

REVIEW

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# Engineering well-defined rare earth oxide-based nanostructures for catalyzing C1 chemical reactions

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C1 chemical reactions have attracted extensive attention in recent decades due to their significant roles in energy transfer and utilization and environmental protection. Among the various catalytic materials, rare earth oxide-based nanocatalysts exhibit superior performances in C1 chemical reactions because of their flexible electronic structures and abundant defect states. In this review, we summarize the nanostructural engineering and applications of rare earth oxide-based nanomaterials with well-defined compositions, crystal phases and shapes for efficiently catalyzing C1 chemical reactions. Initially, we introduce the structural features of rare earth oxides. Subsequently, we present common synthetic approaches and nanostructural engineering strategies toward the preparation of rare earth oxide nanomaterials with well-defined structures. Further, we discuss the structure–function correlation of well-defined rare earth oxide-based nanocatalysts in some important C1 chemical reactions including CO oxidation, water-gas shift reaction, CO<sub>2</sub> hydrogenation, methane oxidation and methanol oxidation. Finally, we prospect the challenges and future research trends in this promising field.

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## 1. Introduction

As a type of important strategic resource, rare earth elements include 15 lanthanide elements (La–Lu) and two other elements, scandium and yttrium. They usually co-exist in minerals and have similar properties, which make their separation challenging.<sup>1</sup> Rare earth elements (except for Sc and Y) have partially unfilled 4f orbitals and abundant electronic energy level structures, thus they have flexible coordination numbers and outstanding catalytic properties for many reactions.<sup>2,3</sup> Rare earth materials play a significant role in various applications such as agriculture, military, petrochemical industry, metallurgy, glass, and ceramics.<sup>4,5</sup>

Nanostructured rare earth oxides are the most common rare earth nanomaterials, which are also the most widely studied.<sup>6</sup> They are cheap and easily obtained, and they have different oxidation states in various conditions. The earliest report of the synthesis of rare earth oxide nanocrystals with a well-defined architecture dates back to the work of Cao's group,<sup>7</sup> which involved the preparation of square Gd<sub>2</sub>O<sub>3</sub> nanoplates *via* a colloidal approach. At almost the same time,

Zhang and Yan's group successively developed various methods for the synthesis of well-defined rare earth oxides with zero-dimensional (0D), one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) nanostructures.<sup>8–11</sup> After development for more than 15 years, researchers have developed various synthetic strategies, and successfully prepared many rare earth oxide nanostructures with diverse well-defined morphologies.

Rare earth oxide nanostructures are broadly applied in catalysis, especially heterogeneous catalysis.<sup>12–15</sup> On the one hand, rare earth oxide nanostructures by themselves are active for some catalytic reactions such as CO oxidation.<sup>12</sup> However, their activity is usually limited due to the weak adsorption of the reagent molecule. On the other hand, rare earth oxide nanostructures can act as supports or promoters to be combined with other metal or metal oxide catalysts.<sup>14</sup> The catalytic properties of composite materials are significantly enhanced due to the synergistic effect between the support materials and loading elements. Further, they are used more widely in catalysis than single rare earth oxide nanostructures.

Among the catalytic reactions, C1 chemical reactions are crucial for addressing both energy and environmental problems faced by mankind in this century due to their important roles in producing essential chemicals (*e.g.* methane and methanol) and controlling pollution (*e.g.* CO and CO<sub>2</sub>).<sup>16–19</sup> Rare earth oxide-based catalysts are a vital class of catalytic nanomaterials for C1 chemical reactions.<sup>20,21</sup> Thus, the devel-

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opment of high-performance rare earth oxide-based catalysts is urgent and significant. Engineering rare earth oxide-based catalysts with well-defined nanostructures is not only beneficial for enhancing their catalytic properties, but also facilitates the study of the relationship between catalytic properties and structure, which can provide guidance for designing catalysts with excellent performances since this is still unclear in many catalytic systems.

Due to the importance of rare earth-based nanomaterials, many groups have reviewed their synthesis and applications in catalysis. For example, Hussein<sup>6</sup> published a thermal analysis and applied pyrolysis review about the formation, characterization and catalytic activity of rare earth oxides. In addition, Zhan *et al.*<sup>3</sup> mainly discussed the catalytic applications of rare earth materials in energy production and utilization, and environmental protection. Guo *et al.*<sup>5</sup> commented on the research advances of rare earth-based catalysts in heterogeneous transformation reactions of small molecules. Richard *et al.*<sup>2</sup> focused on the properties and applications of rare earth elements for CO<sub>2</sub> hydrogenation to methanol. Besides, Huang *et al.*<sup>1</sup> reviewed the synthetic routes and electrochemical applications of rare earth-based nanomaterials. Similarly, the review by Gao *et al.*<sup>4</sup> also discussed and summarized the recent progress on rare earth-based nanocatalysts, but their key point was the incorporation of rare earth elements with transition metals. Although rare earth oxide-based nanostructures were a significant part introduced in the abovementioned reviews, few of them focused on the shape-control of well-defined rare earth nanostructures and their catalytic applications in C1 chemical reactions. Besides, most of the reported

reviews about rare earth oxides mainly focused on the applications of CeO<sub>2</sub> nanomaterials,<sup>22–30</sup> and rarely discussed other rare earth oxides. Therefore, a review that systematically summarizes the morphological engineering of nanostructured rare earth oxides (not only CeO<sub>2</sub>) and highlights their structure–function relationships in some important catalytic reactions is still necessary.

Thus, to meet this demand, in the present review, we focus on the shape-controlled synthesis of well-defined rare earth oxide nanostructures and their catalytic structure–activity correlations. Herein, we introduce the structure features of rare earth oxides and summarize the most common synthetic routes for the preparation of well-defined rare earth oxide nanostructures from the perspective of their morphologies. Moreover, we choose some typical C1 chemical reactions to summarize the relationship between the engineered nanostructures of the rare earth oxide-based nanomaterials and their catalytic properties.

## 2. Structural features of rare earth oxides

Generally, rare earth oxides can be divided into two categories, trivalent oxides and tetravalent oxides. Most of the stable rare earth oxides are trivalent except for CeO<sub>2</sub>, PrO<sub>2</sub> and TbO<sub>2</sub>. The trivalent RE<sub>2</sub>O<sub>3</sub> usually has three types of structures, which are denoted as A, B, and C (Fig. 1a–c, respectively). The A-type RE<sub>2</sub>O<sub>3</sub> is hexagonal, with the *P3m1* space group. The RE<sup>3+</sup> is seven-coordinated with O, in which six O<sup>2–</sup> form an octa-



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Fig. 1 Schematic illustration of the crystal structure of rare earth oxides: (a) A-type  $\text{RE}_2\text{O}_3$ , (b) B-type  $\text{RE}_2\text{O}_3$ , (c) C-type  $\text{RE}_2\text{O}_3$ , and (d) fluorite  $\text{REO}_2$ .

hedron and the last  $\text{O}^{2-}$  is located at one of the facets of the octahedron. The B-type  $\text{RE}_2\text{O}_3$  is monoclinic, with the  $C2/m$  space group. Similarly, the  $\text{RE}^{3+}$  is also seven-coordinated and six  $\text{O}^{2-}$  form an octahedron, but the last  $\text{O}^{2-}$  is a little farther from the  $\text{RE}^{3+}$ . The C-type  $\text{RE}_2\text{O}_3$  is cubic, with the  $Ia\bar{3}$  space group. The  $\text{RE}^{3+}$  is six-coordinated, and the cell structure of C-type  $\text{RE}_2\text{O}_3$  is similar to the cubic fluorite structure, in which only two  $\text{O}^{2-}$  are removed regularly.

$\text{REO}_2$  has a cubic fluorite structure, with the  $Fm\bar{3}m$  space group, in which the  $\text{RE}^{4+}$  is cubic close packing and coordinated with eight  $\text{O}^{2-}$ , and the  $\text{O}^{2-}$  is located in a tetrahedral void and coordinated with four  $\text{RE}^{4+}$  (Fig. 1d). The RE in  $\text{REO}_2$  also has a stable valence of +3, and it can transform between +3 and +4 through the generation and elimination of an oxygen vacancy.

As can be seen in the phase diagram in Fig. 2,  $\text{RE}_2\text{O}_3$  (RE = La–Pr) has an A-type structure,  $\text{RE}_2\text{O}_3$  (RE = Y, Dy–Lu) has a C-type structure, and the others are C-type at low temperature and become B-type at high temperature.



Fig. 2 Phase diagram of  $\text{RE}_2\text{O}_3$ .

### 3. Synthesis of well-defined rare earth oxide nanostructures

Thus far, researchers have developed numerous methods for the synthesis of rare earth oxide nanomaterials with well-defined structures, including 0D nanocubes and nanooctahedra,<sup>8,31–33</sup> 1D nanorods and nanowires,<sup>34–37</sup> 2D nanosheets and nanobelts,<sup>38–41</sup> and 3D dendritic and flower-like structures.<sup>11,42–44</sup> Optimized strategies such as selective adsorption on specific facets, pH adjustment, templating and self-assembly are widely used in engineering well-defined rare earth oxide nanostructures<sup>45,46</sup> (Fig. 3). Rare earth oxide nanomaterials with different shapes usually have diverse physical and chemical properties due to their distinguishable surface structures and chemical states. Hence, controlling the shapes of rare earth oxide nanostructures will support the realization of different functions and applications. In this section, we mainly summarize the synthesis of well-defined rare earth nanostructures considering their morphologies, with the introduction of some typical synthetic examples. Furthermore, it should be noted that most of the rare earth oxides in the cases we discuss below are cubic structure according to their phase diagram. Actually, cubic fluorite  $\text{CeO}_2$  is the most studied nanomaterial based on the current research status of rare earth oxides.

#### 3.1 0D rare earth oxide nanostructures

0D nanomaterials are defined as nanocrystals with a nanoscale size in three dimensions. They usually contain nanocubes, nanooctahedra, nanotetrahedra, nanopolyhedra, etc. In general, nanostructures with different morphologies will have diverse exposed crystal planes. For instance, nanocubes have exposed  $\{100\}$  facets, whereas nanooctahedra and nanotetrahedra have exposed  $\{111\}$  facets. The key factor for the preparation of rare earth oxide nanocrystals with specific shapes is controlling the relative crystal growth rate of specific facets during either the anisotropic growth mode or isotropic growth mode.<sup>8,33</sup>

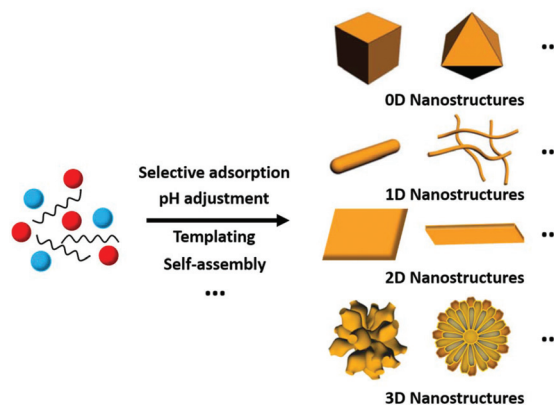


Fig. 3 Schematic illustration of the synthesis of rare earth oxide nanostructures with different morphologies.



Taking the synthesis of rare earth oxide nanocubes as an example, Zhang and Yan's group<sup>8</sup> prepared CeO<sub>2</sub> nanocubes through pH adjustment using a hydrothermal method. The precipitation reaction occurred between Ce(NO<sub>3</sub>)<sub>3</sub> and NaOH, and the secret of gaining CeO<sub>2</sub> nanocubes enclosed with {100} facets was applying a high pH and temperature to achieve a fast dissolution–recrystallization process for the transformation of Ce(OH)<sub>3</sub> into CeO<sub>2</sub> particles. In contrast, a slow dissolution–recrystallization process with a low pH and temperature resulted in the formation of CeO<sub>2</sub> nanopolyhedra with {111} and {100} planes. Besides, the same goal was completed by Dang *et al.*<sup>47</sup> using a liquid–liquid interface with the assistance of oleic acid (OLA). As shown in Fig. 4a, {111}-dominated CeO<sub>2</sub> nanooctahedra or truncated nanooctahedra were obtained in the water phase initially owing to the lower surface energy of the {111} planes, then the OLA selectively adsorbed on the {100} planes, resulting in the transfer of the CeO<sub>2</sub> nanoparticles from the water phase to the toluene phase. Because of the coating of OLA on the {100} planes, the growth rate of the CeO<sub>2</sub> [100] direction was limited, and finally the CeO<sub>2</sub> nanoparticles turned into nanocubes (Fig. 4b). This was a typical case that using selective adsorption on a specific facet controlled the morphologies of the rare earth oxide nanostructures. Specially, Miao *et al.*<sup>48</sup> prepared CeO<sub>2</sub> nanocubes through the doping of F. They concluded that the generation of CeO<sub>2</sub> nanocubes was a result of the etching effect by HF in the crystal growth process.

