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Epoxidation of propene using Au/TiO$_2$: on the difference between H$_2$ and CO as a co-reactant†

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The role of the reducing gas in the direct epoxidation of propene to propene oxide (PO) using O$_2$ over a Au/TiO$_2$ catalyst was studied through experiments and density functional theory calculations. It was found that PO can be obtained using both H$_2$ and CO as co-reactants. The yield of PO was much lower with CO than that with H$_2$. The role of the oxygen atoms of the titania support was studied by quantum-chemical investigations, which show that the mechanism involving CO as a co-reactant should proceed via surface oxygen vacancies, whereas with H$_2$ the well-accepted pathway involving OOH is favored. Steady-state isotopic transient kinetic analysis experiments demonstrate that support oxygen atoms are involved in PO formation when CO is used as the co-reactant.

Introduction

Propene oxide (PO) is an important bulk chemical intermediate, which finds application in the production of a wide range of commercial commodities. The demand for PO is steadily growing. Unlike its homologue ethylene oxide, PO cannot be obtained directly by oxidation of the olefin with oxygen. Accordingly, alternative approaches have been developed for producing this valuable compound. Several of these processes are carried out on an industrial scale, despite some shortcomings such as the production of hazardous wastes (chlorohydrin process), the dependence on the economics of co-products (SMPO and MTBE/PO processes), the requirement of multiple processing steps (chlorohydrin, SMPO, HPPO and cumene recycling process) and the use of an expensive reactant (HPPPO process). Therefore, the one-step synthesis of PO directly from propene and O$_2$ remains the most coveted route.

Despite the development of several catalysts for direct epoxidation of propene, the reported conversions and selectivities are poor. One of the most promising approaches is to use gold nanoparticle catalysts in combination with Ti, either in the form of titania or as isolated Ti species dispersed on silica, in combination with a sacrificial reducing gas such as H$_2$. The use of a reducing co-reactant has been found to be indispensable for obtaining reasonable conversion of propene (5–10%), while maintaining high PO selectivity (>85%). Since this discovery by Haruta et al., significant research efforts have been made to improve the catalyst systems. Some examples of active catalysts are gold dispersed on TS-1, Ti-SiO$_2$, Ti-MCM-41 and Ti-SBA-15. An inherent drawback of this approach is the formation of an excessive amount of water by oxidation of hydrogen. Overall, the low H$_2$ efficiency constitutes a major economic hurdle. It has been reported that water can replace hydrogen, although propene conversion and PO selectivity then become very low.

It is generally assumed that propene oxidation takes place at the interface between Au nanoparticles and Ti sites. Radical 'OOH (hydroperoxo) species formed on gold by the interaction of O$_2$ and H species are thought to be the oxidizing species that convert propene to PO. Theoretical studies have contributed to this discussion by exploring different reaction pathways and reaction intermediates. Quantum-chemical calculations performed by Molina et al. used a one-dimensional gold rod on an anatase-TiO$_2$ (101) slab to model Au/TiO$_2$. This study indicated that propene can be adsorbed with one end on the titania surface and with the other on Au. Reactive 'OOH radicals were argued to be essential for converting propene to a metallacycle C$_3$H$_6$O intermediate. A theoretical study of Delgass and co-workers on Au/TiO$_2$ emphasized the role of gold clusters in forming H$_2$O$_2$ and the role of Ti defect sites in their reaction with propene and H$_2$O to form the desired product. In a later work, the
influence of Au–Ti proximity on the reaction mechanism was studied. Based on the finding that the formation of Ti–OOH on a Au/Ti-defect site model was unfavorable, a concerted mechanism was proposed in which propene is adsorbed on the Au–Ti interface rather than on a Ti site.16 Haruta et al.17 proposed that electron transfer from Au to TiO₂ may lead to the formation of Ti³⁺–O–Au⁺ species. These Ti³⁺ surface sites can activate molecular oxygen with subsequent formation of a hydroperoxo species, which reacts with propene adsorbed on Au to form PO. In summary, although the exact mechanism remains debated, it is clear that ‘OOH radicals and the Au–Ti interface play significant roles in the pathway towards PO formation.

