sub>2</sub>O<sub>3</sub> and Pt/In<sub>2</sub>O<sub>3</sub> catalysts in CO<sub>2</sub> hydrogenation. Free energies of formation of V<sub>O</sub> sites ( $\Delta G_{\text{f},\text{V}_\text{O}}$ ) by H<sub>2</sub> reduction were calculated from eqn (2)

$$\Delta G_{\text{f},\text{V}_\text{O}} = E_{\text{Surface}_\text{V}_\text{O}} + G_{\text{H}_2\text{O}} - E_{\text{Surface}} - G_{\text{H}_2} \quad (2)$$

where  $E_{\text{Surface}_\text{V}_\text{O}}$  and  $E_{\text{Surface}}$  are energies of the In<sub>2</sub>O<sub>3</sub>(111) or Pt/In<sub>2</sub>O<sub>3</sub>(111) surfaces with and without a V<sub>O</sub> site, respectively, and  $G_{\text{H}_2\text{O}}$  and  $G_{\text{H}_2}$  are free energies of molecular H<sub>2</sub>O and H<sub>2</sub> including the experimental entropic corrections at the typical reaction temperature of 573 K. We assume that the additional components for the free energies of the  $E_{\text{Surface}_\text{V}_\text{O}}$  and  $E_{\text{Surface}}$  should mostly cancel, so only their electronic energies are used. A V<sub>O</sub> site with a higher  $\Delta E_{\text{f},\text{V}_\text{O}}$  may facilitate CO<sub>2</sub> adsorption and activation, although its formation by H<sub>2</sub> reduction will be more difficult. For surface-doped Pt/In<sub>2</sub>O<sub>3</sub>(111), CO<sub>2</sub> adsorption and activation may mainly occur at the V<sub>O</sub> site near the Pt site. These factors were considered when choosing the most favourable V<sub>O</sub> site on each model surface for CO<sub>2</sub> hydrogenation, and the catalytic reaction network consists of CO<sub>2</sub> hydrogenation to CH<sub>3</sub>OH and CO *via* the HCOO\* and COOH\* intermediates,



respectively, as well as the further hydrogenation of CO to CH<sub>3</sub>OH.

The adsorption energy of an adsorbate A on a slab surface S is defined by eqn (3)

$$E_{\text{ad}}(\text{A}) = E_{\text{total}} - (E_{\text{slab}} + E_{\text{A}}) \quad (3)$$

where  $E_{\text{total}}$ ,  $E_{\text{slab}}$ , and  $E_{\text{A}}$  are total electronic energies of the slab surface with the adsorbate, the clean slab surface, and the adsorbate as a free molecule, respectively. Adsorption energies of selected adsorbates such as CO<sub>2</sub>, H<sub>2</sub> and CH<sub>3</sub>OH are listed in Table S1 of the ESI.† Although the adsorption energies of H<sub>2</sub> and In-CO<sub>2</sub> are low at 0 K, their surface coverages may be appreciable under high partial pressure conditions.

Similar to the study of Ye *et al.*,<sup>42</sup> the elementary step of the hydrogenation pathway usually involves the reaction of a single H adatom with the intermediate. We performed additional DFT calculations to study the effect of H migration<sup>43</sup> from the hydrogen adsorbed at the surrounding Pt/In sites to the In/O sites near the V<sub>O</sub> site as shown in Fig. S22 and Table S16 (ESI†). In<sub>2</sub>O<sub>3</sub>(111) and Pt<sub>b\_bulk</sub> structures were found to have low energy barriers for H migration from one In to the other In (0.34 eV and 0.26 eV, respectively). The energy barriers for H migration from In to O are relatively high (1.18 eV and 1.14 eV, respectively). However, the Pt<sub>b\_surface</sub> model also has relatively high energy barriers for H migration from one In to another In and O (1.15 eV and 1.11 eV, respectively). Moreover, the presence of a second H adatom does not significantly affect the energy barriers of H migration for these three models. Therefore, we hypothesize that our above simplification of the hydrogenation steps should be reasonable.

We further examine the potential synergistic effect of the surface and bulk Pt dopants on the catalytic activity of the surface oxygen vacancy site. The In<sub>2</sub>O<sub>3</sub>(111) structure is doped with Pt atoms both at the surface and in the bulk (Pt<sub>b\_dual</sub>), where the main active site is the surface oxygen vacancy O<sub>b\_vac</sub> site, and the different pathways of the CO<sub>2</sub> hydrogenation reaction were calculated for this model as shown in Fig. S23–S26 (ESI†). Comparing the potential energy surfaces of the Pt<sub>b\_dual</sub> and Pt<sub>b\_surface</sub> models, the energy barriers of the elementary steps of CO<sub>2</sub> hydrogenation to methanol and the direct CO<sub>2</sub> dissociation pathway of the Pt<sub>b\_dual</sub> model are close to those of the Pt<sub>b\_surface</sub> model, while those of most elementary steps of CO hydrogenation to methanol and the CO<sub>2</sub> indirect dissociation pathway are higher than those of the Pt<sub>b\_surface</sub> model. Therefore, we focus this work on the single atom doping model.

### Microkinetic simulations

The reaction pathways predicted from the DFT calculations for CH<sub>3</sub>OH and CO formations from CO<sub>2</sub> hydrogenation were used to build a multisite microkinetic model for mean-field microkinetic simulations under typical experimental conditions for CO<sub>2</sub> hydrogenation using the CatMAP code.<sup>44,45</sup> Elementary steps in the microkinetic model are given in Table S8 (ESI†), where “s” and “h” denote the V<sub>O</sub> and “hydrogen reservoir” sites, respectively. The structures of all the elementary steps are shown in Fig. S21 (ESI†). The ideal gas approximation and

harmonic-rigid rotor approximation were employed for calculating the entropies and enthalpies of gaseous molecules and surface adsorbates, respectively. The degrees of rate control (DRC) and degrees of selectivity control (DSC)<sup>46,47</sup> proposed by Campbell and implemented in CatMAP were also calculated.

### Catalytic preparation

**Preparation of In<sub>2</sub>O<sub>3</sub> catalyst.** In<sub>2</sub>O<sub>3</sub> sample was prepared by hydrothermal method. Briefly, 4.07 g of In(NO<sub>3</sub>)<sub>3</sub>·4.5H<sub>2</sub>O was dissolved in 32 mL of deionized (DI) water under vigorous stirring. The alkali solution formed by 4 g of urea dissolved in 20 mL of DI water was added dropwise to the above solution, the resulting mixture was stirred vigorously for 2 h before kept in a Teflon-lined stainless autoclave at 393 K for 17 h. The precipitate was washed with DI water until the pH value reached 7, following by drying overnight at 333 K before calcination at 573 K for 5 h.

**Preparation of Pt/In<sub>2</sub>O<sub>3</sub> catalysts.** To obtain platinum-promoted (0–3 wt% Pt) In<sub>2</sub>O<sub>3</sub> catalysts by hydrothermal method. 2 g of H<sub>2</sub>PtCH<sub>6</sub>·6H<sub>2</sub>O was first dissolved in 50 mL of DI water to form standard solution. The as-prepared Pt salt solution (0.63, 1.58, 4.74 g) and In(NO<sub>3</sub>)<sub>3</sub>·4.5H<sub>2</sub>O (4.07 g) were dissolved in deionized (DI) water (32 mL) under vigorous stirring at room temperature. Then the solution formed by urea (2 g, 4 g, 8 g) dissolved in 20 mL DI water was added dropwise to the above solution. Other steps are the same as above for In<sub>2</sub>O<sub>3</sub> catalyst preparation.

**Preparation of Pt/In<sub>2</sub>O<sub>3</sub>-DI catalysts.** 1Pt/In<sub>2</sub>O<sub>3</sub>-DI and 3Pt/In<sub>2</sub>O<sub>3</sub>-DI we prepared Pt/In<sub>2</sub>O<sub>3</sub> by the dry impregnation method. Pt(NO<sub>3</sub>)<sub>2</sub> solution (3.13 and 9.39 g) was added dropwise to the 3 g In<sub>2</sub>O<sub>3</sub> before stirring evenly, the obtained samples were dried at 333 K for 12 h before calcined for 3 h at 573 K in static air.

### Catalyst characterization

Powder X-ray diffraction (XRD) patterns were performed using a Rigaku Ultima IV powder diffractometer equipped with a Cu K $\alpha$  radiation ( $\lambda = 0.15406 \text{ \AA}$ ) operating at 40 kV and 40 mA. The diffractograms were obtained at a  $2\theta$  range of 0–90°.

The loadings of Pt in the samples were measured by inductively coupled plasma-optical emission spectrometry (ICP-OES) on an Agilent 720 spectrometer.

N<sub>2</sub> adsorption–desorption analyses were conducted at 77 K with a Micromeritics ASAP 2420 physisorption analyser. Before the measurement, the samples were outgassed at 300 °C for 10 h under vacuum, and then the surface area was calculated by the Brunauer–Emmett–Teller (BET) method.<sup>48</sup>

The microscopic features of the samples were characterized using a TEM (JEM-2100F) equipped with energy-dispersive X-ray spectroscopy (EDS) operated at 200 kV. The high-angle annular dark-field scanning TEM (HAADF-STEM) was performed using on a JEOL ARM300F equipped with double aberration correctors and a cold field emission gun.

CO<sub>2</sub> temperature-programmed desorption (CO<sub>2</sub>-TPD) experiments were carried out with an OmniStar GSD320 02 mass spectrometer. First, the catalyst (100 mg) was pretreated at



573 K for 60 min in a flow of pure Ar or H<sub>2</sub>. Then, the catalyst was saturated in flowing CO<sub>2</sub> at 323 K for 1 h followed by flushing in Ar for 3 h to remove any physisorbed molecules. The CO<sub>2</sub>-TPD measurement was then performed at 50–1023 K under continuous flow of Ar.

H<sub>2</sub> temperature-programmed reduction (H<sub>2</sub>-TPR) was carried out on a Micromeritics ChemiSorb 2920 with a thermal conductivity detector (TCD). Typically, the catalyst sample (54 mg) was placed in a quartz reactor and pre-treated in flowing Ar at 423 K for 1 h. Then the temperature was raised from 323 to 973 K at a rate of 5 K min<sup>-1</sup> with 5% H<sub>2</sub>/Ar mixture gas.