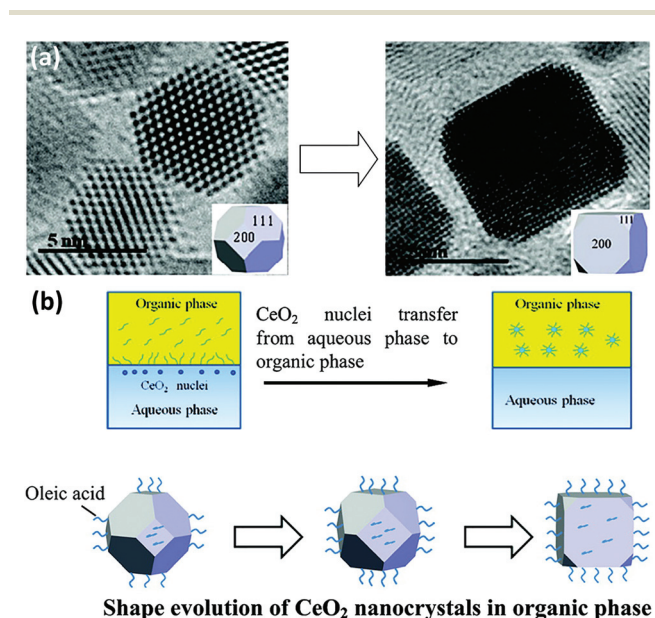
For the preparation of rare earth oxide nanooctahedra, they are easier to be obtained than nanocubes as a consequence of the lower surface energy of the {111} facets than that of the

{100} facets. They can be facily produced by tuning the precipitation step in the hydrothermal method.<sup>32,33</sup> For example, Feng *et al.*<sup>33</sup> synthesized CeO<sub>2</sub> nanooctahedra with a size of around 100 nm using the weak base Na<sub>3</sub>PO<sub>4</sub> in the hydrothermal process. The slow growth rate guaranteed the generation of the more stable morphology of nanooctahedra rather than nanocubes. The authors also demonstrated that replacing Na<sub>3</sub>PO<sub>4</sub> with the strong base NaOH would result in the formation of CeO<sub>2</sub> nanospheres and nanocubes. Similarly, CeO<sub>2</sub> nanooctahedra were successfully synthesized by Ren *et al.*<sup>49</sup> through the hydrothermal route using Ce(NO<sub>3</sub>)<sub>3</sub> and a relatively small amount of NaOH. Also, they also showed that a high concentration of NaOH could yield nanocubes. Specially, single crystalline CeO<sub>2</sub> nanooctahedra were obtained through galvanostatic electrodeposition in a conventional three-electrode cell.<sup>50</sup> It was also the first time that CeO<sub>2</sub> nanooctahedra were prepared *via* the electrochemical route.

In the case of other 0D rare earth oxide nanostructures, nanopolyhedra with no specific shape (called nanoparticles) are common nanomaterials. Their crystal facets usually consist of {100} and {111} planes, and they are easy to obtain because engineering of their morphology is not required. Furthermore, they can be used as reference samples in the study of the plane effect derived from diverse morphologies and are widely used in applications such as catalysis because of their easy accessibility. For their synthesis, Yang *et al.*<sup>51</sup> used the sol–gel method combined with a solvothermal process to obtain CeO<sub>2</sub> nanoparticles with a high surface area. They carried out the solvothermal treatment after they obtained the gel powder, followed by calcination in air to obtain the final product. Additionally, Shiri *et al.*<sup>52</sup> synthesized Sm<sub>2</sub>O<sub>3</sub> nanoparticles using a nitrate bath of Sm(NO<sub>3</sub>)<sub>3</sub> *via* pulse electrochemical deposition assisted by ultrasound. Different from the regular precipitation method, precipitation in reverse microemulsions based on different surfactants was applied to prepare CeO<sub>2</sub> nanoparticles by Shlapa *et al.*<sup>53</sup> A schematic of the synthetic route is shown in Fig. 5. Compared with the traditional precipitation method, the precipitation reaction in reverse microemulsions is limited by the surfactant molecules, and the size can be easily controlled by tuning the length of the hydrophilic part of the surfactant. The as-prepared CeO<sub>2</sub> nanoparticles had a small and uniform size in the range of 6–10 nm and showed good catalase-like activity.

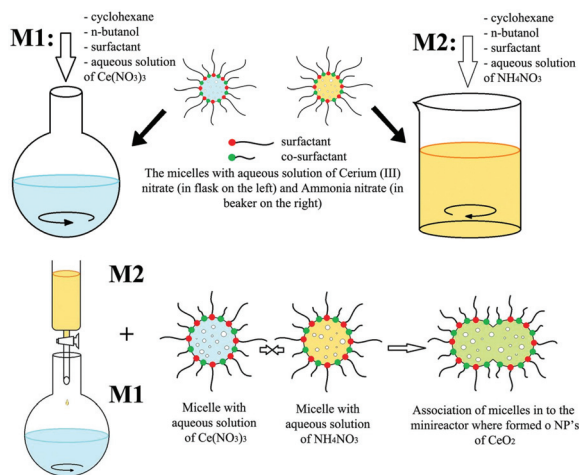
### 3.2 1D rare earth oxide nanostructures

Compared with 0D nanostructures, one non-nanoscale dimension is allowed to exist in 1D nanostructures, while the other two dimensions must be on the nanoscale. 1D rare earth oxide nanostructures including nanorods, nanowires and nanotubes are important nanomaterials for catalysis because of their unique exposed crystal planes, abundant defect sites, and good stability, and they can also provide good models for theoretical simulation.<sup>34,35</sup> In the synthetic strategies for engineering 1D rare earth oxide nanostructures, pH adjustment in the hydrothermal procedure is the most common means because the acid–base balance can influence many key



**Fig. 4** (a) Transmission electron microscopy (TEM) images of the evolution from CeO<sub>2</sub> truncated nanooctahedra to nanocube. (b) Schematic illustration of shape evolution of CeO<sub>2</sub> nanocrystals in the organic phase. Adapted with permission from ref. 47 Copyright 2010, American Chemical Society..





**Fig. 5** Schematic illustration of the synthesis of  $\text{CeO}_2$  nanoparticles *via* precipitation in reverse microemulsions. Adapted with permission from ref. 53. Copyright 2019, Springer Nature.

factors in shape-control such as the crystal growth rate and stability of intermediates.<sup>34–37</sup>

Furthermore, it should be noted that the hydrothermal method for the preparation of rare earth oxides can be divided into two types, alkali and acid methods. The alkali hydrothermal route is very common, for example,  $\text{CeO}_2$  nanorods with a length in the range of 100–300 nm and width of 13–20 nm were firstly prepared by Zhou *et al.*<sup>34</sup> using  $\text{Ce}(\text{NO}_3)_3$  and NaOH. The predominantly exposed facets were the unusually active {001} and {110} planes rather than the {111} plane. The authors provided inspiration for designing and controlling the synthesis of nanocrystals with different shapes. Our group<sup>35</sup> synthesized  $\text{CeO}_2$  nanowires *via* the hydrothermal method at 180 °C using  $\text{CeCl}_3$  and NaOH without the addition of any capping agent. In the synthetic process, NaCl was specially used to obtain uniform wire-like nanostructures dominantly enclosed by {110} facets. We also prepared Ln-doped (Ln = La–Lu)  $\text{CeO}_2$  nanowires using the same method, and the distribution of dopant was very homogeneous. The key was the co-precipitation of  $\text{Ce}^{3+}$  and  $\text{Ln}^{3+}$  to form  $\text{Ce}(\text{OH})_3 \cdot \text{Ln}(\text{OH})_3$ , which transformed into  $\text{CeO}_2 \cdot \text{Ln}$  through calcination. The dopant content was about 10%, and the aspect ratio of most of the  $\text{CeO}_2 \cdot \text{Ln}$  nanowires were smaller than that of the pure  $\text{CeO}_2$  nanowires due to the difference in the ionic radius between Ce and the dopant ion. As another example, Sohn<sup>36</sup> successfully synthesized  $\text{Yb}_2\text{O}_3$  nanowires and nanorods *via* the hydrothermal method at 210 °C using ammonia water as the precipitant, and  $\text{YbCl}_3$  and  $\text{Yb}(\text{NO}_3)_3$  as the precursor, respectively (Fig. 6). The abovementioned cases indicate that besides the vital role of pH adjustment, the formation of 1D rare earth oxide nanostructures also greatly relies on the transformation of the intermediates. It may be difficult to obtain rare earth oxide nanowires or nanorods directly, but it can be easy to obtain their corresponding hydroxides and transform them into oxides. Acid hydrothermal treatment is less used in



**Fig. 6** SEM images of as-synthesized  $\text{Yb}_2\text{O}_3$  (a) nanowires and (b) nanorods. Adapted with permission from ref. 36. Copyright 2018, Elsevier.

the synthesis of 1D rare earth oxide nanostructures. As an example,  $\text{Pr}_2\text{O}_3$  nanowires were prepared by Sobahi<sup>37</sup> using the hydrothermal method by tuning the pH value of the precursor solution of  $\text{Pr}(\text{NO}_3)_3$  to 1.3 and adding glycine as the shaping reagent.

Rare earth oxide nanotubes are another type of important 1D nanomaterials on account of their high surface area and rich defects. Due to the hollow structure of the nanotubes, templating is a very suitable strategy for their preparation. As an example,  $\text{Eu}_2\text{O}_3$  nanotube arrays (Fig. 7a) could be obtained using the sol-gel method assisted by porous anode alumina templates.<sup>54</sup> According to the synthetic mechanism shown in Fig. 7b, the alumina templates were impregnated in the mixture of  $\text{Eu}(\text{NO}_3)_3$  solution and urea, and the solution filled the pores of the templates. After heating the solution, the pH value increased owing to the hydrolysis of urea, resulting in the formation of  $\text{Eu}(\text{OH})_3$  in both the template pores and solution. The sol particles of  $\text{Eu}(\text{OH})_3$  were negatively charged, while the templates were positively charged, and therefore the sol particles gathered at the walls of the templates and gradu-



**Fig. 7** (a) TEM image of  $\text{Eu}_2\text{O}_3$  nanotubes. (b) Schematic illustration of the formation mechanism of  $\text{Eu}_2\text{O}_3$  nanotubes. Adapted with permission from ref. 54. Copyright 2004, American Chemical Society.

ally extended to the center. Finally, the templates were removed from the sol solution and sintered in a furnace, generating  $\text{Eu}_2\text{O}_3$  nanotubes. As another example,  $\text{Tb}_2\text{O}_3$  nanotubes were synthesized by Tang *et al.*<sup>55</sup> through the hydrothermal method using terbium chloride as the precursor and sodium dodecyl benzenesulfonate as the template reagent.  $\text{Tb}(\text{OH})_3$  nanotubes were initially obtained *via* the hydrothermal process after adjusting the solution pH to 12 with NaOH. Finally, they calcined the  $\text{Tb}(\text{OH})_3$  nanotubes at 800 °C under a reducing atmosphere and obtained  $\text{Tb}_2\text{O}_3$  nanotubes. Interestingly,  $\text{Tb}_2\text{O}_3$  nanotubes could also be synthesized through a facile precipitation method using  $\text{Tb}(\text{NO}_3)_3$  and ammonia.<sup>56</sup> The precipitation process involved aging at room temperature for two days, which was necessary for the formation of the tube-like structure under a slow growth rate.

### 3.3 2D rare earth oxide nanostructures

Similar to the definition of 0D and 1D nanostructures, 2D nanostructures allow the existence of two non-nanoscale dimensions, and thus they usually contain nanosheets, nanoplates, nanobelts, *etc.* 2D rare earth oxide nanocrystals have many advantages for catalytic applications such as huge surface area, a variety of defects, and high atomic utilization owing to their thin structure.<sup>57–59</sup> However, it is challenging to prepare 2D rare earth oxide nanomaterials due to the complex requirement of anisotropic growth. In general, a relatively slow growth rate of a specific crystal plane is preferred to realize anisotropic morphologies.