A recent study by Sobolev and co-workers demonstrated that PO can also be formed when H₂ is replaced by CO, using a Au/TiO₂ catalyst.18 An advantage of replacing H₂ with CO is that it largely suppresses the formation of propane,19 which is an undesirable side reaction observed.8,19,20 These authors proposed that the reaction propagates via oxygen vacancy formation on the titania support. They also argued that this mechanism may also be operative in the propene/oxygen/hydrogen case, which is in discord with the well-accepted mechanism involving surface hydrogen peroxide/hydroperoxo (HOOH/OOH) species.16,21 This discrepancy gives rise to a number of important research questions that have not been addressed yet, namely (a) what is the role of support oxygen atoms in the epoxidation of propene, (b) can one indeed replace H₂ with other reducing gases such as CO, and if so (c) what is the underlying mechanism and what role does the support play in such a mechanism. Earlier investigations into the role of the support oxygen atoms in propene epoxidation were inconclusive.22

In this work, we compared the direct epoxidation of propene using a Au/TiO₂ catalyst in the presence of H₂ or CO as co-reactants. Steady-state isotopic transient kinetic analysis (SSITKA) was employed to determine the role of support oxygen atoms. The experimental part of this study was complemented by density functional theory (DFT) calculations of the reaction mechanism using a model consisting of a small Au cluster supported on titania. The catalytic activity measurements show that the PO yield with CO as the co-reactant is much lower than that obtained using H₂ as the co-reactant. Similar observations were made for other catalyst compositions and under different reaction conditions. The DFT calculations explain this difference by identifying different favorable routes for the formation of PO with CO and H₂. Significantly, these data show that the O atoms of titania are involved in the catalytic cycle, a prediction corroborated by SSITKA experiments. The combined experimental and theoretical data provide new insight into the role of the co-reactant in the selective oxidation of propene to PO.

Experimental methods

Catalyst preparation

Au/TiO₂ was prepared by two different preparation methods. A catalyst denoted Au/TiO₂-NM was prepared as outlined by Nijhuis et al.,22 i.e., by deposition–precipitation of Au on titania. In a typical synthesis, 1 g of TiO₂ (Degussa P-25) was suspended in 50 ml of demineralized water. The pH was adjusted to ∼9.5 using a 2.5 wt% ammonia solution. Then, 35.5 μl of HAuCl₄ (Aldrich, 17 wt% Au), diluted in 20 ml of water, was added dropwise (over 15 min) using a burette. The slurry was kept stirring for 1 h, while maintaining the pH at 9.4–9.5 by adding ammonia. Next, the solid was collected by filtration and washed three times using demineralized water. The catalyst was dried overnight at 80 °C and calcined in static air at 120 °C (5 °C min⁻¹, isothermal period = 2 h) and 400 °C (10 °C min⁻¹, isothermal period = 4 h). The resulting catalyst had an intense purple blue color.

Another catalyst, denoted Au/TiO₂-SM, was made as outlined by Sobolev and Koltunov.18,21 A gold precursor solution was made by dissolving 71 μl of HAuCl₄ (Aldrich, 17 wt% Au) in 100 ml of demineralized water and heated to 70 °C. Then, 1 g of TiO₂ (Degussa P-25) was added to the solution and stirring was continued for 1 h. After collecting the solid by centrifugation, it was suspended in 50 ml of NH₄OH (4 M) and the mixture was stirred at 70 °C for 1 h. The suspension was then filtered and washed with 100 ml of demineralized water. Calcination was carried out in static air at 80 °C for 10 h, followed by 300 °C for 4 h. The catalyst had a similar appearance to Au/TiO₂-NM, but was slightly lighter in color suggestive of a lower Au uptake.

The catalyst Au/Ti-SiO₂ was made in the same way as Au/TiO₂-NM. The support was Ti grafted on commercial SiO₂ (Ti-SiO₂). The detailed support preparation can be found in the literature.4,9

Catalyst characterization

Transmission Electron Microscopy (TEM) was used to determine the size distribution of the Au particles in both catalysts. The TEM images were recorded using a FEI Tecnai G2 Sphera transmission electron microscope at an accelerating voltage of 200 kV. Sample preparation involved sonication of the finely ground catalyst in ethanol and application of a few drops of the suspension onto a TEM grid. The size distribution was determined by counting all visible gold particles from approximately 20 images (at least 150 gold particles in total).