Electron paramagnetic resonance (EPR) measurements of the free radicals were recorded by using 5,5-dimethyl-1-pyrroline (> 99.0%) as a probe at a Bruker EMS-plus instrument (Bruker A300).

The X-ray absorption spectroscopy (XAS) experiments were conducted on the BL11B beamline of Shanghai Synchrotron Radiation Facility (SSRF). Before measurement, the samples were diluted by boron nitride and tableted. The data were collected at room temperature under fluorescence mode by using Lytle detector and the extended X-ray absorption fine structure (EXAFS) data were analysed *via* Athena software.

X-ray photoelectron spectrometer (XPS) analyses were performed using a Thermo Fisher Scientific ESCALAB 250Xi analyser with Al K $\alpha$  radiation at 1486.6 eV under  $9.9 \times 10^{-7}$  torr. Binding energy values of all samples were calibrated based on an C 1s peak at 284.6 eV.

The synchrotron near-ambient pressure X-ray photoelectron spectroscopy (NAP-XPS) experiments were performed at beamline BL02B01 of SSRF. The C 1s photoemission line of C-C at 284.8 eV was used for the calibration. For the CO<sub>2</sub> hydrogenation reaction, sample were exposed to a mixture of H<sub>2</sub> (1.5 mTorr) and CO<sub>2</sub> (0.5 mTorr). For the Ar pretreatment, sample was in the environment of pure H<sub>2</sub> at 2 mTorr. For the H<sub>2</sub>/Ar atmosphere, H<sub>2</sub> makes up 10% of all gases.

The *in situ* synchrotron-based vacuum ultraviolet photoionization mass spectrometry (SVUV-PIMS) study was carried out on the mass spectrometry endstation of the National Synchrotron Radiation Laboratory at Hefei, China. The Ar pretreatment products were monitored at an ionization energy of 11.8 eV, which allowed the detection of HCHO, CH<sub>3</sub>OH and HCOOH. To detect the intermediates and products formed during CO<sub>2</sub> hydrogenation, the Ar pretreated Pt/In<sub>2</sub>O<sub>3</sub> catalyst was exposed to H<sub>2</sub>/CO<sub>2</sub> (3 : 1) at a flow rate of 80 mL min<sup>-1</sup> and a pressure of 8 bar at 300 °C; the photoionization efficiency spectra were collected for 300 s at ionization energies in the range 10.6–11.6 eV in steps of 0.03 eV.

### Catalytic evaluation

1.0 g of catalyst (40–60 mesh) with quartz sand mixing in equal volume was placed in a stainless-steel tube reactor. Prior to reaction, the sample was pretreated at 573 K for 1 h in pure Ar (150 mL min<sup>-1</sup>) and then reactant gas mixture with a H<sub>2</sub>/CO<sub>2</sub>/N<sub>2</sub> ratio of 73/24/3 and a pressure of 5.0 MPa at 573 K was introduced into the reactor. The effluents were analysed online with a Shimadzu GC-2010C gas chromatograph equipped with

thermal conductivity and flame ionization detectors. The CO<sub>2</sub> conversion was calculated by an internal normalization method. The catalytic performance after 48 h of reaction was typically used for discussion.

The CO<sub>2</sub> conversion denoted as  $X(\text{CO}_2)$ , CH<sub>3</sub>OH selectivity denoted as  $S(\text{CH}_3\text{OH})$  and space-time yield (STY) of methanol denoted as  $\text{STY}(\text{CO}_2)$  were calculated according to the following equations:

$$X(\text{CO}_2) = \frac{\text{CO}_2 \text{ inlet} - \text{CO}_2 \text{ outlet}}{\text{CO}_2 \text{ inlet}} \times 100\% \quad (4)$$

$$S(\text{CH}_3\text{OH}) = \frac{\text{CH}_3\text{OH}_{\text{outlet}}}{\text{CO}_2 \text{ inlet} - \text{CO}_2 \text{ outlet}} \times 100\% \quad (5)$$

$$\text{STY}(\text{CH}_3\text{OH}) = \frac{\text{GHSV} \times V\%(\text{CO}_2) \times X(\text{CO}_2) \times S(\text{CH}_3\text{OH}) \times M(\text{CH}_3\text{OH})}{22.4 \times 1000 \times m_{\text{cat}}} \times [\text{g g}_{\text{cat}}^{-1} \text{h}^{-1}] \quad (6)$$

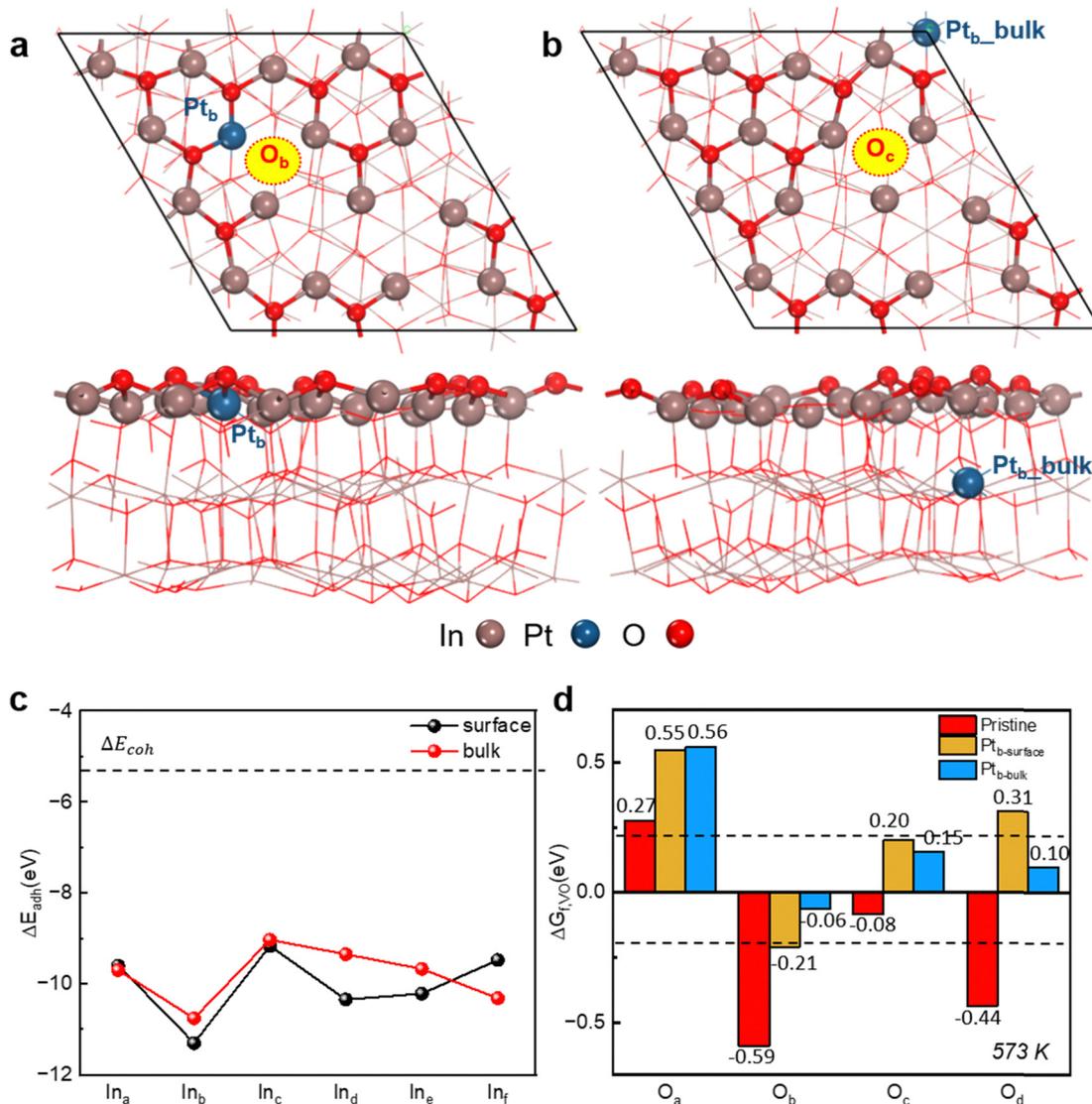
## Results

### Active sites and reaction pathways on Pt/In<sub>2</sub>O<sub>3</sub> SACs

The stoichiometric In<sub>2</sub>O<sub>3</sub>(111) surface shown in Fig. S1a (ESI<sup>†</sup>) has threefold symmetry, so its surface In and O atoms fall into six and four groups, labelled by In<sub>a</sub>–In<sub>f</sub> and O<sub>a</sub>–O<sub>d</sub>, respectively. The most stable single-atom Pt/In<sub>2</sub>O<sub>3</sub>(111) structures, with the Pt dopant located at the surface and in the bulk, are shown in Fig. 1a and b, respectively, based on the calculated  $\Delta E_{\text{adh}}$  of a bulk Pt atom with the In<sub>2</sub>O<sub>3</sub>(111) slab in the presence of a V<sub>In</sub>. As shown in Fig. 1c and Table S2 (ESI<sup>†</sup>), our calculations indicate that the Pt dopant preferably replaces the In<sub>b,surface</sub> site for surface doping (denoted as Pt<sub>b,surface</sub>) and the In<sub>b,bulk</sub> site for bulk doping (denoted as Pt<sub>b,bulk</sub>). In both cases, the  $\Delta E_{\text{adh}}$  values are substantially more negative than the cohesive energy of bulk Pt ( $\Delta E_{\text{coh}}$ ), suggesting the strong interaction of the single atom Pt dopant with the In<sub>2</sub>O<sub>3</sub>(111) slab, which may prevent the Pt dopants from self-aggregation.