Nanoplates are well-known nanomaterials among the 2D rare earth oxide nanostructures, which have been successfully synthesized *via* several methods.<sup>57,59</sup> The first reported synthetic work on 2D rare earth oxide nanostructures was the  $\text{Gd}_2\text{O}_3$  square nanoplates prepared by Cao<sup>7</sup> using a solution-phase decomposition method. Soon afterwards, Zhang and Yan's group<sup>9,10</sup> prepared a series of cubic rare earth (RE = La–Lu, Y) oxide nanoplates or nanodisks *via* a non-hydrolytic route using various rare earth complexes as precursors with the assistance of oleylamine (OM), oleic acid (OA) and 1-octadecene (ODE). Our group carried out control experiments to determine the specific effects of different experimental parameters. As shown in Fig. 8a, the whole shape evolution can be divided into two parts. Firstly, the rare earth oleates are formed through ion exchange with OA in solution. Secondly, decomposition of the rare earth oleates occurs *via* the catalysis of OM. Due to the selective adsorption of OA on the {100} planes, the  $\text{RE}_2\text{O}_3$  crystals can realize anisotropic growth to generate 2D structures. Also, they would result in diverse morphologies because of the difference in growth rate, which is affected by the rare earth precursors. As another illustration,  $\text{La}_2\text{O}_3$  nanoplates were obtained by Wu *et al.*<sup>60</sup> *via* a combination of precipitation and calcination using  $\text{La}(\text{NO}_3)_3$  and formamide. In the precipitation process,  $\text{La}(\text{OH})_3$  nanoparticles were formed through nucleation and aggregated (Fig. 8b). Then they grew into 1D  $\text{La}(\text{OH})_3$  nanorods because hexagonal  $\text{La}(\text{OH})_3$  has an anisotropic crystal structure. During the calci-



**Fig. 8** (a) Schematic of the formation mechanism of  $\text{RE}_2\text{O}_3$  nanoplates and nanodisks. Adapted with permission from ref. 10. Copyright 2007, American Chemical Society. (b) Schematic illustration of the formation mechanism of  $\text{La}_2\text{O}_3$  nanoplates. Adapted with permission from ref. 60. Copyright 2013, Elsevier. (c) Schematic formation evolution of leaf-like  $\text{CeO}_2$  nanosheets and corresponding scanning electron microscopy (SEM) images of the different stages. Adapted with permission from ref. 61. Copyright 2013, Springer Nature.

nation step, the  $-\text{OH}$  groups were removed and the nanocrystals underwent reconstruction to achieve the lowest surface energy. Consequently, the  $\text{La}(\text{OH})_3$  nanorods transformed into hexagonal  $\text{La}_2\text{O}_3$  nanoplates under the driving force of calcination. The high-resolution TEM (HRTEM) results showed the {002} exposed facet, suggesting that preferential growth occurred along the [002] direction.

In the case of engineering of rare earth oxide nanosheets, Hu *et al.*<sup>61</sup> synthesized leaf-like  $\text{CeO}_2$  nanosheets mainly enclosed with {111} and {200} facets *via* the hydrothermal method using  $\text{Ce}(\text{NO}_3)_3$  as the precursor,  $\text{NH}_4\text{HCO}_3$  as the precipitant, and ethylenediamine as the complexant. As displayed in Fig. 8c, the product evolution could be divided into three stages. In the first stage,  $\text{Ce}^{3+}$  reacted with  $\text{NH}_4\text{HCO}_3$  and generated a large amount of  $\text{Ce}(\text{OH})\text{CO}_3$  nanoparticles, which aggregated to form fluffy particles through self-assembly. Afterwards, nanorods and nanosheets emerged due to the dissolution–recrystallization and self-assembly of the fluffy particles. In the last stage, the nanorods continued to grow until the formation of leaf-like nanosheets. In the whole process, ethylenediamine was coordinated with  $\text{Ce}^{3+}$  and controlled the release of  $\text{Ce}^{3+}$ , thus further controlling the crystal growth



direction to form nanosheets. Similarly, Dai *et al.*<sup>62</sup> obtained CeO<sub>2</sub> nanosheets using Ce(NO<sub>3</sub>)<sub>3</sub> and NH<sub>4</sub>HCO<sub>3</sub>, but they did not add ethylenediamine or any other reagents. As an alternative, they selected a low temperature of 30 °C to carry out the precipitation reaction in order to obtain an adequately slow growth rate for the formation of sheet-like nanostructures. As a supplement, the electrochemical method is also good for synthesizing 2D rare earth oxides. For example, Huang *et al.*<sup>38</sup> obtained Eu-doped CeO<sub>2</sub> nanosheets through electrodeposition on a Ti substrate and subsequent calcination in N<sub>2</sub>. However, the formation mechanism was unclear and needs more exploration.

Rare earth oxide nanobelts is another type of 2D nano-materials that are promising candidates for the fundamental study of physical and chemical properties in many fields.<sup>63,64</sup> However, they are difficult to synthesize due to the preference to form 1D nanostructures or other nanocrystals with lower anisotropy. Some groups successfully achieved their synthesis through the solvothermal method, which is suitable for crystal shape control.<sup>63,64</sup> For example, Eu-doped single-crystal Y<sub>2</sub>O<sub>3</sub> nanobelts with an average thickness of *ca.* 10 nm and width of 40–100 nm were obtained by Li *et al.*<sup>63</sup> using a simple solvothermal method without the addition of any templates. The key factors for controlling the belt-like shape and size were the initial pH of the solution and reaction time of the solvothermal process. As another example, Rao *et al.*<sup>64</sup> obtained mesoporous CeO<sub>2</sub> nanobelts *via* the hydrothermal method, and subsequent calcination without any template or surfactant. The authors researched the effect of the experimental conditions in the hydrothermal process on morphologies of the CeO<sub>2</sub> precursors, and they found that the temperature, cationic type of alkali and ratio of alkali/Ce contributed to the final shape of the products (Fig. 9a–e). Fig. 9f further illustrates the possible formation mechanism of the mesoporous CeO<sub>2</sub> nanobelts. Briefly, colloidal Ce(OH)<sub>3</sub> nuclei were initially formed, followed by dissolution–recrystallization in a mixture of OH<sup>−</sup> and HCHO. Formates and carbonates were generated in the solution *via* the disproportionation reactions between OH<sup>−</sup> and HCHO, and they could coexist due to the high concentration and small radius of Na<sup>+</sup>, which was vital for the anisotropic growth to form belt-like nanostructures. During the calcination of the nanobelt precursors, they transformed into polycrystalline CeO<sub>2</sub> nanobelts and a mass of pores was generated *via* the decomposition of formates and carbonates, leaving sodium oxide on the surface. After washing with water, the final mesoporous CeO<sub>2</sub> nanobelts with a thickness of 10–30 nm and a width of 50–250 nm (Fig. 9g) were obtained. Since rare earth oxide nanobelts are similar to 1D nanostructures to a certain degree, the electrospinning method is also suitable for the preparation of rare earth oxide nanobelts. As an example, Eu<sub>2</sub>O<sub>3</sub> nanobelts with a uniform size were obtained *via* the electrospinning process.<sup>65</sup>

### 3.4 3D rare earth oxide nanostructures

3D nanostructures can be regarded as composites of 0D, 1D, and 2D nanomaterials. 3D rare earth oxide nanostructures play



**Fig. 9** (a) Schematic illustration of the synthesis of CeO<sub>2</sub> precursors under various conditions. TEM images of CeO<sub>2</sub> precursors prepared under various conditions: (b) 140 °C, NaOH : Ce = 3.3; (c) 140 °C, NaOH : Ce = 10.8; (d) 120 °C, KOH : Ce = 16.3; and (e) 180 °C, NaOH : Ce = 16.3. (f) Schematic illustration of the mechanism for the formation of mesoporous CeO<sub>2</sub> nanobelts. (g) TEM image of mesoporous CeO<sub>2</sub> nanobelts. Adapted with permission from ref. 64. Copyright 2013, Elsevier.

a significant role in catalytic applications mainly because of three advantages.<sup>11,66–68</sup> First, they usually have good robustness in catalytic processes due to their anti-sintering ability, which is attributed to their large size. Secondly, they possess a large surface area since they consist of small units such as nanoparticles and nanosheets. Thirdly, they are rich in defects and high-index facets due to the oriented attachment of the tiny building blocks. However, unlike 0D, 1D and 2D nanostructures, the 3D rare earth oxide nanostructures hardly have regular morphologies. They have well-known structures such as dendrites and flowers, but most of them are original nanomaterials.<sup>66–69</sup>

As an instructive work, CeO<sub>2</sub> nanoflowers obtained *via* the rapid thermolysis of (NH<sub>4</sub>)<sub>2</sub>Ce(NO<sub>3</sub>)<sub>6</sub> in a mixture of OA/OM were reported by Zhang and Yan's group.<sup>11</sup> The ceria clusters

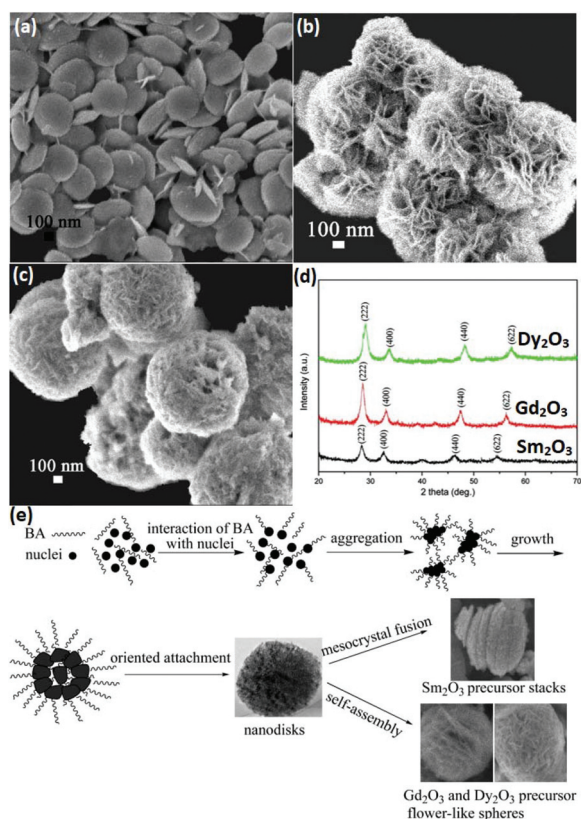


capped with OA and OM were generated as a result of the hydrolysis of  $(\text{NH}_4)_2\text{Ce}(\text{NO}_3)_6$  at a low temperature ( $<220^\circ\text{C}$ ). When the temperature increased to above  $220^\circ\text{C}$ , the capping agents on the surface of the ceria particles disappeared quickly through the redox reaction. Consequently, the small particles spontaneously aggregated *via* 3D oriented attachment and generated  $\text{CeO}_2$  nanoflowers. Self-assembly is often chosen for the construction of 3D rare earth oxide nanostructures, whose driving force is the hydrophobic effect of the surfactants adsorbed on the nanocrystals. For instance, ultra-thin nanodisks of  $\text{Sm}_2\text{O}_3$  and hierarchical flower-like  $\text{Gd}_2\text{O}_3$  and  $\text{Dy}_2\text{O}_3$  (Fig. 10a–c) with abundant high-index  $\{400\}$  facets were prepared by Xiao *et al.*<sup>66</sup> through a benzyl alcohol-based nonaqueous sol-gel route using rare earth acetylacetonates as precursors. The X-ray diffraction (XRD) results showed that all of them were in the cubic phase (Fig. 10d). Also, Fig. 10e shows the possible formation mechanism of these rare earth oxide nanostructures, where nanodisks of the three oxides were obtained in the first stage of the sol-gel process, then  $\text{Sm}_2\text{O}_3$  stacks were formed through mesocrystal fusion, and flower-like spheres of  $\text{Gd}_2\text{O}_3$  and  $\text{Dy}_2\text{O}_3$  were generated *via* self-assembly. The different behaviors in the final stage were

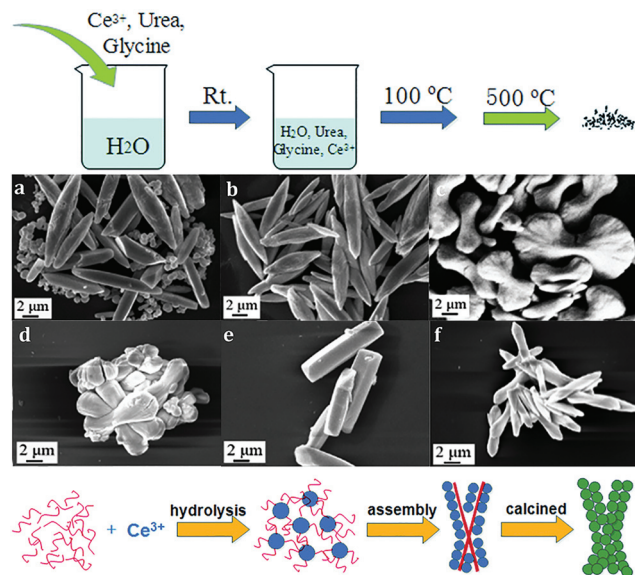
possibly due to their diverse inherent properties such as crystal growth behavior.