The gold loading in the catalysts was analyzed by inductively coupled plasma optical emission spectroscopy (ICP-OES) using a SpectroCiros CCD spectrometer. First, aqua regia was added to the samples, and then these mixtures were heated under stirring for 30 min. The solutions were cooled and then dilute HF (1:15 by volume in water) was added, followed by filtration.

Catalytic activity measurements

Catalytic activity measurements were performed in a flow set-up equipped with an Interscience gas chromatography system (analysis time of ∼5 min), containing two analysis channels with Porabond Q and Molsieve 5A columns and thermal
concentration of oxygenates, which in the case of H$_2$ also includes 5 ml min$^{-1}$ reaching a steady state, the latter two flows (5 ml min$^{-1}$) were switched to a mixture of 30 ml min$^{-1}$ and 5 ml min$^{-1}$ under the given reaction conditions. This makes it unlikely that CO$_2$ formation rates will be much higher when H$_2$ is replaced by CO. Further justification for this assumption is provided in the ESI.$^\dagger$

**Steady-state isotopic transient kinetic analysis (SSITKA)**

SSITKA experiments were performed in a similar way as described in the literature.$^{22}$ In brief, 0.3 g of catalyst was loaded into the reactor after dilution with SiC to maintain a uniform reaction temperature. The reactor feed was then switched to a mixture of 30 ml min$^{-1}$ Ar, 5 ml min$^{-1}$ propene, 5 ml min$^{-1}$ $^{18}$O$_2$ and an additional 5 ml min$^{-1}$ Ar. After reaching a steady state, the latter two flows (5 ml min$^{-1}$ $^{18}$O$_2$ and 5 ml min$^{-1}$ Ar) were replaced by 5 ml min$^{-1}$ $^{18}$O$_2$ and 5 ml min$^{-1}$ Ne. The reaction was then continued for 20 min using $^{18}$O$_2$. Product analysis was performed using a mass spectrometer (MS) and a gas chromatography–mass spectrometry (GC–MS) system.

**Computational methods**

The mechanism of propene oxidation was investigated by spin-polarized periodic DFT calculations using the Vienna $Ab$ $Initio$ Simulation Package (VASP).$^{23}$ The ion–electron interactions were represented by the projector-augmented wave (PAW) method,$^{24}$ and the electron exchange–correlation by the generalized gradient approximation (GGA) with the Perdew–Burke–Ernzerhof (PBE) exchange–correlation functional.$^{25}$ A plane-wave basis set with a cut-off energy of 400 eV was used. The Brillouin zone integration was carried out in the $\Gamma$-point for a Au$_6$ cluster placed on a 5 × 2 supercell of a rutile-TiO$_2$(110) surface containing three O–Ti–O layers, with a vacuum space of 20 Å to avoid spurious self-interactions.$^{26}$ The (110) termination is the most stable among the rutile low-index surfaces. The small 6-atom gold cluster was chosen as a model for gold nanoparticles in their interaction with the titania support. The convergence criteria for the force and the energy were set at 50 meV Å$^{-1}$ and 0.1 meV, respectively. During geometry optimization, the bottom layer was frozen, while the upper two layers were fully relaxed. All adsorbates were fully relaxed during all calculations. The DFT+U methodology ($U$ is a Hubbard-like term describing the on-site Coulomb interactions) was used. $U_{eff}$ was set to 4.0 eV for the Ti 3d orbital.$^{27}$ The climbing image nudged-elastic band (CI-NEB) algorithm was used to search for the minimum energy pathways.$^{28,29}$

**Results and discussion**

**Characterization**

Fig. 1 shows representative TEM images of Au/TiO$_2$-NM and Au/TiO$_2$-SM. These images clearly show the presence of gold nanoparticles homogeneously distributed over the support. Statistical analysis shows that the average particle size and the distribution are comparable between the two catalysts. The average gold particle size is 3.4 nm for Au/TiO$_2$-NM, in close agreement with values reported for gold catalysts synthesized using this method.$^{22}$ The average particle size is 3.1 nm for Au/TiO$_2$-SM, which is slightly higher than the Au particle size reported by Sobolev and Koltunov.$^{21}$ Table 1 lists the targeted and analyzed Au content as determined by ICP-OES. For the TiO$_2$-NM support, the actual Au loading is close to the targeted loading. For Au/TiO$_2$-SM, the actual Au loading is lower than the targeted loading.