Surface V<sub>O</sub> sites are usually considered the active sites for CO<sub>2</sub> hydrogenation, and the V<sub>O</sub> site, which has a higher  $\Delta G_{\text{f},\text{VO}}$ , is usually suggested to have a higher CO<sub>2</sub> reactivity.<sup>8</sup> For the surface and bulk-doped Pt/In<sub>2</sub>O<sub>3</sub>(111) structures, the most favourable V<sub>O</sub> sites further shown in Fig. 1a and b are located at the O<sub>b</sub> and O<sub>c</sub> sites (denoted as O<sub>b,vac</sub> and O<sub>c,vac</sub>), respectively. For the pristine In<sub>2</sub>O<sub>3</sub>(111) slab, the most favourable V<sub>O</sub> site as displayed in Fig. S1b (ESI<sup>†</sup>) is situated at the O<sub>c</sub> site (also denoted as O<sub>c,vac</sub>). The most favourable V<sub>O</sub> site was determined from the calculated  $\Delta G_{\text{f},\text{VO}}$  values of all surface V<sub>O</sub> sites, as shown in Fig. 1d and Table S3 (ESI<sup>†</sup>), considering the Sabatier principle.<sup>49</sup> As noted above, a V<sub>O</sub> site with a higher  $\Delta G_{\text{f},\text{VO}}$  value may interact more strongly with CO<sub>2</sub>, resulting in a higher CO<sub>2</sub> reactivity, although its formation by H<sub>2</sub> reduction becomes thermodynamically and also possibly kinetically more





**Fig. 1** Screening single atom-doped Pt/In<sub>2</sub>O<sub>3</sub> catalyst structures and active sites. (a) Top and side views of the most stable surface-doped Pt/In<sub>2</sub>O<sub>3</sub>(111) structure with the Pt dopant located at the Pt<sub>b\_surface</sub> position and the surface oxygen vacancy (V<sub>O</sub>) situated at the O<sub>b</sub> site. (b) Top and side views of the most stable bulk-doped Pt/In<sub>2</sub>O<sub>3</sub>(111) structure with the Pt dopant located at the Pt<sub>b\_bulk</sub> position and the surface V<sub>O</sub> site placed at the O<sub>c</sub> site. (c) Calculated adhesive energies of a bulk-doped (red) or surface-doped (black) Pt atom with an In vacancy (V<sub>In</sub>) in In<sub>2</sub>O<sub>3</sub>(111), which are compared with the cohesive energy of bulk Pt. (d) Calculated free formation energies of surface V<sub>O</sub> on pristine (red), surface (yellow), and bulk (blue) doped Pt/In<sub>2</sub>O<sub>3</sub>(111) for H<sub>2</sub> reduction at 573 K. The dashed lines (±0.2 eV) represent a region of near thermoneutrality for the free formation energies considering the typical accuracies of DFT predictions.

difficult. Therefore, the most favourable V<sub>O</sub> site should have the highest ΔG<sub>f,V<sub>O</sub></sub> value, provided that its formation by H<sub>2</sub> reduction is exothermic or nearly thermoneutral at the typical reaction temperature, as indicated by the dashed lines in Fig. 1d. For the surface-doped Pt/In<sub>2</sub>O<sub>3</sub>(111) model, the O<sub>b\_vac</sub> site adjacent to the Pt<sub>b\_surface</sub> site is chosen, as CO<sub>2</sub> prefers to adsorb at the Pt<sub>b\_surface</sub>-O<sub>b\_vac</sub> dual site. As shown in Fig. 1d, introducing the Pt dopant either at the surface or in the bulk of the In<sub>2</sub>O<sub>3</sub>(111) slab substantially increases the ΔG<sub>f,V<sub>O</sub></sub> values for all four types of surface V<sub>O</sub> sites, which can be attributed to the deeper reduction of the metal sites surrounding the V<sub>O</sub> site (Fig. S2 and S3, ESI<sup>†</sup>). Surface doping of In<sub>2</sub>O<sub>3</sub>(111) leads to a deeper reduction of the three metal sites around the O<sub>b\_vac</sub> site,

which suggests a lower stability, consistent with the increase in the ΔG<sub>f,V<sub>O</sub></sub> value from -0.59 eV of the pristine In<sub>2</sub>O<sub>3</sub>(111) to -0.21 eV upon introducing the Pt<sub>b\_surface</sub> dopant. Similarly, a deep reduction also occurs at three metal sites around the O<sub>c\_vac</sub> site in the bulk-doped Pt/In<sub>2</sub>O<sub>3</sub> model, which corresponds to an increase in the ΔG<sub>f,V<sub>O</sub></sub> value from the pristine In<sub>2</sub>O<sub>3</sub>(111) of -0.08 eV to 0.15 eV upon Pt doping.

The optimized structures of the important reaction intermediates for CO<sub>2</sub> hydrogenation to CH<sub>3</sub>OH and CO over the surface and bulk-doped Pt/In<sub>2</sub>O<sub>3</sub>(111) models are presented in Fig. S4–S6 (ESI<sup>†</sup>), with their calculated adsorption energies summarized in Table S1 (ESI<sup>†</sup>). At the O<sub>c\_vac</sub> site on the pristine In<sub>2</sub>O<sub>3</sub>(111) surface, CO<sub>2</sub> can weakly physisorb in the



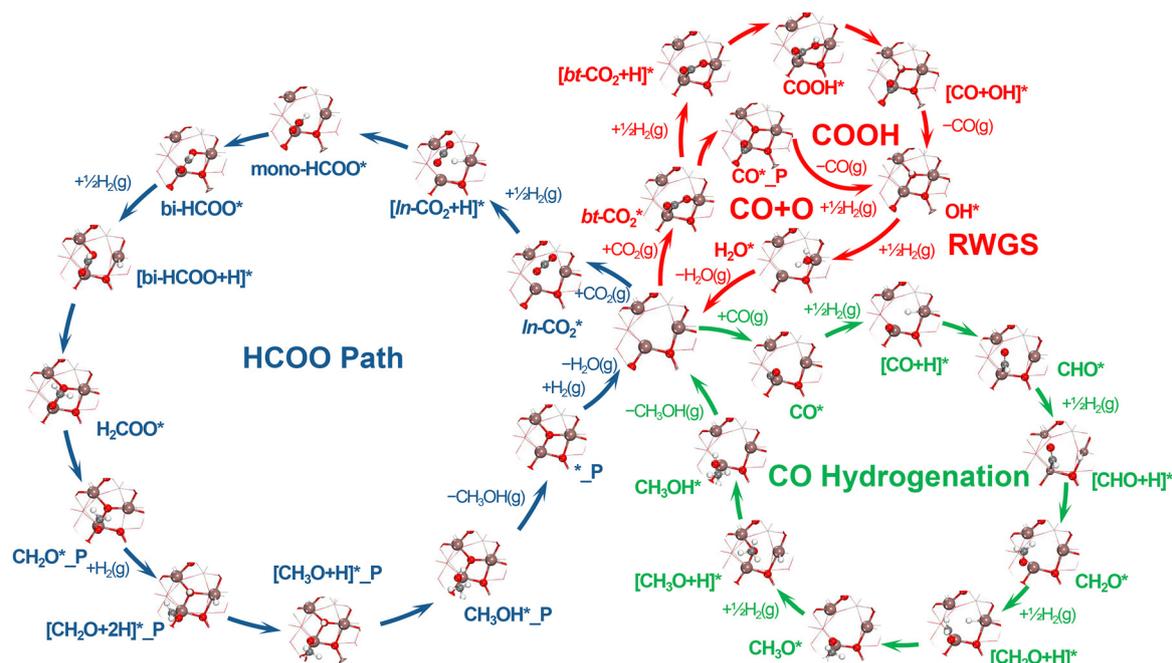


Fig. 2 Catalytic cycles for CO<sub>2</sub> hydrogenation to CH<sub>3</sub>OH and CO over Pt/In<sub>2</sub>O<sub>3</sub> SACs. Methanol can form directly from CO<sub>2</sub> hydrogenation via the HCOO pathway (blue), or indirectly from the CO intermediate via CO hydrogenation (green), whereas CO can form by direct CO<sub>2</sub> dissociation or indirectly by the COOH route (red). \_D\* and \_P\* represent the defective and perfect structures with and without an oxygen vacancy, respectively.

In-CO<sub>2</sub>\* structure or chemisorb in the bt-CO<sub>2</sub>\* structure. Surface Pt doping greatly strengthens CO<sub>2</sub> chemisorption at the Pt<sub>b,surface</sub>-O<sub>b,vac</sub> site in the bt-CO<sub>2</sub>\* structure by approximately 1.9 eV, so its CO<sub>2</sub> adsorption energy changes from being quite endothermic to quite exothermic. Similarly, CO adsorption at the Pt<sub>b,surface</sub> site on the surface-doped Pt/In<sub>2</sub>O<sub>3</sub>(111) is also much stronger than that at the O<sub>c,vac</sub> site on the pristine In<sub>2</sub>O<sub>3</sub>(111) surface by 0.8 eV. In contrast, bulk Pt doping only slightly affects the adsorption energies of the various species at the Pt<sub>b,bulk</sub>-O<sub>c,vac</sub> site by <0.2 eV, when compared with those at the O<sub>c,vac</sub> site on the pristine In<sub>2</sub>O<sub>3</sub>(111) surface. Thus, our calculations show that surface and bulk Pt doping result in distinct impacts on the adsorption properties of Pt/In<sub>2</sub>O<sub>3</sub> SACs. Fig. 2 shows the entire reaction network for CO<sub>2</sub> hydrogenation to CH<sub>3</sub>OH and CO over the Pt/In<sub>2</sub>O<sub>3</sub> SACs. Our calculations show that CH<sub>3</sub>OH can form directly *via* the HCOO pathway from stepwise CO<sub>2</sub> hydrogenation, or indirectly *via* the CO hydrogenation pathway from the CO intermediate, which can be produced by direct CO<sub>2</sub> dissociation or indirectly *via* the COOH pathway. Our predicted reaction pathways for CO<sub>2</sub> hydrogenation to CH<sub>3</sub>OH and CO are generally consistent with those found in the recent literature for related catalysts.<sup>12,50</sup>

Fig. S7 (ESI<sup>†</sup>) compares the energy profiles of CH<sub>3</sub>OH formation from direct CO<sub>2</sub> hydrogenation *via* the HCOO pathway (the blue cycle in Fig. 2), with the detailed relative energies given in Table S4 (ESI<sup>†</sup>). Compared with the relative energies for the pristine In<sub>2</sub>O<sub>3</sub>(111) surface, those for the surface-doped Pt/In<sub>2</sub>O<sub>3</sub>(111) model are less negative, whereas those for the bulk-doped Pt/In<sub>2</sub>O<sub>3</sub>(111) model are more negative except for the HCOO\* and [CH<sub>2</sub>O + 2H]\* intermediates. Relative energies

of most reaction intermediates and energy barriers of most transition states for the HCOO pathway at the Pt<sub>b,surface</sub>-O<sub>b,vac</sub> site on the Pt<sub>b,surface</sub> model are the highest, and the rate-determining step (RDS) is CH<sub>3</sub>O\* hydrogenation to CH<sub>3</sub>OH\* with an energy barrier of 2.49 eV. The RDS at the Pt<sub>b,bulk</sub>-O<sub>c,vac</sub> site on the Pt<sub>b,bulk</sub> model is HCOO\* hydrogenation to H<sub>2</sub>COO\* with an energy barrier of 0.69 eV, indicating that the bulk-doped model is beneficial for methanol formation *via* the HCOO\* pathway.