With respect to rare earth oxide dendrites, Zhang *et al.*<sup>67</sup> developed a combination method of hydrothermal treatment and thermal decomposition to prepare  $\text{CeO}_2$  dendrites with a three-fold shape. In the hydrothermal procedure, the authors chose  $\text{Ce}(\text{NO}_3)_3$  and urea as reactants to react in a water-triethanolamine (TEA) mixed solvent. It is established that TEA can steadily coordinate with  $\text{Ce}^{3+}$ , which will notably lower the concentration of free  $\text{Ce}^{3+}$  in solution. Thus, the rate of  $\text{Ce}(\text{OH})\text{CO}_3$  formation would be extremely slow, which is beneficial for the crystallization and separation of the nucleation and growth stage. Consequently, the nuclei aggregated with each other and formed three-fold branched units, then these building units connected together through self-assembly and generated the final dendrites. An identical function as TEA could be realized using ammonia water or hydrazine hydrate in the studies by Zhang *et al.*<sup>43,68</sup> They obtained three-fold and four-fold  $\text{CeO}_2$  dendrites by intentionally using ammonia water and hydrazine hydrate, respectively. Both reagents had an important effect on engineering the shape of the  $\text{CeO}_2$  dendrites through decreasing the  $\text{Ce}^{3+}$  concentration and lowering the crystal growth rate, which are crucial for obtaining branched architectures.

Besides 3D dendritic and flower-like rare earth oxides, Qu *et al.*<sup>69</sup> obtained  $\text{La}_2\text{O}_3$  hollow spheres with multi shells *via* a one-pot hydrothermal method combined with calcination. They used a mixture of D-glucose and lanthanum nitrate as the precursor solution, and the special evolution mechanism could be ascribed to the template effect of the carbon in the structure. With a continuous increase in the calcination temperature, the carbon contained in the spheres was oxidized to  $\text{CO}_2$ , resulting in the formation of a multi-shell structure. Besides, Dong *et al.*<sup>70</sup> reported the preparation of coral-shaped  $\text{Dy}_2\text{O}_3$  through an environmentally friendly solvothermal method combined with calcination. They used dysprosium acetylacetonate and carbamide as reagents and methanol as the solvent. The formation of the coral-like  $\text{Dy}_2\text{O}_3$  was based on the spontaneous accumulation of small particles with a size of about 12 nm. Moreover, 3D porous  $\text{CeO}_2$  with various shapes was obtained by Jiang *et al.*<sup>44</sup> *via* a simple precipitation method using glycine as a soft bio-template. The preparation procedure, which involved stirring at room temperature, drying at  $100^\circ\text{C}$ , and calcination at  $500^\circ\text{C}$ , was very facile, as shown in Fig. 11a. By modulating the reagent ratio of  $\text{Ce}^{3+}$ , urea and glycine, shuttle-like, bowknot-like, prism-like, and dumbbell-like  $\text{CeO}_2$  were obtained (Fig. 11b–g). Furthermore, the authors investigated the formation mechanism of the  $\text{CeO}_2$  products, as shown in Fig. 11h. As a bio-template, the glycine provided place for the reaction of  $\text{Ce}^{3+}$  and urea to produce nanospheres since  $\text{Ce}^{3+}$  was adsorbed on the surface of glycine. Then the final product was formed through the self-assembly of the nanospheres. The morphologies could be tuned by the reagent ratio because of its influence on the dispersion and hydrolysis rate of  $\text{Ce}^{3+}$ .



**Fig. 10** SEM images of (a)  $\text{Sm}_2\text{O}_3$  nanodisks; (b)  $\text{Gd}_2\text{O}_3$ ; and (c)  $\text{Dy}_2\text{O}_3$  flower-like spheres. (d) XRD patterns and (e) schematic illustration of the possible formation process of  $\text{Sm}_2\text{O}_3$  nanodisks or  $\text{Gd}_2\text{O}_3$  and  $\text{Dy}_2\text{O}_3$  flower-like spheres. Adapted with permission from ref. 66. Copyright 2009, American Chemical Society.



**Fig. 11** (a) Procedure for the synthesis of 3D porous  $\text{CeO}_2$ . SEM images of  $\text{CeO}_2$  prepared with different ratios of reagents ( $\text{Ce}^{3+}$  : urea : glycine) of (b) 3:0:1; (c) 3:1:1; (d) 3:2:1; (e) 3:40:1; (f) 3:4:2; and (g) 6:2:1. (h) Schematic illustration of the formation of the 3D porous  $\text{CeO}_2$  with a bowknot shape. Adapted with permission from ref. 44. Copyright 2018, Royal Society of Chemistry.

## 4. Catalytic applications of rare earth oxide nanomaterials in C1 chemical reactions

Rare earth oxide nanomaterials are very promising for catalytic applications due to their abundant electronic structures and flexible oxidation states and coordination numbers.<sup>3–5</sup> Also, researchers have already studied and utilized rare earth oxide-based nanocatalysts in many important reactions such as C1 chemical reactions.<sup>20,21</sup> C1 chemical reactions are vital because they are closely related with the generation, storage and conversion of energy and environmental protection.<sup>16–19</sup> Therefore, the development of novel well-defined rare earth oxide nanomaterials with high catalytic performances in C1 chemical reactions has important implications for alleviating the increasing energy and environment crisis. In this section, we employ several typical C1 chemical reactions including the CO oxidation reaction, water gas-shift reaction (WGSR),  $\text{CO}_2$  hydrogenation reaction, methane oxidation reaction and methanol oxidation reaction (MOR) to summarize the nanostructural engineering of rare earth oxide nanomaterials in catalytic applications and reveal the corresponding structure–performance relationship, assisted by some representative works.

### 4.1 CO oxidation reaction

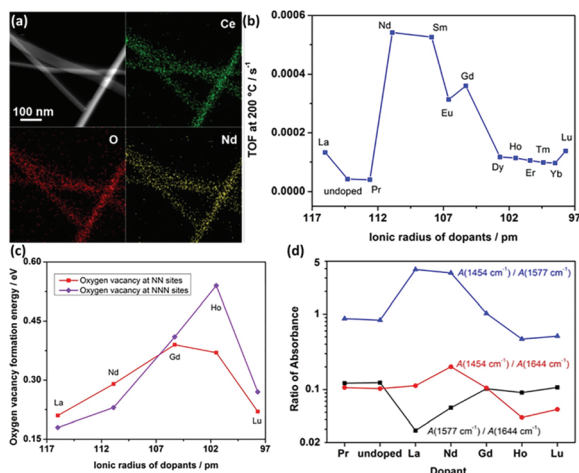
The CO oxidation reaction ( $\text{CO} + \text{O}_2 \rightarrow \text{CO}_2$ ) is often used as a probe reaction to study the structure–activity relationship of catalysts owing to its simple reaction formula and mechanism. Besides, it also has applied value in practical applications such

as automobile tail gas purification, CO sensors, and indoor air purification.<sup>71,72</sup> For the mechanism of the CO oxidation reaction, the Mars-van Krevelen mechanism is accepted by most researchers, that is, a CO molecule reacts with the lattice oxygen of the oxide and *in situ* generates an oxygen vacancy, and then the oxygen molecule fills the vacancy and finishes the cycle. Consequently, oxygen vacancies play a vital role in the catalytic CO oxidation reaction, which are abundant in many rare earth oxide nanomaterials.

Obviously, rare earth oxide nanomaterials can independently catalyze the CO oxidation reaction without modulation with other non-rare earth metals, and their performance is closely correlated with their morphologies.<sup>11,34,73</sup> As an example, the  $\text{CeO}_2$  nanorods synthesized by Zhou *et al.*<sup>34</sup> exhibited a  $T_{50}$  (temperature of 50% CO conversion) of  $186^\circ\text{C}$  towards CO oxidation, which is much lower than that of  $\text{CeO}_2$  nanoparticles. The enhanced activity was ascribed to the well-defined reactive {001} and {110} planes. Our group<sup>73</sup> implemented the dimension-manipulated synthesis of  $\text{CeO}_2$  nanostructures and obtained 0D uniform crystals, 2D polycrystalline assembly, and 3D mesoporous framework. The 2D polycrystalline assembly sample showed the highest activity ( $T_{50} = 310^\circ\text{C}$ ) for CO oxidation, while the 3D mesoporous framework had the lowest activity ( $T_{50} = 390^\circ\text{C}$ ), and all three nanocatalysts were much more active than bulk  $\text{CeO}_2$ . In addition, Kang *et al.*<sup>74</sup> prepared hexagonal  $\text{Pr}(\text{OH})_3$  and cubic  $\text{Pr}_6\text{O}_{11}$  nanorods and tested their activity for CO oxidation. The  $\text{Pr}(\text{OH})_3$  nanorods had a  $T_{10}$  (temperature of 10% CO conversion) of  $525^\circ\text{C}$  in the first run and then transformed into  $\text{Pr}_6\text{O}_{11}$  nanorods after the first run. Subsequently, in the second run, the  $T_{10}$  was  $465^\circ\text{C}$  due to the transformation from  $\text{Pr}(\text{OH})_3$  to  $\text{Pr}_6\text{O}_{11}$ . Although their activity was lower than that of commercial catalysts, they can be applied in catalysis and sensing. As another example, Zhang *et al.*<sup>75</sup> synthesized 3D ordered porous  $\text{Pr}_6\text{O}_{11}$  and  $\text{Tb}_4\text{O}_7$  using a hard template method. The  $\text{Pr}_6\text{O}_{11}$  and  $\text{Tb}_4\text{O}_7$  nanostructures showed a  $T_{50}$  of  $305^\circ\text{C}$  and  $360^\circ\text{C}$ , respectively, which were much more active than commercial  $\text{Pr}_6\text{O}_{11}$  ( $550^\circ\text{C}$ ). The enhanced activity may have originated from their large surface area, abundant oxygen vacancies, and higher low-temperature reducibility.

Doping is a common strategy for enhancing the catalytic activity of rare earth oxide nanomaterials. For instance, the  $\text{CeO}_2$  nanowires prepared by our group<sup>35</sup> could catalyze the CO oxidation reaction with a  $T_{50}$  of  $350^\circ\text{C}$ , which may be ascribed to the facile formation of oxygen vacancies in the  $\text{CeO}_2$  {110} facet. We successfully doped lanthanide elements in the  $\text{CeO}_2$  nanowires (Fig. 12a) to enhance the activity of  $\text{CeO}_2$ , and the most active sample of Nd-doped  $\text{CeO}_2$  nanowires showed an order of magnitude higher activity (TOF at  $200^\circ\text{C} = 5.4 \times 10^{-4} \text{ s}^{-1}$ ) than that of the pure  $\text{CeO}_2$  nanowires (TOF at  $200^\circ\text{C} = 4.1 \times 10^{-5} \text{ s}^{-1}$ , Fig. 12b). We also found that the big difference in the activity of the doped catalysts was derived from two aspects. On the one hand, the oxygen vacancy formation energy of the light rare earth-doped samples was much lower than that of the heavy rare earth-doped samples (Fig. 12c), indicating that the former had more oxygen vacancies, which





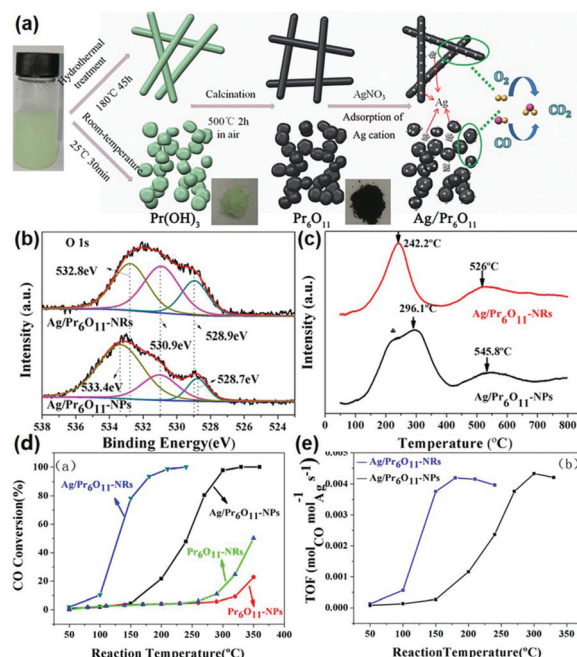
**Fig. 12** (a) EDS mapping images of CeO<sub>2</sub>:Nd. (b) Catalytic activity for the oxidation reaction of lanthanide-doped CeO<sub>2</sub> nanowires versus the radius of the dopants. (c) Oxygen vacancy formation energy of CeO<sub>2</sub>:Ln. (d) Variation of IR intensity at 1454 (unidentate carbonates), 1577 (bidentate carbonates), and 1644 cm<sup>-1</sup> (bicarbonates) with different dopants. Adapted with permission from ref. 35. Copyright 2013, American Chemical Society.

are beneficial for the catalytic activity. On the other hand, the concentration of the active intermediates of unidentate carbonates was also crucial for governing the activity, and Fig. 12d exhibits that CeO<sub>2</sub>:Nd had the largest amount of these active species. These two factors together resulted in the volcano-like relationship between the catalytic activity and the ionic radius of the dopant elements. Similarly, Li *et al.*<sup>76</sup> also demonstrated that doping with La remarkably enhanced the catalytic activity of CeO<sub>2</sub> for the CO oxidation reaction with a *T*<sub>50</sub> of 245 °C because the formation of non-stoichiometric Ce<sub>1-x</sub>La<sub>x</sub>O<sub>2-δ</sub> increased the formation of oxygen vacancies, and the optimal value of *x* is 0.5. Besides doping to boost the concentration of oxygen vacancies in rare earth oxides, reduction treatment is also a suitable method for obtaining higher activity for the CO oxidation reaction. As an example, Gao *et al.*<sup>12</sup> enhanced the activity of as-prepared CeO<sub>2</sub> nanorods *via* chemical redox etching with ascorbic acid.