![Fig. 1](image-url)
Catalytic activity measurements

The performance of Au/TiO₂-NM and Au/TiO₂-SM in propene epoxidation was evaluated using a gas feed composed of either H₂/O₂/C₃H₆ or CO/O₂/C₃H₆. The reaction conditions were a temperature of 50 °C, a GHSV of 10 000 mL g⁻¹ h⁻¹ and a volumetric feed composition of H₂ (or CO)/O₂/C₃H₆/He = 1/1/1/7. The catalyst prepared as outlined by Sobolev and Koltunov²¹ was also tested at 70 °C, a GHSV of 6000 mL g⁻¹ h⁻¹, and a volumetric feed composition of H₂ (or CO)/O₂/C₃H₆/He = 5 : 10 : 5 : 80 for reasons of comparison to literature data.¹⁸,²¹

Fig. 2 and 3 show the performance in terms of the rate of formation of PO with time on stream of Au/TiO₂-NM and Au/TiO₂-SM, respectively. For both catalysts, the rate of PO formation is higher when H₂ is used as the reducing gas in comparison with CO. With time on stream, the catalysts display initially increasing activity followed by a sharp decline, which is typical for titania-supported gold catalysts used in propene oxidation.³⁰ The maximum PO yield using H₂ for Au/TiO₂-NM is 1.6% (≈20 gPO kg⁻¹ h⁻¹) and the selectivity to PO is higher than 99%, which is in good accordance with the literature.⁴ When CO is used in place of H₂, the maximum yield obtained is 0.6% (≈14 gPO kg⁻¹ h⁻¹) with similarly high PO selectivity. It should be mentioned here that CO₂ was excluded from the conversion and selectivity data when CO was the co-reactant. This is based on the assumption that CO₂ is the product of CO oxidation rather than a full combustion product from propene. Water is the undesired by-product of combustion of the H₂ co-reactant. The rates of H₂O and CO₂ formation for both co-reactants are shown in Fig. 4. These data trend with time on stream in the same way as the PO formation rate, suggesting that the active sites for PO formation and co-reactant combustion are similar. Water is primarily formed by the undesired oxidation of hydrogen at Au sites.²,⁴,⁸,¹⁸ Au/TiO₂ is a known catalyst for CO oxidation to CO₂, so it is reasonable to argue that the majority of the CO₂ product stems from the oxidation of CO at Au sites.²⁶,³¹,³² There are strong indications that the Au–TiO₂ interface plays an important role in catalyzing CO oxidation.²⁶,³³ In both cases, the co-reactant efficiency, defined as the ratio of PO to CO₂ or H₂O, is around 20–25%.

The strong deactivation observed for both catalysts has been extensively studied in the past and is attributed to the strong adsorption of reaction products on the catalyst surface, possibly involving subsequent oligomerization.⁶,³⁴ The activity can be fully recovered by treating the catalysts in 10 vol% O₂/He at 300 °C for 1 h. This regeneration is effective for catalysts operated with either H₂ or CO as a co-reactant. This may indicate that the deactivation mechanism for both cases is the same.

The present results are at odds with those of Sobolev and Koltunov,¹⁸,²¹ who reported higher PO yields when CO was the co-reactant. The present data show that PO is formed when CO is the co-reactant, but the activity is substantially lower in comparison with that obtained using H₂ as the co-reactant. To ensure that the slightly different reaction conditions are not the cause of this discrepancy, Table 1 lists the Au loading obtained for each catalyst, as determined by ICP-OES and TEM microscopy.

Table 1 ICP-OES and TEM of Au/TiO₂ catalysts

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Au loading, wt% (target)</th>
<th>Au loading, wt% (real)</th>
<th>Particle size (\text{b}) (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au/TiO₂-NM</td>
<td>1</td>
<td>0.94</td>
<td>3.4 ± 0.9</td>
</tr>
<tr>
<td>Au/TiO₂-SM</td>
<td>2</td>
<td>0.60</td>
<td>3.1 ± 0.8</td>
</tr>
</tbody>
</table>

\(\text{a}\) Determined by ICP-OES.  \(\text{b}\) Determined by TEM.

Fig. 2. Time-on-stream formation rate of PO during a 2 h catalytic test over Au/TiO₂-NM at X/O₂/C₃H₆/He = 1 : 1 : 1 : 7, where X = CO (black box) and H₂ (red circles), at 50 °C and GHSV = 10 000 mL g⁻¹ h⁻¹ (N.B.: 1 × 10⁻⁷ mol g⁻¹ s⁻¹ corresponds to 20.9 gPO kg⁻¹ h⁻¹; solid lines are drawn to guide the eye).