Fig. S8 and S9 (ESI<sup>†</sup>) show the energy profiles for CO formation from CO<sub>2</sub> direct dissociation and *via* the indirect COOH pathway (red cycle in Fig. 2), with the detailed relative energies given in Tables S5 and S6 (ESI<sup>†</sup>). The potential energies of the CO<sub>2</sub> direct dissociation pathway are generally lower than those of the indirect COOH pathway, suggesting the former to potentially play a more important role than the latter in CO formation. Furthermore, compared with the energy profiles for the pristine In<sub>2</sub>O<sub>3</sub>(111) surface, those for the surface-doped Pt/In<sub>2</sub>O<sub>3</sub>(111) model are more downhill, whereas those for the bulk-doped Pt/In<sub>2</sub>O<sub>3</sub>(111) are more uphill, indicating that CO formation may be suppressed and accelerated by surface and bulk Pt doping, respectively.

Fig. S10 (ESI<sup>†</sup>) compares the energy profiles for CH<sub>3</sub>OH formation from the CO intermediate *via* the CO hydrogenation pathway (the green cycle in Fig. 2), with the detailed relative energies given in Table S7 (ESI<sup>†</sup>). Compared with the potential energies for the pristine In<sub>2</sub>O<sub>3</sub>(111) surface, those for the surface-doped Pt/In<sub>2</sub>O<sub>3</sub>(111) model are lower, whereas those for the bulk-doped Pt/In<sub>2</sub>O<sub>3</sub>(111) model are rather similar, implying that bulk Pt doping has a less pronounced effect on



this route than surface Pt doping. The RDS at the  $\text{Pt}_{\text{b\_surface}}\text{-O}_{\text{b\_vac}}$  site on the  $\text{Pt}_{\text{b\_surface}}$  model is  $\text{CH}_3\text{O}^*$  hydrogenation to  $\text{CH}_3\text{OH}^*$  with an energy barrier of 1.37 eV, and that at the  $\text{Pt}_{\text{b\_bulk}}\text{-O}_{\text{c\_vac}}$  site on the  $\text{Pt}_{\text{b\_bulk}}$  model is  $\text{CH}_2\text{O}^*$  hydrogenation to  $\text{CH}_3\text{O}^*$  with an energy barrier of 1.23 eV. From the energy barrier of the RDS, compared with the  $\text{Pt}_{\text{b\_surface}}$  model, the  $\text{Pt}_{\text{b\_bulk}}$  model may be more favorable for CO hydrogenation to  $\text{CH}_3\text{OH}$ .

For the  $\text{CO}_2$  hydrogenation pathway on the  $\text{In}_2\text{O}_3(111)$  surface, the earlier study of Frei *et al.*<sup>11</sup> indicates that  $\text{HCOO}^*$  is formed by hydrogenation of the chemisorbed carb- $\text{CO}_2^*$  with an energy barrier of 0.44 eV, whereas in our work, it is formed by hydrogenation of the physisorbed  $\text{In-CO}_2^*$  with a much lower energy barrier of 0.01 eV. In addition, our previous calculations<sup>12,41</sup> suggest carb- $\text{CO}_2^*$  is a spectator species. carb- $\text{CO}_2^*$  protonation to  $\text{CO}_2\text{OH}^*$  must overcome an energy barrier of 0.72 eV, whereas the reverse reaction has a much lower energy barrier of 0.25 eV, indicating that it is kinetically more favourable for  $\text{CO}_2\text{OH}^*$  dissociation back to the carb- $\text{CO}_2^*$ , *i.e.*, the reaction is endoergic. Furthermore,  $\text{CO}_2\text{OH}^*$  dissociation to  $[\text{In-CO}_2 + \text{OH}]^*$  needs to overcome an energy barrier of 0.61 eV, which is higher than that for  $\text{CO}_2\text{OH}^*$  dissociation back to the carb- $\text{CO}_2^*$  of 0.25 eV. The above two findings indicate that carb- $\text{CO}_2^*$  is a spectator species. Finally, our previous calculations<sup>41</sup> also suggest carb- $\text{CO}_2^*$  hydrogenation to the bi- $\text{HCOO}^*$  to be kinetically unfavourable with an energy barrier of 1.01 eV.

The previous work of Cannizzaro *et al.*<sup>23</sup> focused on Ni-promoted  $\text{In}_2\text{O}_3$  catalysts using the  $\text{Ni}_1$ -doped,  $\text{Ni}_1$ -adsorbed, and  $\text{Ni}_8$ -cluster models. For  $\text{CO}_2$  hydrogenation in the  $\text{HCOO}^*$  pathway, the RDS for the  $\text{Ni}_1$ -doped model is  $\text{HCOO}^*$  hydrogenation to  $\text{H}_2\text{COO}^*$  with a high energy barrier of 3.26 eV, whereas the energy barrier of this step for the  $\text{Pt}_{\text{b\_surface}}$  model is much lower at 0.55 eV. On the other hand, the RDS on the surface-doped  $\text{Pt}/\text{In}_2\text{O}_3$  model is  $\text{CH}_3\text{O}^*$  hydrogenation to  $\text{CH}_3\text{OH}^*$  with an energy barrier of 2.49 eV, whereas the energy barrier of this step for the  $\text{Ni}_1$ -doped model is much lower at 1.02 eV from their calculations.<sup>23</sup> In addition, for the  $\text{Ni}_1$ -doped model, their calculations<sup>23</sup> show that the  $\text{CH}_2\text{O}^*$  intermediate is obtained from  $\text{H}_2\text{COOH}^*$  dissociation, and the subsequent cleavage of the C–O bond in  $\text{H}_2\text{COOH}^*$  yields  $\text{CH}_2\text{O}^*$  and  $\text{OH}^*$  with an energy barrier of 1.01 eV. In comparison, for the  $\text{Pt}_{\text{b\_surface}}$  model, our calculations show that  $\text{CH}_2\text{O}^*$  is formed by  $\text{H}_2\text{COO}^*$  dissociation with an energy barrier of 1.34 eV. For CO formation *via* the  $\text{CO}_2$  direct dissociation pathway, they predicted an energy barrier of 2.40 eV for the  $\text{Ni}_1$ -doped model,<sup>23</sup> which is rather similar to that of 2.71 eV for the  $\text{Pt}_{\text{b\_surface}}$  model from our calculations. However, they did not study the  $\text{CO}_2$  indirect dissociation pathway *via* the  $\text{COOH}^*$  intermediate for the  $\text{Ni}_1$ -doped model.<sup>23</sup> For the  $\text{Pt}_{\text{b\_surface}}$  model, our calculations show that the RDS is  $\text{CO}_2$  hydrogenation to  $\text{COOH}^*$  with an energy barrier of 1.70 eV, considerably lower than that for the  $\text{CO}_2$  direct dissociation pathway. The above comparison thus indicates that despite the apparent similarity between the catalyst model and the metal dopant for the surface-doped  $\text{Ni}/\text{In}_2\text{O}_3$  and  $\text{Pt}/\text{In}_2\text{O}_3$  SACs, the energy

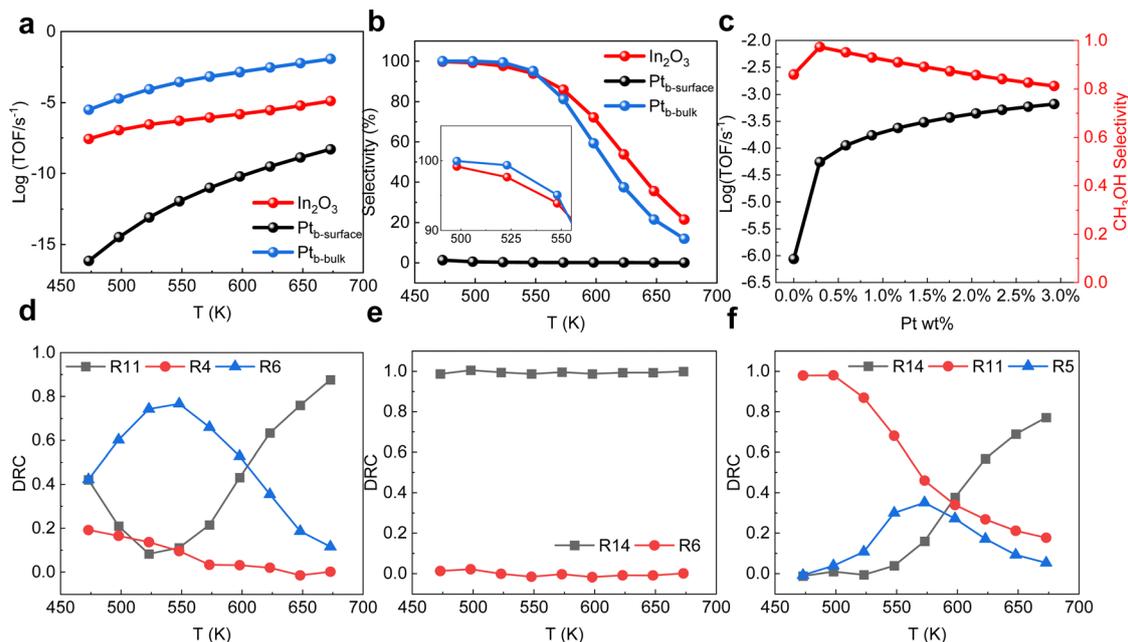
barriers of the elementary steps and the identity of the RDS can be quite different especially for  $\text{CH}_3\text{OH}$  formation *via* the  $\text{HCOO}$  pathway.