According to the above examples, it can be concluded that single rare earth oxide nanocatalysts have limited activity for the CO oxidation reaction, and thus the introduction of other metals and engineering the local metal-support structure is a valid and common strategy for boosting their activity, in which rare earth oxide nanomaterials can act as a support.<sup>77–79</sup> For example, our group<sup>77</sup> systematically investigated the effect of the local coordination structure of Pt/CeO<sub>2</sub> nanocatalysts on their activity for CO oxidation. We prepared Pt/CeO<sub>2</sub> catalysts with different Pt–O coordination numbers by tuning the reduction temperature of the samples. A decrease in the activity of the catalysts was observed with an increase in the Pt–O coordination number, and the most active sample had a TOF at 50 °C of  $2.0 \times 10^{-2} \text{ s}^{-1}$ . The Pt atoms were over-stabilized at the catalyst surface, resulting in the inactivation of

some of the Pt atoms when the Pt–O coordination number kept increasing, and thus the activity of the catalyst decreased. Specifically, it was the local structural effect that determined the catalytic performance. As another example, Huang *et al.*<sup>78</sup> prepared Pr<sub>6</sub>O<sub>11</sub> nanorods with a diameter of 20–40 nm and length of several microns using a hydrothermal method. They found that the pure Pr<sub>6</sub>O<sub>11</sub> nanorods were not active for CO oxidation until 220 °C. However, when they loaded gold nanoparticles with a size of 8–12 nm on the surface of the Pr<sub>6</sub>O<sub>11</sub> nanorods, the composites could achieve 100% CO conversion at 140 °C, and were also much more active than the Au/Pr<sub>6</sub>O<sub>11</sub> bulk. Similarly, Zhang *et al.*<sup>79</sup> synthesized and studied nanostructured Ag/Pr<sub>6</sub>O<sub>11</sub> for CO oxidation. The authors prepared Pr<sub>6</sub>O<sub>11</sub> nanorods and nanoparticles using different routes, and utilized them as supports to couple with Ag species *via* the conventional impregnation method (Fig. 13a). The XPS results indicated that the Ag/Pr<sub>6</sub>O<sub>11</sub> nanorods possessed more oxygen vacancies than that of the Pr<sub>6</sub>O<sub>11</sub> nanoparticles (Fig. 13b). Besides, the H<sub>2</sub>-TPR profiles showed a stronger synergistic effect between Ag and Pr<sub>6</sub>O<sub>11</sub> in the Ag/Pr<sub>6</sub>O<sub>11</sub> nanorods (Fig. 13c), suggesting higher activity for this catalyst. As expected, the Ag/Pr<sub>6</sub>O<sub>11</sub> nanorods showed a better performance than the Ag/Pr<sub>6</sub>O<sub>11</sub> nanoparticles for CO oxidation, where the *T*<sub>50</sub> of the Ag/Pr<sub>6</sub>O<sub>11</sub> nanorods was around 125 °C (Fig. 13d and e).

The well-known shape effect of rare earth oxide nanomaterials also has a vital influence on the catalytic activity for



**Fig. 13** (a) Schematic illustration of the synthetic routes for Pr<sub>6</sub>O<sub>11</sub> nanostructures. (b) O 1s XPS spectra of Ag/Pr<sub>6</sub>O<sub>11</sub> catalysts. (c) H<sub>2</sub>-TPR profiles of Ag/Pr<sub>6</sub>O<sub>11</sub> catalysts. (d) CO conversion of Pr<sub>6</sub>O<sub>11</sub> and Ag/Pr<sub>6</sub>O<sub>11</sub> samples for CO oxidation. (e) TOF of Pr<sub>6</sub>O<sub>11</sub> and Ag/Pr<sub>6</sub>O<sub>11</sub> samples for CO oxidation. Adapted with permission from ref. 79. Copyright 2017, American Chemical Society.



CO oxidation when they act as a support.<sup>80,81</sup> Taking the work of Lykaki *et al.*<sup>80</sup> as an example, they prepared CeO<sub>2</sub> nanorods (NR), nanopolyhedra (NP), and nanocubes (NC) *via* the hydrothermal method, and explored the shape effect of Cu/CeO<sub>2</sub> on their catalytic properties. The results of the catalytic test showed that the activity ( $T_{50}$ ) of both the pure CeO<sub>2</sub> and Cu/CeO<sub>2</sub> followed the same order of NR (320/72 °C) > NP (350/83 °C) > NC (385/92 °C). The authors used multiple characterizations to investigate the structure–function correlation, and found that the activity had a direct correlation with the amount of Cu<sup>+</sup> and oxygen defects. They proposed the reaction mechanism based on the Mars-van Krevelen mechanism, which highlighted the significant roles of oxygen vacancies and Cu<sup>+</sup> in this benchmark reaction. Furthermore, it is known that the shape effect is equal to the plane effect. Also, NR have mainly exposed {110} and {100} facets, while NP are enclosed with {111} and {100} facets, and NC have exposed {100} facets. Therefore, the CeO<sub>2</sub> {110} planes were beneficial for CO oxidation due to their easy generation of oxygen defects.

In general, the nanostructural engineering of rare earth oxide-based catalysts for the CO oxidation reaction is mainly focused on the tuning of oxygen vacancies, the effect of which mainly embodied in stabilizing the metal loading on the surface of the rare earth oxides and providing sites for the adsorption and activation of O<sub>2</sub>. Also, the strategies for modulating oxygen vacancies usually involve reduction treatment, doping, controlling the size and morphology, *etc.* Besides, other factors such as the surface area and metallic oxidation state of the rare earth oxide-based catalysts also have a significant effect on the catalytic performance. Thus, researchers should consider all these factors in the design of catalysts with excellent properties for CO oxidation.

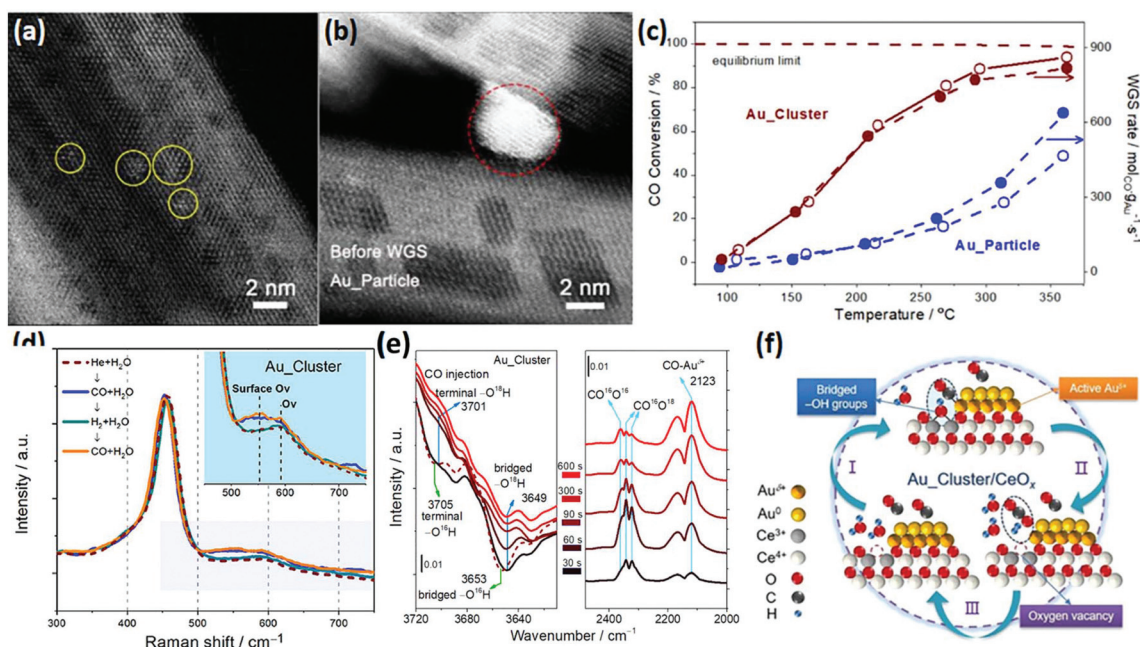
## 4.2 WGS

The WGS ( $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$ ) is mainly used for converting CO to CO<sub>2</sub> and H<sub>2</sub> in syngas, which has important application value in hydrogen production, fuel cells and ammonia synthesis.<sup>82</sup> Most of the catalysts for the WGS are supported nanomaterials since single materials hardly exhibit activity. Rare earth oxide nanomaterials are widely used as a support for the WGS due to their good stability and abundant oxygen vacancies, which are significant for stabilizing the metal loading and activating H<sub>2</sub>O molecules.<sup>83,84</sup> Also, a good way for improving the catalytic performance is through tuning the morphologies of rare earth oxides since the shape effect is also important for the WGS.

Among the various catalytic systems, noble metals such as Au and Pt supported by well-defined rare earth oxide nanostructures have been extensively applied for the WGS because of their high activity and good stability.<sup>83–86</sup> For example, Si *et al.*<sup>87</sup> investigated the catalytic performance of Au/CeO<sub>2</sub> with nanorod, nanocube and nanopolyhedra structures. They found that the WGS performance strongly depended on the exposed facets, and the sample of Au/CeO<sub>2</sub> nanorods showed the highest activity among the three samples. This could be explained by the lowest anion vacancy formation energy on the

{110} planes, which meant more oxygen vacancies boosted the catalytic activity. As another example, Fu *et al.*<sup>15</sup> prepared two types of Au/CeO<sub>2</sub> catalysts, including Au nanoclusters (<2 nm) and Au nanoparticles (3–4 nm), for the WGS (Fig. 14a and b, respectively). Specially, the Au nanoclusters were *in situ* generated in the reaction process from Au single atoms. The Au nanoclusters showed higher activity (rate at 200 °C =  $5.0 \times 10^2 \text{ mol g}_{\text{Au}}^{-1} \text{ s}^{-1}$ ) compared with that of the Au particles (rate at 200 °C =  $1.0 \times 10^2 \text{ mol g}_{\text{Au}}^{-1} \text{ s}^{-1}$ ) because of their more abundant interfacial sites (Fig. 14c). The results of *in situ* Raman spectroscopy demonstrated that the oxygen vacancies were involved in the catalytic reaction, which were the most abundant in the Au<sub>cluster</sub>/CeO<sub>x</sub> sample (Fig. 14d). The authors also performed *in situ* infrared spectroscopy (IR) to investigate the reaction mechanism, and they found that the bridged surface –OH groups were essential for the conversion of the CO adsorbed on the Au<sup>δ+</sup> species to CO<sub>2</sub>, which was verified by the isotopic labelling experiment, where one of the O atoms in CO<sub>2</sub> came from the bridged –OH group (Fig. 14e). Fig. 14f shows the whole cycle of the catalytic process, where H<sub>2</sub>O was activated at the oxygen vacancy and generated a bridged –OH group in the first stage, then the bridged –OH group reacted with the CO adsorbed on the Au<sup>δ+</sup> species to produce CO<sub>2</sub> in the second stage, and finally the CO<sub>2</sub> desorbed and left a new oxygen vacancy. The moderate Au<sup>δ+</sup> species, bridged –OH group and oxygen vacancies were essential in the WGS.