Fig. 3. Time-on-stream formation rate of PO during a 2 h catalytic test over Au/TiO₂-SM at X/O₂/C₃H₆/He = 1 : 1 : 1 : 7, where X = CO (black box) and H₂ (red circles), at 50 °C and GHSV = 10 000 mL g⁻¹ h⁻¹.
conditions do not cause this difference, we evaluated the catalytic performance of Au/TiO2-SM, the same catalyst explored by Sobolev and Koltunov, under the same conditions. The results shown in Fig. 5 confirm that the PO formation rates are lower with CO than those with H2. Deactivation is more pronounced in this case and the PO formation rate drops to negligible values after about 1 h.

We noted that the Au loading in our case was lower than that reported in the literature. Therefore, we prepared a 2 wt% Au-loaded catalyst (Au/TiO2-NM) by deposition–precipitation as this method ensures complete uptake of the gold in the solution. The resulting performance of this catalyst with CO and H2 (ESI†) confirmed that H2 is the preferred co-reactant. Finally, as it is also known that catalysts based on Ti sites dispersed on silica as the support for gold exhibit more stable and active catalytic performance, we compared the performance of 0.1% Au/Ti–SiO2 in both reactions (Fig. 6). We found that the PO formation rates were stable and significantly higher with H2 as the co-reactant.

Computational modeling

Adsorption of C3H6 and O2. Fig. 7a shows the surface model consisting of a Au6 cluster placed on the (110) surface of rutile TiO2. Two Ti3+ ions are reduced to Ti3+ due to electron transfer from the Au6 cluster to TiO2(110). The two reduced Ti ions are in the second Ti layer of the support. We verified the existence of Ti3+ ions by determining the spin magnetic moment of all Ti atoms in the unit cell. In this way, we identified the presence of two Ti centers with a 3d spin magnetic moment of 0.83 μB, indicative of the localization of an unpaired localized electron in the 3d orbital. Fig. 7a depicts the iso-surface of the spin density, highlighting the presence of two Ti3+ ions. We first examined candidate adsorption sites of propylene and oxygen at the Au6/TiO2(110) interface. Adsorption of C3H6 via the double bond onto a single Au atom is much stronger (−176 kJ mol−1) than bridged adsorption (−94 kJ mol−1) (Fig. 7b). Metiu et al. reported that C3H6 adsorption is much weaker than the adsorption of O2, as shown in Fig. 7c.
stronger on a single Au atom of a positively charged Au5+ cluster (−170 kJ mol⁻¹) than that on a single Au atom of a neutral Au3 cluster (−122 kJ mol⁻¹). The former binding energy is close to our result and the development of a positive charge on the gold cluster is due to the reduction of the support. O₂ prefers to adsorb on Ti Lewis acid sites with an adsorption energy of −118 kJ mol⁻¹. The adsorption energy of O₂ on Au is only −44 kJ mol⁻¹ (Fig. 7c). After O₂ adsorption on a Ti Lewis acid site, the spin magnetic moment of all Ti atoms is 0.00 μB, showing that the electrons initially present in the 3d orbital of the two Ti centers have been transferred to the O₂ adsorbate. The disappearance of the two Ti³⁺ ions and the elongation of the O–O bond of Ti-adsorbed O₂ to 1.41 Å show that O₂ has a superoxide O₂⁻ character.