### Microkinetic simulations of $\text{CO}_2$ hydrogenation on $\text{Pt}/\text{In}_2\text{O}_3$ SACs

For quantitative prediction of the catalytic performance of the  $\text{Pt}/\text{In}_2\text{O}_3$  SACs, multisite mean-field microkinetic simulations using our DFT energetics were performed; all the reaction routes shown in Fig. 2 were included in the microkinetic models. Fig. 3a shows the calculated turnover frequencies (TOFs) for  $\text{CO}_2$  consumption under the typical reaction conditions of 473–673 K and 5 MPa ( $\text{H}_2 : \text{CO}_2 = 3 : 1$ ). We predict that the  $\text{Pt}_{\text{b\_bulk}}\text{-O}_{\text{c\_vac}}$  and  $\text{Pt}_{\text{b\_surface}}\text{-O}_{\text{b\_vac}}$  sites exhibit considerably higher and lower  $\text{CO}_2$  reactivity, respectively, indicating that bulk Pt doping, not surface Pt doping, may facilitate the  $\text{CO}_2$  hydrogenation reaction. Fig. 3b further displays the calculated  $\text{CH}_3\text{OH}$  selectivities under the above reaction conditions, which consistently decrease as the reaction temperature increases for all three model surfaces. For the pristine  $\text{In}_2\text{O}_3(111)$  surface, we predict that the  $\text{CH}_3\text{OH}$  selectivity decreases from  $\sim 97\%$  at 523 K to  $\sim 85\%$  at 573 K, in reasonable agreement with the experimental observations for the pure  $\text{In}_2\text{O}_3$  catalyst described in the following section. The bulk-doped  $\text{Pt}/\text{In}_2\text{O}_3(111)$  model is predicted to exhibit a very similar profile for the  $\text{CH}_3\text{OH}$  selectivity in the simulated temperature range, whereas the surface-doped  $\text{Pt}/\text{In}_2\text{O}_3(111)$  model is found to clearly favour CO formation with a very low  $\text{CH}_3\text{OH}$  selectivity even at the low reaction temperature of 473 K. Further simulations were performed to study the effect of Pt loading on  $\text{CO}_2$  reactivity and  $\text{CH}_3\text{OH}$  selectivity at 573 K for the bulk-doped  $\text{Pt}/\text{In}_2\text{O}_3(111)$  model as shown in Fig. 3c, indicating that at a relatively low reaction temperature, increasing the Pt loading for bulk doping may enhance the  $\text{CO}_2$  reactivity  $100\times$  without significantly lowering  $\text{CH}_3\text{OH}$  selectivity.

Fig. 3d shows the calculated DRC for  $\text{CO}_2$  consumption at the  $\text{O}_{\text{c\_vac}}$  site on the pristine  $\text{In}_2\text{O}_3(111)$  surface, indicating a strong dependence of the DRCs on reaction temperature. At relatively low reaction temperatures from 473 K to 598 K, the DRC of  $\text{H}_2\text{CO}^*$  hydrogenation to  $\text{H}_3\text{CO}^*$  (R6) is the largest, suggesting that this elementary step is the rate-determining step, and that lowering this energy barrier will lead to higher  $\text{CO}_2$  reactivity. At a higher reaction temperature,  $\text{OH}^*$  hydrogenation to  $\text{H}_2\text{O}^*$  to form an oxygen vacancy (R11) is the RDS, whereas lowering the energy barrier of  $\text{H}_2\text{CO}^*$  hydrogenation to  $\text{H}_3\text{CO}^*$  has a much less pronounced effect on the overall  $\text{CO}_2$  reactivity. Fig. 3e displays the calculated DRC values for the  $\text{CO}_2$  reaction rate at the  $\text{Pt}_{\text{b\_surface}}\text{-O}_{\text{b\_vac}}$  site on the surface-doped  $\text{Pt}/\text{In}_2\text{O}_3(111)$  model.  $\text{CO}_2^*$  direct dissociation (R14) is the RDS for  $\text{CO}_2$  conversion at 473–673 K, suggesting that lowering its energy barrier should lead to higher  $\text{CO}_2$  reactivity. This result is consistent with the very high energy barrier of 2.71 eV for  $\text{CO}_2$  direct dissociation on the surface-doped  $\text{Pt}/\text{In}_2\text{O}_3(111)$  model (Fig. S8 and Table S5, ESI<sup>†</sup>), although the  $\text{bt-CO}_2^*$  structure has a very negative adsorption energy of  $-0.78$  eV. On the other hand, the DRCs of the elementary steps related to  $\text{CH}_3\text{OH}$  formation are consistently low above 473 K, as the product





**Fig. 3** Microkinetic simulations of the catalytic performance of Pt/In<sub>2</sub>O<sub>3</sub> SACs. (a) and (b) Plots of the calculated turn-over frequencies (TOFs) for CO<sub>2</sub> consumption (a) and CH<sub>3</sub>OH selectivities (b) for CO<sub>2</sub> hydrogenation over the pristine In<sub>2</sub>O<sub>3</sub>(111) surface (black) and the surface and bulk-doped Pt/In<sub>2</sub>O<sub>3</sub>(111) models (red and blue, respectively) under the reaction conditions of 473–673 K, 5 MPa, and H<sub>2</sub> : CO<sub>2</sub> = 3 : 1. (c) Plots of simulated TOFs for CO<sub>2</sub> consumption (black) and CH<sub>3</sub>OH selectivities (red) for CO<sub>2</sub> hydrogenation over the bulk-doped Pt/In<sub>2</sub>O<sub>3</sub>(111) model catalyst at different Pt loadings at 573 K. (d)–(f) Calculated DRC for the elementary steps during CO<sub>2</sub> hydrogenation over the pristine In<sub>2</sub>O<sub>3</sub>(111) surface (d) and the surface and bulk-doped Pt/In<sub>2</sub>O<sub>3</sub>(111) models (e and f, respectively).

composition is dominated by CO. Fig. 3f further shows the calculated DRCs for the CO<sub>2</sub> reaction rate at the Pt<sub>b,bulk</sub>–O<sub>c,vac</sub> site on the bulk-doped Pt/In<sub>2</sub>O<sub>3</sub>(111) model. Below 600 K, the DRCs of the OH\* hydrogenation to generate the V<sub>O</sub> site (R11) are largest, suggesting V<sub>O</sub> formation to be the rate determining step, consistent with the much higher free formation energy of the O<sub>c,vac</sub> site on this surface (Fig. 1d). This also agrees with the calculated coverages of the surface species shown in Fig. S11c (ESI<sup>†</sup>), suggesting that the free sites are mostly occupied by OH\* at relatively low temperatures. At higher reaction temperatures, the DRC of direct CO<sub>2</sub>\* dissociation (R14) becomes largest, as CO becomes the main product. The calculated DSC for CH<sub>3</sub>OH shown in Fig. S12 (ESI<sup>†</sup>) are also very sensitive to the reaction temperature, especially for the pristine In<sub>2</sub>O<sub>3</sub>(111) surface and the bulk-doped Pt/In<sub>2</sub>O<sub>3</sub>(111) model.

To reveal the effect of Pt doping on the electronic structure of the In site on the catalyst surface, projected density of states (PDOS) analysis was performed for the relevant structures. As shown in Fig. S13a (ESI<sup>†</sup>) for the In<sub>c</sub> site in the presence of both H\* and HCOO\* adsorbates, the PDOS of the various In<sub>c</sub> orbitals as well as the H\* orbitals are all shifted to lower energies upon introducing a bulk Pt dopant. Similar observations were made for the effects of the bulk Pt dopant on the PDOS of the In<sub>c</sub> orbitals without the presence of either the H\* or HCOO\* adsorbate, suggesting that introducing the bulk Pt dopant has significant influence on the redox property of the surface In<sub>c</sub> site. Meanwhile, as discussed earlier, the Bader charge analyses shown in Fig. S2 and S3 (ESI<sup>†</sup>) suggest a deeper

reduction of the three In sites around the O<sub>c,vac</sub> site upon introduction of the bulk Pt dopant, consistent with an increase in the ΔG<sub>F,VO</sub> value.

Furthermore, crystal orbital Hamilton population (COHP) and integrated COHP (ICOHP) analyses were also performed as shown in Fig. S13b (ESI<sup>†</sup>) to understand the effect of the bulk Pt dopant on the interaction between In<sub>c</sub> and H\* in the presence of HCOO\*. The increase in the negative ICOHP value at the Fermi surface indicates that introducing the bulk Pt dopant will strengthen the orbital interaction between In<sub>c</sub> and H\*, consistent with the predicted stronger H\* adsorption and the lower effective energy barrier of HCOO\* hydrogenation (Table S4, ESI<sup>†</sup>), leading to enhanced reactivity of the bulk-doped In<sub>2</sub>O<sub>3</sub> catalyst. However, CO<sub>2</sub> adsorption on the surface-doped Pt/In<sub>2</sub>O<sub>3</sub>(111) model is too strong, leading to much higher energy barriers for its subsequent hydrogenation. Whereas the RDS step in the HCOO pathway for the Pt<sub>b,bulk</sub> model is HCOO\* hydrogenation to H<sub>2</sub>COO\* with a modest energy barrier of 0.69 eV, that for the Pt<sub>b,surface</sub> model is CH<sub>3</sub>O\* hydrogenation to CH<sub>3</sub>OH\* with a much higher energy barrier of 2.49 eV.