The use of non-Ce rare earth oxides for supporting noble metals has been less applied in the WGS compared with CeO<sub>2</sub>. For instance, novel Au/La<sub>2</sub>O<sub>3</sub> and Au/La<sub>2</sub>O<sub>2</sub>SO<sub>4</sub> catalysts for the low-temperature WGS were synthesized by Lessard *et al.*<sup>13</sup> through an anion adsorption method. They found that both Au/La<sub>2</sub>O<sub>3</sub> and Au/La<sub>2</sub>O<sub>2</sub>SO<sub>4</sub> had a good WGS activity, and Au/La<sub>2</sub>O<sub>2</sub>SO<sub>4</sub> showed higher activity compared with that of Au/La<sub>2</sub>O<sub>3</sub> which may be because of its higher content of Au<sup>3+</sup>, as confirmed by the X-ray photoelectron spectroscopy (XPS) results. Besides, the authors carried out chemical leaching of the catalysts using NaCN, and the leached samples exhibited no difference in activity, indicating that the support of La<sub>2</sub>O<sub>3</sub> and La<sub>2</sub>O<sub>2</sub>SO<sub>4</sub> could well stabilize the Au species. Besides, Pt supported by a composite oxide of Ce<sub>0.6</sub>Y<sub>0.4</sub>O<sub>2</sub> for the WGS was obtained by Lee *et al.*<sup>86</sup> *via* a sol–gel method. As can be seen in Fig. 15a, the activity of Pt/Ce<sub>0.6</sub>Y<sub>0.4</sub>O<sub>2</sub> (TOF at 250 °C =  $5.5 \times 10^{-1} \text{ s}^{-1}$ ) was much higher than that of both Pt/CeO<sub>2</sub> (TOF at 250 °C =  $1.6 \times 10^{-1} \text{ s}^{-1}$ ) and Pt/Y<sub>2</sub>O<sub>3</sub> (TOF at 250 °C =  $1.3 \times 10^{-1} \text{ s}^{-1}$ ), and also higher than that of many reported Pt-based WGS catalysts. The H<sub>2</sub>-TPR results (Fig. 15b) showed that the introduction of Y to CeO<sub>2</sub> obviously enhanced the reducibility and the oxygen mobility of the support. Furthermore, the CO-TPR profiles indicated that there were much more OH species in the Pt/Ce<sub>0.6</sub>Y<sub>0.4</sub>O<sub>2</sub> sample than the other two catalysts (Fig. 15c and d), which are beneficial for the WGS. The authors also performed diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) to explore the surface reactions on these catalysts (Fig. 15e). The results clearly showed that the CO adsorption on Pt/Ce<sub>0.6</sub>Y<sub>0.4</sub>O<sub>2</sub> was weaker than that on Pt/CeO<sub>2</sub> and Pt/Y<sub>2</sub>O<sub>3</sub>, indicating its more



**Fig. 14** High-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) images of (a) Au-cluster/CeO<sub>x</sub> and (b) Au-particle/CeO<sub>x</sub> catalyst. (c) Catalytic activity for the WGS reaction by the Au-cluster/CeO<sub>x</sub> and Au-particle/CeO<sub>x</sub> catalysts. (d) *In situ* Raman spectra of Au-cluster/CeO<sub>x</sub> under different atmospheres at 150 °C. (e) *In situ* time-resolved IR spectra of Au-cluster/CeO<sub>x</sub> under CO injection with isotope prelabeling using H<sub>2</sub>O<sup>18</sup>. (f) Schematic illustration of the reaction mechanism of Au-cluster/CeO<sub>x</sub> catalyst for the WGS. Adapted with permission from ref. 15. Copyright 2019, American Chemical Society.

efficient activation of CO. In general, the enhanced reducibility of the support and reduced CO adsorption contributed to the higher activity.

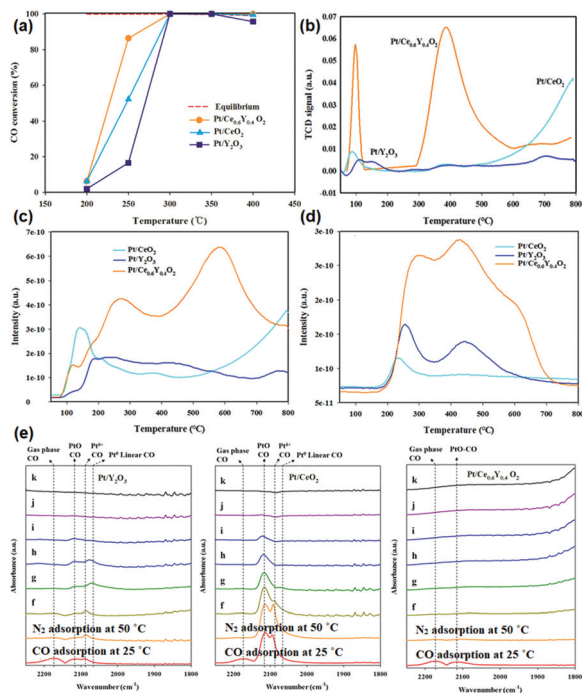
Although supported noble catalysts have superior catalytic properties for the WGS, their high price limits their large-scale application. Accordingly, nowadays, many researchers aim to use a base metal in the nanostructural engineering of catalysts to obtain high performances for the WGS.<sup>88–90</sup> For instance, Ren *et al.*<sup>49</sup> studied the plane effect on the activity of Cu/CeO<sub>2</sub> catalysts for the WGS. The results showed that the Cu catalysts supported on CeO<sub>2</sub> nanooctahedra with {111} facets were more active than that of supported on nanorods and nanocubes, which could be attributed to the best dispersion of Cu, strongest Cu–CeO<sub>2</sub> interactions and the largest amount of Cu species with a moderate valence. She *et al.*<sup>88</sup> studied the doping effect of RE<sub>2</sub>O<sub>3</sub> (RE = Y, La, Sm, Nd) on the WGS activity of CuO/CeO<sub>2</sub> catalysts. The evaluation of their catalytic performance showed that the introduction of La<sub>2</sub>O<sub>3</sub> and Nd<sub>2</sub>O<sub>3</sub> was beneficial for enhancing the activity and stability of CuO/CeO<sub>2</sub>, but the doping of Y<sub>2</sub>O<sub>3</sub> and Sm<sub>2</sub>O<sub>3</sub> exhibited negative effects. The Raman spectra showed that the CuO/CeO<sub>2</sub>–La<sub>2</sub>O<sub>3</sub> and CuO/CeO<sub>2</sub>–Nd<sub>2</sub>O<sub>3</sub> samples had more oxygen vacancies than CuO/CeO<sub>2</sub>, while that of the Y and Sm-doped samples were less. Besides, the authors measured the Cu dispersion using N<sub>2</sub>O and found out that the order of Cu dispersion was consistent with the order of activity. The H<sub>2</sub>-TPR results showed three peaks for non-crystalline copper oxide, moderate copper oxide (crystalline) and surface ceria.

Interestingly, the order of the peak area for moderate copper oxide was also consistent with that of activity. In summary, the difference in activity mainly originated from the concentration of oxygen vacancies, Cu dispersion, and moderate Cu valence. Another Cu/CeO<sub>2</sub> catalyst for the WGS was synthesized by Chen *et al.*<sup>89</sup> using a co-precipitation method. In order to improve the activity, the authors attempted to calcine the catalyst at 300 °C in air, vacuum and H<sub>2</sub>. They found that the catalyst annealed in H<sub>2</sub> had the highest performance due to the highest amount of oxygen vacancies and strongest synergistic interaction between CuO and CeO<sub>2</sub>.

Based on the research thus far, it can be concluded that rare earth oxide nanomaterials are rarely used alone for the WGS on account of their weak adsorption of CO. They are always used as a support and additive to improve the catalytic performance through the construction of well-defined structures and controlling the electronic and geometric structure of the catalysts. The effects of rare earth oxide nanomaterials are mainly reflected in dispersing metal catalysts, providing active sites such as oxygen vacancies and enhancing the metal support interaction and synergistic effect.

### 4.3 CO<sub>2</sub> hydrogenation reaction

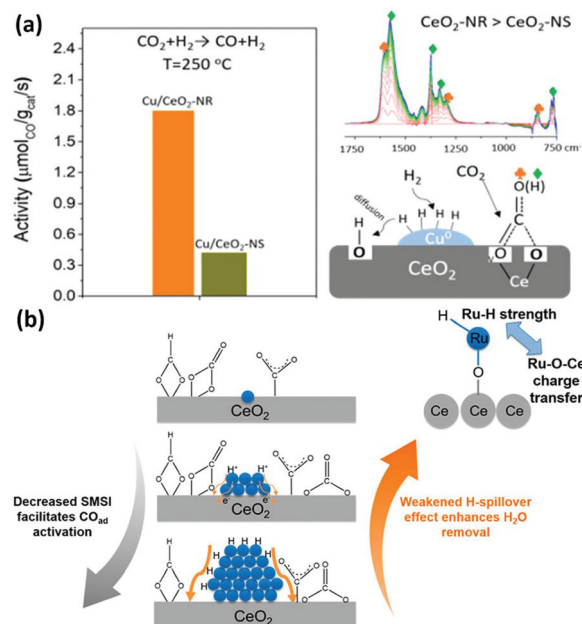
The CO<sub>2</sub> hydrogenation reaction is not a specific reaction since it has several possible products, such as CO, methane and methanol. It is a significant reaction because it not only can weaken the greenhouse effect, but also ease the energy crisis.<sup>91</sup> However, the high chemical stability of the CO<sub>2</sub> molecule and



**Fig. 15** (a) CO conversion of Pt/Y<sub>2</sub>O<sub>3</sub>, Pt/CeO<sub>2</sub> and Pt/Ce<sub>0.6</sub>Y<sub>0.4</sub>O<sub>2</sub> in the WGS. (b) H<sub>2</sub>-TPR profiles of Pt/Y<sub>2</sub>O<sub>3</sub>, Pt/CeO<sub>2</sub> and Pt/Ce<sub>0.6</sub>Y<sub>0.4</sub>O<sub>2</sub>. CO-TPR profiles of Pt/Y<sub>2</sub>O<sub>3</sub>, Pt/CeO<sub>2</sub> and Pt/Ce<sub>0.6</sub>Y<sub>0.4</sub>O<sub>2</sub>: (c) CO<sub>2</sub> profile and (d) H<sub>2</sub> profile. (e) DRIFTS spectra of Pt/Y<sub>2</sub>O<sub>3</sub>, Pt/CeO<sub>2</sub> and Pt/Ce<sub>0.6</sub>Y<sub>0.4</sub>O<sub>2</sub>: (f) N<sub>2</sub> adsorption at 100 °C; (g) N<sub>2</sub> adsorption at 150 °C; (h) N<sub>2</sub> adsorption at 200 °C; (i) N<sub>2</sub> adsorption at 250 °C; (j) N<sub>2</sub> adsorption at 300 °C; and (k) N<sub>2</sub> adsorption at 350 °C. Adapted with permission from ref. 86. Copyright 2018, American Chemical Society.

the complexity of its products are a big challenge for catalysts for this reaction. The abundant electronic structures and flexible oxidation states of rare earth oxide nanomaterials are beneficial for the CO<sub>2</sub> hydrogenation reaction, which is ascribed to their facile activation of CO<sub>2</sub> and selectivity control.<sup>92</sup> Nevertheless, pure rare earth oxides are less used for catalyzing this reaction due to their poor activity. Here, we summarize the nanostructural engineering of rare earth oxide nanomaterials utilized in the CO<sub>2</sub> hydrogenation reaction according to the different products.

The CO<sub>2</sub> hydrogenation reaction is also known as the reverse water gas shift (RWGS) reaction ( $\text{CO}_2 + \text{H}_2 \rightarrow \text{CO} + \text{H}_2\text{O}$ ) when the product is CO and H<sub>2</sub>O. The morphologies of rare earth oxides have a significant influence on their catalytic performance.<sup>93,94</sup> As an example, CeO<sub>2</sub> nanocatalysts with different morphologies synthesized by Dai *et al.*<sup>93</sup> using various methods showed extremely different activities for the RWGS reaction. CeO<sub>2</sub> with a 3D porous structure was much more active than the loosely aggregated CeO<sub>2</sub> nanoparticles and bulk CeO<sub>2</sub> due to its largest surface area and oxygen vacancy concentration. As another example, Lin *et al.*<sup>94</sup> prepared Cu/CeO<sub>2</sub> nanorods and Cu/CeO<sub>2</sub> nanospheres and investigated their catalytic performance for the CO<sub>2</sub> hydrogenation reaction. They found that both catalysts mainly produced CO



**Fig. 16** (a) Activity and schematic illustration of the mechanism of the RWGS reaction for Cu/CeO<sub>2</sub> nanorods and Cu/CeO<sub>2</sub> nanospheres. Adapted with permission from ref. 94. Copyright 2018, American Chemical Society. (b) Schematic illustration of the complete effect between SMSI and H-spillover on Ru/CeO<sub>2</sub> catalysts for the CO<sub>2</sub> methanation reaction. Adapted with permission from ref. 96. Copyright 2018, American Chemical Society.