**Oxygen vacancy formation.** To explore the role of the co-reagent, we investigated the reaction of surface oxygen atoms of the titania support with H₂ and CO at the interface between the Au₆ cluster and the TiO₂(110) surface. Molecular hydrogen is strongly adsorbed on the interfacial Au atom with an energy of −117 kJ mol⁻¹. Its dissociation is almost barrierless (ESI†), suggesting that the adsorption of hydrogen will be dissociative. Water formation involves a relatively high activation barrier of 69 kJ mol⁻¹ and is endothermic (ΔE = 61 kJ mol⁻¹) via reaction of the initially formed OH groups on titania with Au–H (ESI†). Water desorption, which results in an oxygen vacancy, costs 123 kJ mol⁻¹. Such a vacancy can also be obtained by oxidation with CO. In this case, adsorption of CO takes place on a surface Ti site with an energy of −55 kJ mol⁻¹, which is consistent with the reported values on TiO₂. CO can also adsorb on coordinatively unsaturated Au sites, and the adsorption energy is weaker than −1.00 eV. We argue that these sites should be covered by propene because of its much stronger binding to these Au sites. The Ti-adsorbed CO can react with a surface oxygen at the Au₆/TiO₂(110) interface, resulting in an oxygen vacancy. The barrier to form CO₂ is only 55 kJ mol⁻¹, and this process is exothermic by 36 kJ mol⁻¹. As the CO₂ molecule binds only weakly to the surface, the recombinative desorption step is endothermic (ΔE = 42 kJ mol⁻¹). We found that this reaction can also proceed without the Au cluster with a lower barrier of 22 kJ mol⁻¹. These values show that surface oxygen vacancy formation is much easier with CO than with H₂. Accordingly, we explored the mechanisms of PO formation for two cases, i.e., (i) through the formation of a surface oxygen vacancy with CO as the co-reagent and (ii) without such a surface vacancy with H₂ as the co-reagent.

**Propene epoxidation over Au₆/TiO₂(110) without a co-reagent.** We first explored the reaction pathways without the presence of co-reactants (Fig. 9). The adsorption energies of propene on the Au₆ cluster and of O₂ between two adjacent Ti sites are −176 kJ mol⁻¹ and −118 kJ mol⁻¹, respectively. The excess electrons of titania transfer to adsorbed O₂, resulting in the formation of an O₂⁻ species in which the O–O bond is pre-activated. The formation of PO overcomes an energy barrier of 107 kJ mol⁻¹, being exothermic by 76 kJ mol⁻¹. In the transition state for PO formation, the O–O and C₁–O bond lengths are 1.74 Å and 1.83 Å, respectively; those between Au and C₁ and C₂ are 2.67 Å and 2.18 Å, respectively. Following PO desorption which costs 122 kJ mol⁻¹, one oxygen atom is left behind. In the next step, another propene adsorbs on the Au cluster (E_ads = −147 kJ mol⁻¹) and reacts with this leftover O to form another PO; this process overcomes an energy barrier of 87 kJ mol⁻¹. Desorption of the second PO molecule costs 137 kJ mol⁻¹.

**Propene epoxidation over Au₆/TiO₂(110) with H₂.** In the pathway involving H₂ (Fig. 9), we explored H₂ dissociation on Au and O₂ adsorbed between two Lewis acid Ti sites. We started from the surface model with propene adsorbed on the interfacial Au site. Formation of ‘OH and a bridging ‘OH species in this way involves an energy barrier of 69 kJ mol⁻¹. This reaction is strongly exothermic (ΔE = −198 kJ mol⁻¹). The O atom of the OOH species then reacts with the C–C double bond of the adsorbed propene, involving a barrier of 63 kJ mol⁻¹ (TS2), resulting in the formation of an OH group on the surface. Desorption of PO costs 137 kJ mol⁻¹ and the adsorbed OH intermediate reacts with the acidic OH group to form water (barrier of 14 kJ mol⁻¹). The reaction cycle ends by the desorption of water (ΔE = 112 kJ mol⁻¹).

It is interesting to compare the transition states for PO formation involving OOH and O₂ (see the ESI†). In the former case, the C₁–O bond is substantially longer and the C₂–Au bond is shorter than those in the O₂-assisted pathway. In the transition state TS2, the O–O and C₁–O bond lengths are 1.74 and 2.00 Å, and the Au–C₁ and Au–C₂ bond lengths are 2.47 and 2.20 Å. In the transition state TS1 for PO formation, the O–O and C₁–O bond lengths are 1.74 Å and 1.83 Å, respectively; those between Au and C₁ and C₂ are 2.67 Å and 2.18 Å, respectively. The O–O bond length of ‘OH is 1.46 Å, which is longer than that of adsorbed O₂ (1.41 Å), demonstrating that the O–O bond becomes weakened after hydrogenation. Moreover, one ‘OH species is left after the reaction of ‘OH with propene, while one isolated oxygen is left on the surface without H₂. The presence of hydrogen stabilizes the isolated oxygen atom.