The formal oxidation states of the Pt single atom sites in the surface-doped and bulk-doped Pt/In<sub>2</sub>O<sub>3</sub> models are estimated to be both +3.5 based on the calculated Bader charges, when compared with those of bulk Pt and its various oxides as shown in Fig. S13b and Table S14 (ESI<sup>†</sup>). Upon the formation of a V<sub>O</sub> on the surface, the formal oxidation states of the Pt single atom sites in the surface-doped and bulk-doped Pt/In<sub>2</sub>O<sub>3</sub> models become +1.9 and +3.5, respectively. Thus, the formal oxidation



state of the surface-doped Pt is significantly affected by the formation of the nearby  $V_{\text{O}}$ , as the Bader charge of  $\text{Pt}_{\text{b\_surface}}$  significantly decreases from 1.40  $|e|$  to 0.81  $|e|$  upon the formation of  $\text{O}_{\text{b\_vac}}$  near  $\text{Pt}_{\text{b\_surface}}$  (Fig. S2, ESI<sup>†</sup>). In contrast, the formation of a surface  $V_{\text{O}}$  on the bulk-doped Pt/ $\text{In}_2\text{O}_3$  model has little effect on the formal oxidation state of the bulk Pt dopant, whose Bader charge remains essentially the same at 1.39  $|e|$ . Therefore, our DFT-based microkinetic simulations show that selectively introducing bulk Pt dopants to the  $\text{In}_2\text{O}_3$  catalyst can greatly enhance  $\text{CH}_3\text{OH}$  productivity by substantially increasing  $\text{CO}_2$  reactivity while largely maintaining  $\text{CH}_3\text{OH}$  selectivity, which suppresses the RWGS activity usually promoted by surface Pt dopants.

### Preparation and catalytic performance of Pt-modified $\text{In}_2\text{O}_3$

Based on our theoretical predictions, a series of  $\text{In}_2\text{O}_3$  and Pt/ $\text{In}_2\text{O}_3$  samples with different Pt contents were synthesized by the hydrothermal method.<sup>8</sup> The actual Pt loadings of the Pt/ $\text{In}_2\text{O}_3$  samples were measured by ICP-OES to be 0.44, 1.24 and 2.82 wt%, denoted as 0.5Pt/ $\text{In}_2\text{O}_3$ , 1Pt/ $\text{In}_2\text{O}_3$  and 3Pt/ $\text{In}_2\text{O}_3$  catalysts, respectively. For comparison, 1Pt/ $\text{In}_2\text{O}_3$ -DI and 3Pt/ $\text{In}_2\text{O}_3$ -DI samples with similar Pt concentrations of 1.37 and 3.01 wt%, respectively, were also prepared by the dry

impregnation method, in which the Pt species are mostly present on the  $\text{In}_2\text{O}_3$  surface. Comparative analysis of surface sensitive XPS and ICP-OES results reveals that compared to 1Pt/ $\text{In}_2\text{O}_3$ -DI and 3Pt/ $\text{In}_2\text{O}_3$ -DI, the Pt species in the 1Pt/ $\text{In}_2\text{O}_3$  and 3Pt/ $\text{In}_2\text{O}_3$  catalysts are mostly distributed in the bulk of  $\text{In}_2\text{O}_3$  (Fig. 4a). CO chemisorption provides further evidence that Pt on 1Pt/ $\text{In}_2\text{O}_3$  and 3Pt/ $\text{In}_2\text{O}_3$  mainly exists in the bulk phase (Table S9, ESI<sup>†</sup>).

Compared to the pristine  $\text{In}_2\text{O}_3$  catalyst, all Pt-doped  $\text{In}_2\text{O}_3$  catalysts show much higher activity and methanol yields at 573 K. With increasing Pt content, the  $\text{CO}_2$  conversion increased significantly to 25.1% over 3Pt/ $\text{In}_2\text{O}_3$ , which is nearly three times that achieved with pristine  $\text{In}_2\text{O}_3$  (8.8%). The methanol selectivity decreased slightly from 75.2% over  $\text{In}_2\text{O}_3$  to approximately 70% over 1Pt/ $\text{In}_2\text{O}_3$  (Fig. 4b), consistent with our theoretical predictions in Fig. 3b, and then decreased sharply to 46.8% for 3Pt/ $\text{In}_2\text{O}_3$ . The STY of methanol for 1Pt/ $\text{In}_2\text{O}_3$  is as high as 0.41  $\text{g g}_{\text{cat}}^{-1} \text{h}^{-1}$  with a  $\text{CO}_2$  conversion of 18.9%, which is more than twice that of  $\text{In}_2\text{O}_3$ . The STY of methanol was further enhanced by increasing the GHSV, and that for the 1Pt/ $\text{In}_2\text{O}_3$  catalyst reached 1.25  $\text{g g}_{\text{cat}}^{-1} \text{h}^{-1}$  with a methanol selectivity of 84.8% at 54 000  $\text{mL g}_{\text{cat}}^{-1} \text{h}^{-1}$  (Fig. 4c). Fig. 4f and Table S10 (ESI<sup>†</sup>) show that 1Pt/ $\text{In}_2\text{O}_3$  and 3Pt/ $\text{In}_2\text{O}_3$

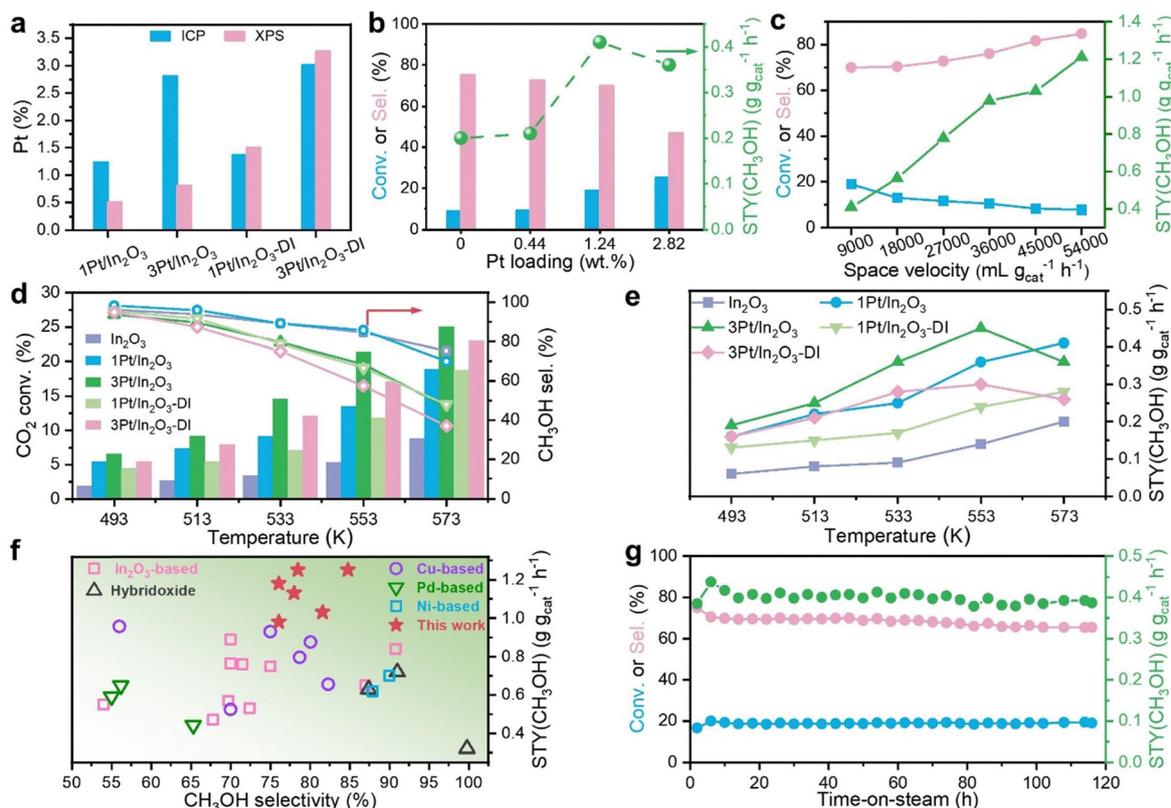


Fig. 4 Catalytic properties of  $\text{In}_2\text{O}_3$  and various Pt-modified  $\text{In}_2\text{O}_3$  catalysts. (a) Pt contents of various catalysts characterized via ICP and XPS. (b) Effects of Pt content on  $\text{CO}_2$  conversion and methanol selectivity over Pt modified  $\text{In}_2\text{O}_3$  catalysts prepared by the hydrothermal method. (c) Catalytic performance of 1Pt/ $\text{In}_2\text{O}_3$  under different space velocities. (d) and (e) Comparison of  $\text{CO}_2$  conversion, methanol selectivity (d) and methanol yield (e) as a function of temperature over  $\text{In}_2\text{O}_3$  and various Pt-modified  $\text{In}_2\text{O}_3$  catalysts. (f) Comparison of the STY and selectivity of methanol over the 1Pt/ $\text{In}_2\text{O}_3$  and 3Pt/ $\text{In}_2\text{O}_3$  samples in this work and other state-of-the-art catalysts (see Table S8 for more details, ESI<sup>†</sup>). (g) Stability test of 1Pt/ $\text{In}_2\text{O}_3$  under standard reaction conditions (5 MPa, 573 K,  $\text{H}_2/\text{CO}_2 = 3:1$ , GHSV = 9000  $\text{mL g}_{\text{cat}}^{-1} \text{h}^{-1}$ ).