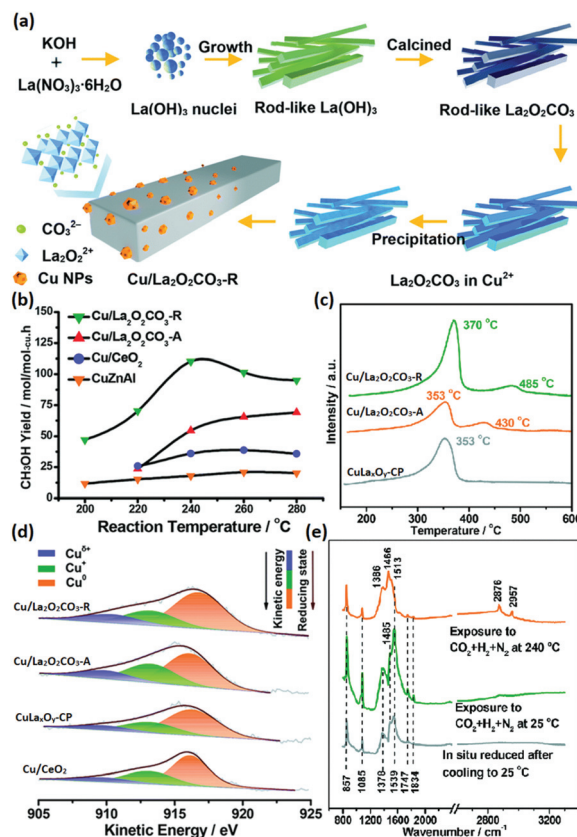
through the RWGS reaction and the Cu/CeO<sub>2</sub> nanorods exhibited higher activity (rate at 250 °C = 1.8 μmol g<sub>cat</sub><sup>-1</sup> s<sup>-1</sup>) (Fig. 16a). The results of multiple *in situ* characterizations showed that the active intermediates of formates and bidentate carbonates were preferentially generated on the CeO<sub>2</sub> {110} facet and CO<sub>2</sub> could also be activated and dissociated more effectively on the CeO<sub>2</sub> {110} facets. Consequently, the Cu/CeO<sub>2</sub> nanorods with more abundant {110} terminations were more active, indicating that researchers can design high-performance CeO<sub>2</sub>-based catalysts by engineering their structure. Additionally, Liu *et al.*<sup>95</sup> synthesized LaNiO<sub>3</sub> perovskite catalysts and tested them for the RWGS reaction in a dielectric barrier discharge plasma reactor. After reduction, the Ni species were extracted from the perovskite structure, and the Ni/La<sub>2</sub>O<sub>3</sub> catalysts were thus formed. The highest CO yield among these catalysts was 39.1% at around 100 °C. The activity was closely correlated with the Ni particle size, Ni dispersion and metal-support interactions.

The CO<sub>2</sub> methanation reaction ( $\text{CO}_2 + \text{H}_2 \rightarrow \text{CH}_4 + \text{H}_2\text{O}$ ) is one of the CO<sub>2</sub> hydrogenation reactions and its product is methane. Although this reaction is thermodynamically preferred, the 8-electron reduction process is a big hindrance for obtaining high activity and selectivity. Thus, engineering the morphologies of rare earth oxides to obtain well-defined structures is beneficial to solve this problem. For example, our group<sup>96</sup> synthesized three types of catalysts containing Ru single atoms, nanoclusters and nanoparticles supported by



CeO<sub>2</sub> nanowires for the CO<sub>2</sub> methanation reaction. We found that the sample of Ru nanoclusters showed the highest activity (TOF at 190 °C =  $7.4 \times 10^{-3} \text{ s}^{-1}$ ), which was also much higher than that of other reported Ru/CeO<sub>2</sub> catalysts. Unexpectedly, the order of activity was not consistent with that of the concentration of oxygen vacancies. According to our investigation, the strong metal support interaction (SMSI) decreased with an increase in the Ru size and benefited the activation of adsorbed CO species, while the H-spillover effect weakened with a decrease in the Ru size and facilitated the removal of H<sub>2</sub>O. Accordingly, the competition between the SMSI and H-spillover effect together determined the activity of the Ru/CeO<sub>2</sub> catalysts (Fig. 16b). In the case of other rare earth oxides used in CO<sub>2</sub> methanation, Ilseman *et al.*<sup>97</sup> obtained novel Sm<sub>2</sub>O<sub>3</sub>-Ni xerogel catalysts through the sol-gel method for the CO<sub>2</sub> methanation reaction. The optimal loading of Ni was 39 wt%, which showed the highest activity. Also, the catalysts had a good score in the stability test, and their activity could easily recover by a reduction treatment. Díez-Ramírez *et al.*<sup>98</sup> studied the effect of different supports (CeO<sub>2</sub>, ZrO<sub>2</sub>, Gd<sub>2</sub>O<sub>3</sub>, and ZnO) on the activity of Co catalysts for the CO<sub>2</sub> methanation reaction. The methane yield of Co/CeO<sub>2</sub> was much higher than that of the other catalysts due to the enhanced reducibility related with Co-CeO<sub>2</sub> interactions.

The selective hydrogenation of CO<sub>2</sub> to methanol has attracted increasing attention in recent years because methanol is an important basic chemical in many chemical industries.<sup>99–102</sup> Chen *et al.*<sup>103</sup> synthesized rod-like La<sub>2</sub>O<sub>2</sub>CO<sub>3</sub> through a facile hydrothermal method (Fig. 17a) and used it as a support for Cu catalysts (denoted as Cu/La<sub>2</sub>O<sub>2</sub>CO<sub>3</sub>-R) in the CO<sub>2</sub> hydrogenation to methanol. They also prepared Cu supported by amorphous La<sub>2</sub>O<sub>2</sub>CO<sub>3</sub> (denoted as Cu/La<sub>2</sub>O<sub>2</sub>CO<sub>3</sub>-A), Cu supported by rod-like CeO<sub>2</sub> (denoted as Cu/CeO<sub>2</sub>) and a co-precipitation catalyst of CuLa<sub>x</sub>O<sub>y</sub> (denoted as CuLa<sub>x</sub>O<sub>y</sub>-CP) for comparison. The Cu/La<sub>2</sub>O<sub>2</sub>CO<sub>3</sub>-R catalyst had a much better catalytic performance (TOF at 240 °C =  $7.0 \times 10^{-3} \text{ s}^{-1}$ , selectivity = 92.5%) compared with the control samples and commercial CuZnAl catalyst (TOF at 240 °C =  $4.0 \times 10^{-3} \text{ s}^{-1}$ , selectivity = 68%) (Fig. 17b). The CO<sub>2</sub> temperature-programmed desorption (TPD) results (Fig. 17c) showed that Cu/La<sub>2</sub>O<sub>2</sub>CO<sub>3</sub>-R had a stronger and larger amount of CO<sub>2</sub> adsorption, indicating that it could activate CO<sub>2</sub> more efficiently. Besides, the order of the Cu<sup>δ+</sup> ratio was consistent with that of the activity, as can be seen in Fig. 17d, which suggested that Cu<sup>δ+</sup> species were the active sites. The authors also performed *in situ* DRIFTS to reveal the reaction mechanism, and they found that the HCOO and CH<sub>3</sub>O species were the main active intermediates (Fig. 17e), which were stable on the catalyst surface and not easily transformed into CO. In brief, it was the synergistic basic sites of the Cu<sup>δ+</sup> species tuned by the structure of the metal-support interface that contributed to the high activity. Some groups used rare earth oxide as promoters to adjust the catalyst structure for CO<sub>2</sub> hydrogenation to methanol and obtained positive results.<sup>104,105</sup> For instance, Ban *et al.*<sup>104</sup> verified that the using of La and Ce as promoters boosted the methanol production of CuZnZr catalyst, especially Ce. However, the



**Fig. 17** (a) Schematic illustration of the synthetic route for Cu/La<sub>2</sub>O<sub>2</sub>CO<sub>3</sub>-R. (b) CH<sub>3</sub>OH yield of the catalysts for CO<sub>2</sub> hydrogenation to methanol. (c) CO<sub>2</sub>-TPD profiles of Cu/La<sub>2</sub>O<sub>2</sub>CO<sub>3</sub>-R, Cu/La<sub>2</sub>O<sub>2</sub>CO<sub>3</sub>-A, and CuLa<sub>2</sub>O<sub>3</sub>-CP. (d) Cu LMM Auger spectra of Cu/La<sub>2</sub>O<sub>2</sub>CO<sub>3</sub>-R, Cu/La<sub>2</sub>O<sub>2</sub>CO<sub>3</sub>-A, CuLa<sub>2</sub>O<sub>3</sub>-CP, and Cu/CeO<sub>2</sub>. (e) *In situ* DRIFTS spectra of Cu/La<sub>2</sub>O<sub>2</sub>CO<sub>3</sub>-R under different conditions. Adapted with permission from ref. 103. Copyright 2018, Royal Society of Chemistry.

introduction of Pr and Nd as additives decreased the activity. The opposite effect of the different rare earth promoters on activity was mainly due to the enhanced synergistic effect and H<sub>2</sub> adsorption caused by the addition of La and Ce, which were not found in the catalysts with Pr and Nd as additives. Similarly, Kourtelesis *et al.*<sup>105</sup> found that La<sub>2</sub>O<sub>3</sub> could promote 30% of the methanol yield for the CuO/ZnO/Al<sub>2</sub>O<sub>3</sub> catalyst. La<sub>2</sub>O<sub>3</sub> could be easily introduced by a co-precipitation method, and the enhanced methanol yield could be attributed to enhanced adsorption of CO<sub>2</sub> and active intermediates.

Considering the complexity of the product of the CO<sub>2</sub> hydrogenation reaction, the choice and design of catalysts must be based on selectivity and avoiding side reactions. Thus, reasonably engineering catalysts with well-defined structures is vital. Based on the reported works, using rare earth oxide nanomaterials in the CO<sub>2</sub> hydrogenation reaction as support or promoter can usually enhance the adsorption of CO<sub>2</sub> and metal support interactions, which will result in improved activity and selectivity.

#### 4.4 Methane oxidation reaction

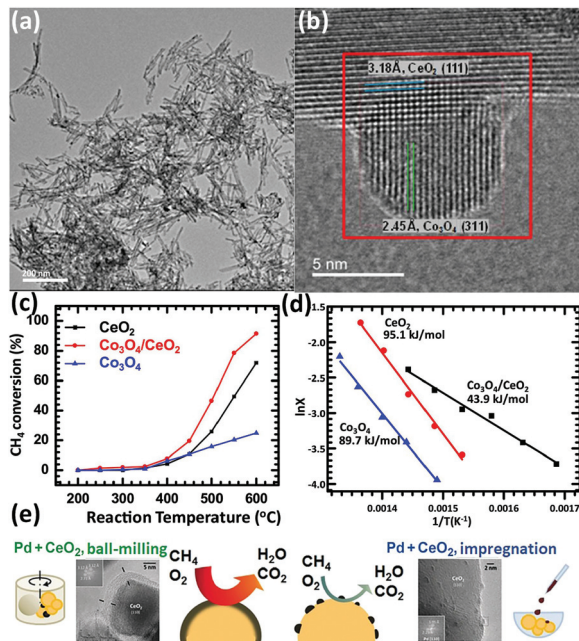
Methane is an important resource due to its applications such as fuel and chemical synthesis. The methane oxidation reaction can be divided into two types, total oxidation and partial oxidation. The total oxidation of methane can be used for energy and heat production or solving the global warming caused by methane.<sup>106,107</sup> The partial oxidation of methane can produce the syngas for further utilization.<sup>108–110</sup> Rare earth oxide nanomaterials are widely applied in both reactions<sup>111–118</sup> as supports or promoters.