As mentioned earlier, two Ti³⁺ ions are present in the Au₆/TiO₂(110) model (Fig. 8a). When O₂ is adsorbed, the Ti³⁺ ions are reoxidized to Ti⁴⁺ and the adsorbed O₂ molecule becomes negatively charged, obtaining a superoxide character. H₂ adsorption and dissociation will reduce two Ti³⁺ into Ti⁴⁺ ions again and generate the OOH⁻ anion involved in propylene...
epoxidation. Obviously, the Ti$^{3+}$ cation plays an important role in the overall reaction, which increases the reducibility of the support surface and catalyzes the O$_2^2-/OOH^-$ anion formation for subsequent propene epoxidation.

Propene epoxidation over Au$_6$/TiO$_2$(110) with CO. For the reaction involving CO, we explored a reaction cycle with an oxygen vacancy in the titania surface (Fig. 10). Molecular oxygen adsorbs strongly on the oxygen vacancy. Adsorption of propene on the interfacial Au atom is slightly less favorable ($E_{ads} = -122$ kJ mol$^{-1}$) than adsorption on the model without a surface vacancy. The PO precursor is formed by dissociation of the O$_2$ molecule, resulting in its coordination to Au and the C$_2$ atom of propene. The barrier for this concerted process is 83 kJ mol$^{-1}$ and the reaction is strongly exothermic ($\Delta E = -144$ kJ mol$^{-1}$). The PO precursor is an oxometallacycle intermediate. The formation of PO occurs by coordination of the O atom to a Lewis acid Ti site, which is 79 kJ mol$^{-1}$ more stable than the precursor. Desorption of PO costs 145 kJ mol$^{-1}$ and the surface returns to its initial state.

It is useful to compare the energy barriers to alternative mechanisms involving only titania or gold. Molina et al. reported a barrier of $\sim$150 kJ mol$^{-1}$ for PO formation on titania. Another study focusing on gold itself showed that adsorption of molecular oxygen is weak ($E_{ads} > -20$ kJ mol$^{-1}$) and the barrier for PO formation via the 'OOH radical is $\sim$95 kJ mol$^{-1}$. Both of these mechanisms are more difficult than that of the reaction explored by our group at the Au–TiO$_2$ interface. Accordingly, the present results emphasize the important role of the Au–Ti interface, in line with experimental data.
We summarize the DFT calculations by comparing the different pathways without and with co-reactants. In the absence of a co-reactant, the activation barrier for PO formation is 107 kJ mol\(^{-1}\), while the involvement of OOH due to the presence of H\(_2\) lowers this activation energy to 63 kJ mol\(^{-1}\). When CO is used as the co-reactant, the mechanism proceeds via a surface oxygen vacancy and the corresponding activation energy is found to be 83 kJ mol\(^{-1}\). We observe that these trends are in good agreement with the experimental findings, where PO is not reported to be formed in the absence of a sacrificial agent on Au–Ti catalysts\(^{1,2}\) and the PO yield in the CO-assisted epoxidation of propene is much lower than that in its hydro-epoxidation, as also revealed by the catalytic performance data in the present study.

SSITKA

From the catalytic experiments, we established that CO can be used as an alternative co-reactant in the direct epoxidation of propene, while DFT calculations for this reaction revealed that support oxygen plays a crucial role in the reaction mechanism towards PO formation. To explore the role of support oxygen experimentally, SSITKA studies were carried out by switching \(^{16}\)O\(_2\) with \(^{18}\)O\(_2\) under steady-state reaction conditions.

Scheme 1 shows the mechanism of PO formation with CO as the co-reactant, as proposed by DFT calculations and the most likely surface species present in the SSITKA experiment. The product stream is expected to predominantly consist of \(\text{C}_3\text{H}_6\text{O}\) (PO\(^{18}\)), \(\text{C}_6\text{O}^{18}\text{O}\) and \(\text{C}_6\text{O}_2\). \(\text{C}_6\text{O}_2\) is expected as a combustion product of PO\(^{18}\) and to be present only in small amounts given the low PO yield.