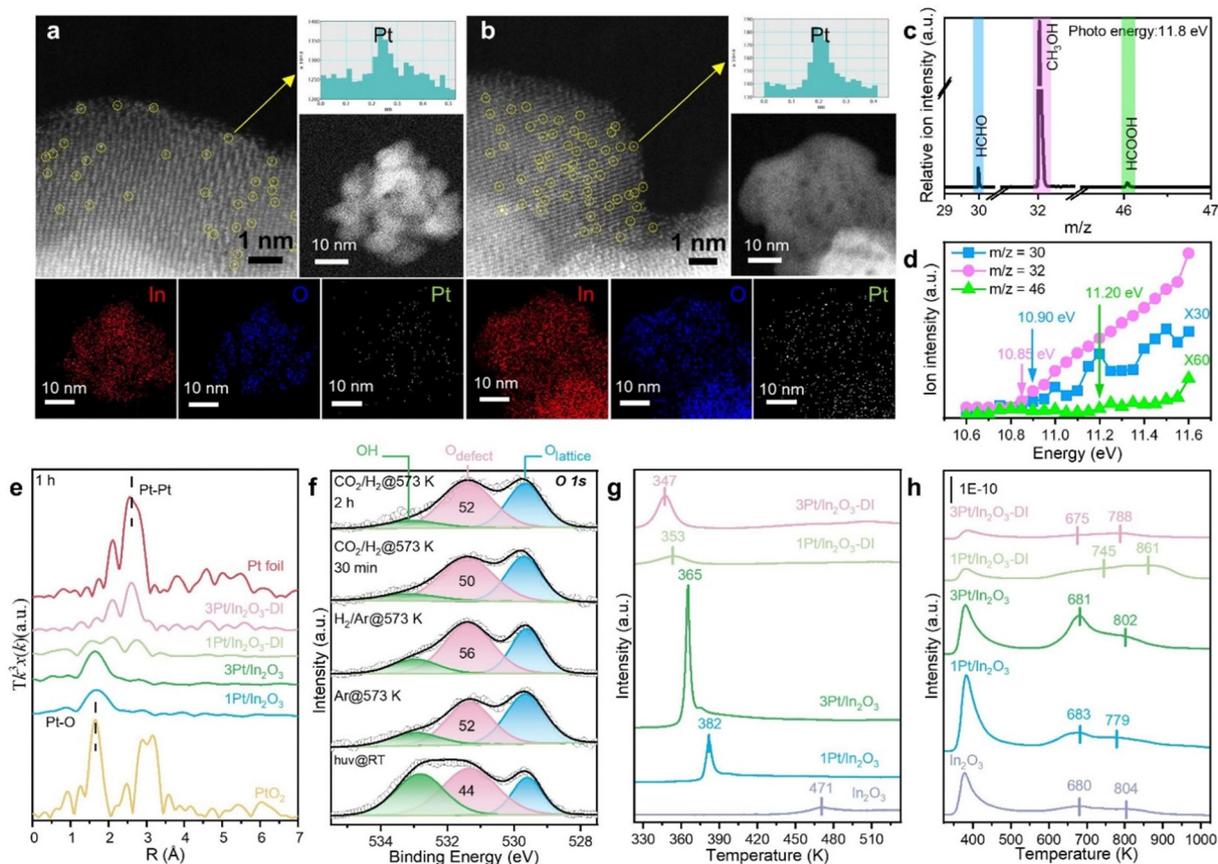
delivered high STYs of methanol together with high methanol selectivity compared with various metal-modified  $\text{In}_2\text{O}_3$  and other state-of-the-art catalysts reported in the literature under similar reaction conditions.<sup>5,15,16,51–63</sup>

The catalytic performances of  $1\text{Pt}/\text{In}_2\text{O}_3\text{-DI}$  and  $3\text{Pt}/\text{In}_2\text{O}_3\text{-DI}$  are much worse than those of bulk-doped  $1\text{Pt}/\text{In}_2\text{O}_3$  and  $3\text{Pt}/\text{In}_2\text{O}_3$ , respectively, especially above 513 K (Fig. 4d and e). The methanol selectivity of  $1\text{Pt}/\text{In}_2\text{O}_3$  is nearly identical to that of  $\text{In}_2\text{O}_3$  in the entire temperature range studied, whereas  $3\text{Pt}/\text{In}_2\text{O}_3$  has much lower methanol selectivity, similar to  $1\text{Pt}/\text{In}_2\text{O}_3\text{-DI}$ , suggesting that the high Pt content in  $3\text{Pt}/\text{In}_2\text{O}_3$  may also increase the content of surface Pt doping. As the reaction temperature increases, the methanol selectivity over  $1\text{Pt}/\text{In}_2\text{O}_3\text{-DI}$  decreases more rapidly than that over  $1\text{Pt}/\text{In}_2\text{O}_3$ , consistent with our theoretical predictions. Compared with  $1\text{Pt}/\text{In}_2\text{O}_3$  and  $1\text{Pt}/\text{In}_2\text{O}_3\text{-DI}$ , the increase in the  $\text{CO}_2$  conversion over  $3\text{Pt}/\text{In}_2\text{O}_3$  and  $3\text{Pt}/\text{In}_2\text{O}_3\text{-DI}$  is slower with increasing temperature, resulting in a lower STY of methanol at 573 K. Arrhenius plots for methanol formation in Fig. S14b (ESI<sup>†</sup>) show that the apparent activation energy for methanol formation for  $1\text{Pt}/\text{In}_2\text{O}_3$  and  $3\text{Pt}/\text{In}_2\text{O}_3$  are 54.0 and 50.5  $\text{kJ mol}^{-1}$ , respectively, which are

lower than those for  $1\text{Pt}/\text{In}_2\text{O}_3\text{-DI}$  (61.8  $\text{kJ mol}^{-1}$ ) and  $3\text{Pt}/\text{In}_2\text{O}_3\text{-DI}$  (68.9  $\text{kJ mol}^{-1}$ ). This also indicates that bulk-doped  $1\text{Pt}/\text{In}_2\text{O}_3$  and  $3\text{Pt}/\text{In}_2\text{O}_3$  are kinetically more favourable with lower energy barriers for methanol synthesis. Moreover, the  $\text{CO}_2$  conversion and methanol yield over  $1\text{Pt}/\text{In}_2\text{O}_3\text{-DI}$  decrease rapidly from 13.0% and 0.26  $\text{g g}_{\text{cat}}^{-1} \text{h}^{-1}$  at 16 h, respectively, to 10.7% and 0.20  $\text{g g}_{\text{cat}}^{-1} \text{h}^{-1}$  at 118 h (Fig. S14e, ESI<sup>†</sup>). A significant deactivation was also detected for  $3\text{Pt}/\text{In}_2\text{O}_3\text{-DI}$  (Fig. S14f, ESI<sup>†</sup>). However, the catalytic performance remains almost constant throughout the 118 h reaction for  $\text{In}_2\text{O}_3$ ,  $1\text{Pt}/\text{In}_2\text{O}_3$  and  $3\text{Pt}/\text{In}_2\text{O}_3$  (Fig. 4g and Fig. S14c, d, ESI<sup>†</sup>).

### Characterizations of Pt-modified $\text{In}_2\text{O}_3$

For samples prepared by the hydrothermal method, the specific surface area significantly increases to 126  $\text{m}^2 \text{g}^{-1}$  for  $3\text{Pt}/\text{In}_2\text{O}_3$  (Fig. S15a and b, ESI<sup>†</sup>). In contrast, the surface areas of  $1\text{Pt}/\text{In}_2\text{O}_3\text{-DI}$  and  $3\text{Pt}/\text{In}_2\text{O}_3\text{-DI}$  are much lower than  $\text{In}_2\text{O}_3$ , indicating that the Pt species might block the pores (Table S9, ESI<sup>†</sup>). Lattice fringes identified at multiple locations in the HRTEM images of all the samples yield a  $d$ -spacing of 0.292 nm, corresponding to the (222) planes of  $\text{In}_2\text{O}_3$  (Fig. S16a and b, ESI<sup>†</sup>).



**Fig. 5** Characterization of various catalysts. (a) and (b) HAADF-STEM images with the corresponding line-scanning intensity profiles obtained on the magnified areas and the TEM-EDS elemental mappings of  $1\text{Pt}/\text{In}_2\text{O}_3$  (a) and  $3\text{Pt}/\text{In}_2\text{O}_3$  (b). (c) *In situ* SVUV-PIMS detection of gas-phase products during the  $\text{CO}_2$  hydrogenation process. (d) Photoionization efficiency spectra of the signals of  $m/z$  30, 32 and 46 during the  $\text{CO}_2$  hydrogenation process. (e) The  $k^3$ -weighted Fourier transform of EXAFS spectra of Pt modified  $\text{In}_2\text{O}_3$  catalysts after the  $\text{CO}_2$  hydrogenation reaction for 1 h. (f) The *in situ* NAP-XPS spectra collected in the simulated reaction process. (g) and (h)  $\text{H}_2$ -TPR (g) and  $\text{CO}_2$ -TPD (h) profiles of pristine  $\text{In}_2\text{O}_3$  and various Pt-modified  $\text{In}_2\text{O}_3$  catalysts pretreated in Ar at 573 K for 1 h.



As shown in Fig. S15c (ESI<sup>†</sup>), only the XRD peaks of the body-centred cubic In<sub>2</sub>O<sub>3</sub> crystalline lattice were observed for all samples. No characteristic diffraction peaks of Pt species were detected, suggesting that the Pt species are highly dispersed on the In<sub>2</sub>O<sub>3</sub>, which is attributed to the strong interaction between Pt and In<sub>2</sub>O<sub>3</sub>. This is further confirmed by aberration-corrected HAADF-STEM characterization, which showed no obvious Pt nanoparticles (Fig. 5a and b). EDS mappings reveal that Pt is uniformly dispersed throughout the sample. No Pt–Pt contribution, but only the Pt–O contribution is observed by the EXAFS spectroscopy at the Pt L<sub>3</sub>-edge for all fresh samples (Fig. S17a, ESI<sup>†</sup>), indicating that the Pt species exist predominantly as isolated atoms, consistent with the HAADF-STEM observations. The fitted Pt–O coordination numbers (CNs) for 1Pt/In<sub>2</sub>O<sub>3</sub>-DI and 3Pt/In<sub>2</sub>O<sub>3</sub>-DI are 4.1 and 3.8, respectively (Table S11, ESI<sup>†</sup>), consistent with the surface-doped Pt/In<sub>2</sub>O<sub>3</sub>(111) model. These coordination numbers are lower than those for 1Pt/In<sub>2</sub>O<sub>3</sub> (CN = 4.7) and 3Pt/In<sub>2</sub>O<sub>3</sub> (CN = 4.4). X-ray absorption near edge structure spectra in Fig. S17c (ESI<sup>†</sup>) show that the white-line intensities for the 1Pt/In<sub>2</sub>O<sub>3</sub>-DI and 3Pt/In<sub>2</sub>O<sub>3</sub>-DI samples are similar to those of PtO<sub>2</sub>, whereas those for the 1Pt/In<sub>2</sub>O<sub>3</sub> and 3Pt/In<sub>2</sub>O<sub>3</sub> are between those of Pt foil and PtO<sub>2</sub>, indicating the oxidation state of Pt species (Pt<sup>n+</sup>, 0 < n < 4).<sup>24,64</sup> The Pt 4d<sub>5/2</sub> XPS peak can be deconvoluted into three peaks located at 314.2, 315.3 and 317.0 eV (Fig. S18, ESI<sup>†</sup>), belonging to Pt<sup>0</sup>, Pt<sup>2+</sup> and Pt<sup>4+</sup>, respectively.<sup>21</sup> The atomically dispersed Pt species in the fresh and thermally pretreated samples carry significant amounts of positive charges. These Pt<sup>n+</sup> (Pt<sup>2+</sup> and Pt<sup>4+</sup>) cations may thus replace the In<sup>3+</sup> ions in the In<sub>2</sub>O<sub>3</sub> lattice or occupy the interstitial sites of 1Pt/In<sub>2</sub>O<sub>3</sub> and 3Pt/In<sub>2</sub>O<sub>3</sub>, strongly binding with lattice O<sup>2-</sup>. For 1Pt/In<sub>2</sub>O<sub>3</sub>-DI and 3Pt/In<sub>2</sub>O<sub>3</sub>-DI, the Pt<sup>n+</sup> cations may be located at defect sites on the In<sub>2</sub>O<sub>3</sub> surface.