Fig. 11 shows the transients for CO\(_2\) isotopomers during epoxidation with CO, after switching from \(^{16}\)O\(_2\) to \(^{18}\)O\(_2\). All three CO\(_2\) isotopomers are observed and their relative concentrations at the (pseudo) steady state are \(\text{C}^{16}\text{O}_2 : \text{C}^{16}\text{O}^{18}\text{O} : \text{C}^{18}\text{O}_2 \sim 9 : 6 : 1\). That is to say, the predominant product is \(\text{C}^{16}\text{O}_2\) and it is still seen 15 min after the isotopic switch, indicating the contribution of the support surface oxygen atoms to the reaction mechanism. If the O atoms of the support were not involved, we would expect the predominant product to be \(\text{C}^{16}\text{O}^{18}\text{O}\), with the \(\text{C}^{16}\text{O}_2\) concentration dropping to negligible levels within a very short time after the switch. Nevertheless, it can be argued that some of the formed \(\text{C}^{16}\text{O}^{18}\text{O}\) exchanges with support oxygen to give \(\text{C}^{16}\text{O}_2\). This was for instance observed in a SSITKA study of CO oxidation on Au/TiO\(_2\), but the relative amount of \(\text{C}^{16}\text{O}_2\) was much lower with a \(\text{C}^{16}\text{O}_2 : \text{C}^{16}\text{O}^{18}\text{O} : \text{C}^{18}\text{O}_2\) ratio of \(\sim 1 : 2 : 1\).\(^{1,12}\) Hence, even upon considering some exchange with support oxygen, it is highly unlikely that \(\text{C}^{16}\text{O}_2\) would be the predominant product. Based on these observations, we infer that the steady release of \(\text{C}^{16}\text{O}_2\) is due to the reaction of \(\text{C}^{16}\text{O}\) with support oxygen, \((\text{O})_s\) as described in eqn (3.2) (Scheme 1). It must be noted that the amount of PO was too low to be quantified accurately in the SSITKA experiments and therefore is not shown here. Qualitatively, however, it can be said that PO\(^{18}\) was observed as soon as the switch was made, which is in agreement with Scheme 1.

Conclusions

The present study explores the role of co-reactants in the direct epoxidation of propene to PO on Au/TiO\(_2\) catalysts, using experimental and theoretical tools. When H\(_2\) was substituted by CO as a co-reactant, PO formation was observed but with lower PO yields. PO selectivity, on the other hand, was >99% in both cases and catalyst deactivation, which is a common feature on Au/TiO\(_2\), was also observed in the case of CO, with time on stream.

\begin{align}
\text{C}^{16}\text{O} + \Delta &\rightarrow \text{C}^{16}\text{O} \Delta \\
\text{C}^{16}\text{O} \Delta + (^{16}\text{O})_s &\rightarrow \text{C}^{16}\text{O}_2 \Delta + (\text{O})_s \\
\text{C}_3\text{H}_6 + * &\rightarrow \text{C}_3\text{H}_6 * \\
\text{C}_3\text{H}_6 + + 16\text{O}_2 + (\text{O})_s &\rightarrow \text{C}_3\text{H}_6 16\text{O} * + (^{16}\text{O})_s \\
\text{C}^{16}\text{O} \Delta + (^{16}\text{O})_s &\rightarrow \text{C}^{16}\text{O} 16\text{O} \Delta + (\text{O})_s
\end{align}

Scheme 1 Surface species expected, before and after isotopic switch, in the direct epoxidation of propene with CO.
DFT calculations were employed to explore the probable reaction mechanism for CO-assisted epoxidation and to obtain further insight into the role of support oxygen en route to PO formation. These calculations revealed that formation of oxygen vacancies on the support is energetically more feasible using CO, as compared to H₂. Hence, PO formation with CO as the co-reactant was calculated via this route and the resulting activation energy was 83 kJ mol⁻¹. It was also found that epoxidation without the use of any sacrificial agent on Au/TiO₂ is energetically highly demanding (107 kJ mol⁻¹) and hence improbable. The use of H₂ was found to redirect the mechanism through OOH radical formation, which subsequently lowered the activation energy to 63 kJ mol⁻¹ – the lowest among the three pathways explored. Accordingly, the theoretical findings are in agreement with the experimental observations where the PO yield was observed to be the highest in hydro-epoxidation, followed by CO-assisted epoxidation, and negligible in the absence of any reducing gas. Furthermore, isotopic (SSITKA) measurements experimentally revealed the role of support oxygen in the case of CO epoxidation. This study provides valuable fundamental insight into the important role of a co-reactant in the direct epoxidation of propene and the corresponding mechanisms leading to PO formation on Au–Ti catalysts.

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