When the SACs were exposed to reducing conditions, the interaction between the metal atoms and the support usually became weaker, resulting in aggregation of the metal atoms.<sup>18</sup> Notably, the Pt species in 1Pt/In<sub>2</sub>O<sub>3</sub> and 3Pt/In<sub>2</sub>O<sub>3</sub> remain in the Pt<sup>n+</sup> oxidation state after reaction for 48 h (Fig. S17b and e, ESI<sup>†</sup>), although the Pt–O CN significantly decreases to 2.4 for 1Pt/In<sub>2</sub>O<sub>3</sub> and 2.3 for 3Pt/In<sub>2</sub>O<sub>3</sub> (Table S11, ESI<sup>†</sup>). Additionally, a lack of Pt–Pt bonds also confirms the atomic dispersion of Pt species in the spent 1Pt/In<sub>2</sub>O<sub>3</sub> and 3Pt/In<sub>2</sub>O<sub>3</sub> SACs. These results indicate the very high stability of the Pt SACs even at a high Pt loading of 2.82 wt%. For the spent 1Pt/In<sub>2</sub>O<sub>3</sub> and 3Pt/In<sub>2</sub>O<sub>3</sub>, the Pt–O bond distance remains close to that in PtO<sub>2</sub>, suggesting strong interactions between Pt and In<sub>2</sub>O<sub>3</sub>. However, the Pt species in 1Pt/In<sub>2</sub>O<sub>3</sub>-DI and 3Pt/In<sub>2</sub>O<sub>3</sub>-DI were obviously reduced to metallic Pt (Fig. S17b, d and e, ESI<sup>†</sup>), as Pt–Pt bonds originated from the sintering of surface Pt atoms were formed after reaction for only 1 h (Fig. 5e), which promotes the RWGS reaction. In addition, based on the Pt 4d XPS spectra of 1Pt/In<sub>2</sub>O<sub>3</sub>-DI and 3Pt/In<sub>2</sub>O<sub>3</sub>-DI, the Pt<sup>0</sup> peak appeared after reaction for only 1 h, further confirming the aggregation of Pt species. The ratio of Pt<sup>0</sup> changed slightly when the reaction time was extended to 48 h (Table S12, ESI<sup>†</sup>).

XPS analysis was carried out to investigate the chemical states of surface O sites (Fig. S19, ESI<sup>†</sup>). The O 1s peak at

531.7 eV was assigned to oxygen defect sites (O<sub>defect</sub>), and no significant change in the O<sub>defect</sub> content was observed for the 1Pt/In<sub>2</sub>O<sub>3</sub> and 3Pt/In<sub>2</sub>O<sub>3</sub> SACs after reaction for 1 h and 48 h. In contrast, the surface O<sub>defect</sub> content increased markedly for 1Pt/In<sub>2</sub>O<sub>3</sub>-DI and 3Pt/In<sub>2</sub>O<sub>3</sub>-DI due to the over-reduction of In<sub>2</sub>O<sub>3</sub> during CO<sub>2</sub> hydrogenation, which might inhibit the dissociation of dihydrogen.<sup>65</sup> Although the spent 1Pt/In<sub>2</sub>O<sub>3</sub>-DI and 3Pt/In<sub>2</sub>O<sub>3</sub>-DI have higher surface O<sub>defect</sub> contents than the corresponding 1Pt/In<sub>2</sub>O<sub>3</sub> and 3Pt/In<sub>2</sub>O<sub>3</sub> SACs, this does not necessarily mean that they will have higher activities because XPS can probe several nanometres in depth for the samples. Synchrotron NAP-XPS measurements further confirm the change in surface oxygen defects and also provide insights into changes in the outer layers during the reaction. The *in situ* NAP-XPS data consist of (i) pretreatment at 573 K in 1.5 mTorr Ar, (ii) reduction with 10% H<sub>2</sub>/Ar (1.5 mTorr) to simulate the initial stage of the reaction, and (iii) reaction at 573 K in 2.0 mTorr of the reaction gas mixture (H<sub>2</sub>/CO<sub>2</sub> = 3 : 1). As shown in Fig. 5f, the 1Pt/In<sub>2</sub>O<sub>3</sub> sample pretreated at 573 K in Ar contains more thermally induced oxygen vacancies, and exposure to the H<sub>2</sub>/Ar atmosphere also leads to more H<sub>2</sub>-induced vacancies. Additionally, the V<sub>O</sub> content in the reaction atmosphere decreases slightly and remains stable, consistent with the high stability of 1Pt/In<sub>2</sub>O<sub>3</sub>. *In situ* SVUV-PIMS was employed to detect the gas phase products during CO<sub>2</sub> hydrogenation on 1Pt/In<sub>2</sub>O<sub>3</sub> as shown in Fig. 5c and d. The signals of *m/z* at 30, 32, and 42 have ionization thresholds of 10.90, 10.85 and 11.20 eV, respectively, suggesting the presence of HCHO, CH<sub>3</sub>OH, and HCOOH species during CO<sub>2</sub> hydrogenation, which supports our proposed reaction mechanism.

The H<sub>2</sub>-TPR peak at 469 K shifts to much lower temperatures with the introduction of Pt (Fig. 5g), indicating that the active H adatoms spilling over from the Pt species to In<sub>2</sub>O<sub>3</sub> can enhance the reduction of the In<sub>2</sub>O<sub>3</sub> surface. Additionally, the surface reduction peaks of 1Pt/In<sub>2</sub>O<sub>3</sub> and 3Pt/In<sub>2</sub>O<sub>3</sub> are located at much higher temperatures than those of 1Pt/In<sub>2</sub>O<sub>3</sub>-DI and 3Pt/In<sub>2</sub>O<sub>3</sub>-DI, so bulk Pt doping makes it more difficult to create V<sub>O</sub> sites on the In<sub>2</sub>O<sub>3</sub> surface compared to surface doping. CO<sub>2</sub>-TPD measurements show that for samples prepared by the hydrothermal method, the amount of thermally induced V<sub>O</sub> sites increases significantly with the increasing Pt loading, while the opposite occurs for surface Pt doping (Fig. 5h and Table S13, ESI<sup>†</sup>). 1Pt/In<sub>2</sub>O<sub>3</sub> has the largest total amount of V<sub>O</sub> sites induced by thermal treatment and H<sub>2</sub> reduction among all samples (Fig. S20, ESI<sup>†</sup>), which is further confirmed by the greater intensity of the EPR signal (Fig. S15d, ESI<sup>†</sup>) for 1Pt/In<sub>2</sub>O<sub>3</sub> than for the other samples, contributing to its higher methanol production.

## Conclusions

This study demonstrates the strength of computer-aided design for constructing oxide-based catalysts for industrial reactions; the simulations predicted a bulk-doped SAC with high performance. Our DFT-based microkinetic simulations suggest that



introducing bulk Pt dopants to an  $\text{In}_2\text{O}_3$  catalyst promotes  $\text{CO}_2$  reactivity while maintaining  $\text{CH}_3\text{OH}$  selectivity. Our theoretical prediction facilitates the development of Pt/ $\text{In}_2\text{O}_3$  catalysts with Pt single-atom dopants in the dominantly bulk-doped form, which show more than twice the  $\text{CO}_2$  conversion rate and high catalytic stability while having similar  $\text{CH}_3\text{OH}$  selectivity compared with the pristine  $\text{In}_2\text{O}_3$  catalyst. Our synthesized Pt/ $\text{In}_2\text{O}_3$  SACs thus exhibit great potential for industrial applications in methanol synthesis from  $\text{CO}_2$  hydrogenation, and methanol productivity reaches  $1.25 \text{ g}_{\text{cat}}^{-1} \text{ h}^{-1}$  under the reaction conditions of 5.0 MPa, 573 K and 54 000 mL  $\text{g}_{\text{cat}}^{-1} \text{ h}^{-1}$ , far exceeding the current reported maximum methanol productivity, which is less than  $1.0 \text{ g}_{\text{cat}}^{-1} \text{ h}^{-1}$ .

## Author contributions

S. L., D. A. D. and P. G. conceived the project. Y. W., Z. Z., Q. C., S. L., D. A. D. and P. G. designed the study, analysed the data, and wrote the paper. Y. W., Q. C., B. Q., Y. H., and Y. B. performed DFT calculations. Q. C., Y. W. and K. L. performed microkinetic simulations. Z. Z., S. D., and H. Y. prepared and characterized the samples, and performed the catalytic evaluation. J. M. and J. L. assisted with the XAS experiments. Y. L. assisted with the XPS experiments. All authors discussed the results and commented on the manuscript.

## Data availability

The data supporting this article have been included as part of the ESI.†

## Conflicts of interest

There are no conflicts to declare.

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