In the total oxidation of methane,  $\text{CeO}_2$  is often used as a catalyst support on account of its high concentration of oxygen vacancies.<sup>111,112</sup> Also, the well-defined structures of  $\text{CeO}_2$ -based catalysts are conducive for catalytic activity. For instance,  $\text{Co}_3\text{O}_4$  nanoparticles supported by  $\text{CeO}_2$  nanorods (Fig. 18a and b) for methane combustion were synthesized by Dou *et al.*<sup>111</sup> using a deposition precipitation method. The catalyst of  $\text{Co}_3\text{O}_4/\text{CeO}_2$  ( $T_{50} = 475^\circ\text{C}$ ) was found to be much more active than pure  $\text{Co}_3\text{O}_4$  and  $\text{CeO}_2$  due to the synergistic effect between  $\text{Co}_3\text{O}_4$  and  $\text{CeO}_2$ , and also the activation energy, which was also much lower in the case of  $\text{Co}_3\text{O}_4/\text{CeO}_2$  (Fig. 18c and d). Pd-based nanomaterials are some of the most effective catalysts for the total oxidation of methane, and using rare earth oxides as a support can be further beneficial due to their unique redox properties. As an example, Ozawa *et al.*<sup>113</sup> tested

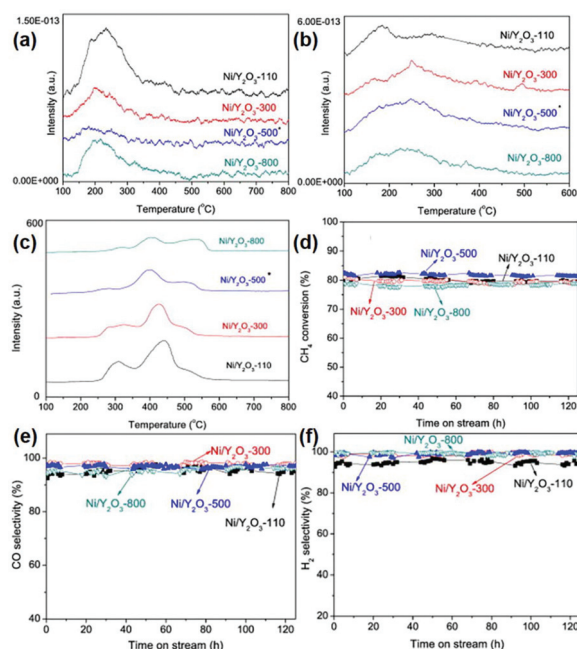
the influence of the addition of  $\text{La}_2\text{O}_3$  and  $\text{Nd}_2\text{O}_3$  to  $\text{PdO}/\text{Al}_2\text{O}_3$  for the combustion of methane. They found that adding  $\text{La}_2\text{O}_3$  or  $\text{Nd}_2\text{O}_3$  alone had an effect of stabilizing  $\text{Al}_2\text{O}_3$  and enhancing the activity. However, when the authors introduced both  $\text{La}_2\text{O}_3$  and  $\text{Nd}_2\text{O}_3$  to  $\text{PdO}/\text{Al}_2\text{O}_3$ , they observed reduced activity and an extended lifetime. Besides, this group also investigated the stabilizing effect of  $\text{La}_2\text{O}_3$ ,  $\text{Nd}_2\text{O}_3$ , and  $\text{ZrO}_2$  on  $\text{PtPdO}/\text{Al}_2\text{O}_3$  for methane combustion.<sup>114</sup> Similarly, the introduction of both  $\text{La}_2\text{O}_3$  and  $\text{Nd}_2\text{O}_3$  prevented the deactivation of the catalyst, but the addition of  $\text{ZrO}_2$  caused deactivation. Also, the addition of all three oxides resulted in the longest lifetime among the catalysts. As another example, Danielis *et al.*<sup>115</sup> prepared Pd-embedded  $\text{CeO}_2$  catalysts *via* a dry ball-milling method. The Pd- $\text{CeO}_2$  catalysts showed a core-shell structure, in which the shell consisted of Pd and  $\text{CeO}_2$ . The as-prepared catalyst could activate methane at a much lower temperature ( $T_{10} = 291^\circ\text{C}$ ) compared with that with the conventional Pd/ $\text{CeO}_2$  catalyst ( $T_{10} = 346^\circ\text{C}$ ) synthesized by impregnation (Fig. 18e). The superior performance was ascribed to the creation of highly active and stable sites due to the robust contact between Pd and  $\text{CeO}_2$ .

In the partial oxidation of methane reaction, 1D rare earth oxide nanostructures are often used. For instance, Zhu *et al.*<sup>119</sup> prepared a core-shell Ni/nanorod- $\text{CeO}_2/\text{SiO}_2$  catalyst using a microemulsion method. The as-prepared catalyst showed better activity and stability than that of Ni/nanorod- $\text{CeO}_2$  and Ni@ $\text{SiO}_2$ , benefitting from the greater amount of oxygen vacancies and stronger anti-sintering of Ni particles derived from the enhanced metal-support interactions. Even after testing at  $750^\circ\text{C}$  for 140 h, the catalyst maintained a  $\text{CH}_4$  conversion of 86% and CO selectivity of 94%. Besides, Ru nanoparticles supported over  $\text{Ce}_{0.5}\text{Zr}_{0.5}\text{O}_2$  nanorods obtained by Das *et al.*<sup>120</sup> were proven to be more active than Ru/ $\text{CeO}_2$  and Ru/ $\text{ZrO}_2$ . Specifically, the stronger metal-support interactions and higher oxygen storage capacity of the  $\text{CeO}_2$ - $\text{ZrO}_2$  solid solution contributed to the increased catalytic performance. Innovatively, Singha *et al.*<sup>118</sup> reported 3D Pt- $\text{CeO}_2$  nanoporous spheres with a bimodal pore structure for the partial oxidation of methane. The unique bimodal pore structure was confirmed by an  $\text{N}_2$ -adsorption study, which resulted in a high surface area. The as-prepared Pt- $\text{CeO}_2$  catalysts were highly active and selective for the production of syngas (TOF at  $400^\circ\text{C} = 1.3 \times 10^3 \text{ s}^{-1}$ , CO selectivity = 50.0%). Briefly, the unique bimodal pore structure resulted in a high surface area and metal-support interactions as well as abundant oxygen vacancies, contributing to the superior catalytic performance for the partial oxidation of methane to produce syngas.

In the case of other rare earth oxides used in the partial oxidation of methane besides  $\text{CeO}_2$ , Ferreira *et al.*<sup>116</sup> tested the catalytic performance of  $\text{LnNi}$  ( $\text{Ln} = \text{Pr}, \text{Gd}, \text{Lu}$ ) binary oxides. They found that  $\text{NiO-Gd}_2\text{O}_3$  and  $\text{NiO-Lu}_2\text{O}_3$  exhibited much higher activity than that of  $\text{NiO-Pr}_2\text{O}_3$ , which was even comparable with that of the commercial 5%  $\text{Pt}/\text{Al}_2\text{O}_3$  catalyst. The authors believed that there was an unusual synergistic effect between the two oxides, resulting in high activity and selecti-



**Fig. 18** (a) TEM image of  $\text{CeO}_2$  nanorods. (b) HRTEM image of  $\text{Co}_3\text{O}_4/\text{CeO}_2$  nanocomposite. (c) Catalytic activity of  $\text{CeO}_2$ ,  $\text{Co}_3\text{O}_4$  and  $\text{Co}_3\text{O}_4/\text{CeO}_2$  for methane combustion. (d) Arrhenius plots and corresponding activation energy of  $\text{CeO}_2$ ,  $\text{Co}_3\text{O}_4$  and  $\text{Co}_3\text{O}_4/\text{CeO}_2$ . Adapted with permission from ref. 111. Copyright 2018, Elsevier. (e) Schematic illustration of the preparation method, catalyst morphology and catalytic activity for the methane combustion reaction using Pd/ $\text{CeO}_2$  catalysts. Adapted with permission from ref. 115. Copyright 2018, Wiley-VCH.



**Fig. 19** (a)  $\text{NH}_3$ -TPD profiles of the  $\text{Ni}/\text{Y}_2\text{O}_3$  samples. (b)  $\text{CO}_2$ -TPD profiles of the  $\text{Ni}/\text{Y}_2\text{O}_3$  samples. (c) TPR profiles of the  $\text{Ni}/\text{Y}_2\text{O}_3$  samples. Catalytic performance of the  $\text{Ni}/\text{Y}_2\text{O}_3$  samples in the partial oxidation of methane: (d)  $\text{CH}_4$  conversion; (e) CO selectivity; and (f)  $\text{H}_2$  selectivity. Adapted with permission from ref. 117. Copyright 2014, Elsevier.

activity for  $\text{H}_2$  and CO. Similarly, Liu *et al.*<sup>117</sup> developed another Ni-based catalyst,  $\text{Ni}/\text{Y}_2\text{O}_3$ , for methane oxidation conversion to syngas. They controlled the structural effect by tuning the calcination temperature of the catalysts (Fig. 19a–c), and showed that  $\text{Ni}/\text{Y}_2\text{O}_3$  calcined at 500 °C had the highest activity and high anti-carbon deposition ability (Fig. 19d–f). All the  $\text{Ni}/\text{Y}_2\text{O}_3$  catalysts showed an extremely low signal in the  $\text{NH}_3$ -TPD profiles (Fig. 19a) because  $\text{Y}_2\text{O}_3$  was a basic oxide. Also, the amount of basic sites and reducible oxygen decreased with an increase in the calcination temperature (Fig. 19b and c). The reason for the highest activity of  $\text{Ni}/\text{Y}_2\text{O}_3$ -500 was its appropriate amount of reducible oxygen and moderate interaction between Ni and  $\text{Y}_2\text{O}_3$ , and both factors were controlled by the calcination temperature. Importantly, Choudhary *et al.*<sup>121</sup> studied the catalytic properties of Pt- and Pd-based alkaline and rare earth oxide catalysts for the partial oxidation of methane. Among the Pt (Pd)/MgO (CaO,  $\text{La}_2\text{O}_3$ ,  $\text{Pr}_6\text{O}_{11}$ ,  $\text{Nd}_2\text{O}_3$ ,  $\text{Sm}_2\text{O}_3$ ,  $\text{Gd}_2\text{O}_3$ ,  $\text{Dy}_2\text{O}_3$ , and  $\text{Er}_2\text{O}_3$ ) catalysts, Pt/ $\text{Gd}_2\text{O}_3$  and Pd/ $\text{Sm}_2\text{O}_3$  showed the best performance with a CO productivity of 9.5 and 7.9 mol  $\text{g}^{-1} \text{h}^{-1}$ , respectively. Besides, both catalysts had high CO selectivity but low  $\text{H}_2$  selectivity due to the RWGS reaction. These results also indicated that the rare earth oxides not only acted as supports, but also played an essential role in deciding the activity and selectivity.

In many cases, the total and partial oxidation of methane occurs simultaneously; therefore, it is a challenge to control the product selectivity. Different rare earth oxide nanomaterials may have different preferences towards the two reactions. Thus, researchers can realize diverse goals by choosing

suitable rare earth oxides with designed well-defined structures as a support or promotor.

#### 4.5 MOR

The MOR discussed below refers to the anode reaction of direct methanol fuel cells (DMFCs), which is very important for alleviating the energy crisis since it can directly transform chemical energy to electrical energy.<sup>122–125</sup> Besides, methanol has a high energy density and is easier to store and transport compared with hydrogen. The catalytic application of rare earth oxide nanomaterials in the MOR is not as extensive as in other C1 chemical reactions such as the CO oxidation and  $\text{CO}_2$  hydrogenation reactions because of their weak conductivity. Although it is difficult for rare earth oxide nanomaterials to be used as a single catalyst in MOR, there are many cases that combine rare earth oxide nanomaterials with other well-conducting catalysts for the MOR.<sup>126–133</sup> This not only can enhance the electronic metal support interactions, but also tune the chemical adsorption of the reactants and intermediates. As an example, Li *et al.*<sup>126</sup> studied the introduction of  $\text{Y}_2\text{O}_3$  on the MOR activity of the Pd/C catalyst. A 1.5 times higher specific activity ( $\text{SA} = 145 \text{ mA cm}^{-2}$ ) was observed with the assistance of  $\text{Y}_2\text{O}_3$  due to the relatively well-dispersed Pd nanoparticles, enhanced electrochemically active surface area and the synergistic interaction between Pd and  $\text{Y}_2\text{O}_3$ .

In the case that the role of rare earth oxides is a promotor in the MOR, a well-defined structure can also have a positive influence on the catalytic performance. As a good example, Feng *et al.*<sup>33</sup> synthesized three types of well-defined  $\text{CeO}_2$  nanostructures containing nanooctahedra, nanospheres and nanocubes as promotors for Pt catalysts. Consequently, the Pt catalyst decorated with  $\text{CeO}_2$  nanospheres exhibited the best performance in both activity and stability. The explanation for the enhanced activity could be divided into two parts. One was that the loosened structure of nanospheres was beneficial for the dispersion of Pt particles, thus generating a strong physical interaction between Pt and  $\text{CeO}_2$ . The other was the oxygen vacancies, which were the most abundant in the nanospheres. The rich oxygen vacancies led to the transfer of surplus electrons from  $\text{CeO}_2$  to Pt, and thereby increased the intrinsic activity of Pt. Besides, Wang *et al.*<sup>129</sup> investigated the effect of the introduction of  $\text{La}_2\text{O}_3$  in the Pd/C catalyst for the MOR. As can be seen in Fig. 20a, the Pd nanoparticles (*ca.* 2.6 nm) were uniform and well dispersed. Compared with the Pd/C catalyst, Pd- $\text{La}_2\text{O}_3$ /C exhibited a lower onset potential and higher current density (Fig. 20b). The XPS results indicated that the introduction of  $\text{La}_2\text{O}_3$  resulted in the formation of more metallic Pd species (Fig. 20c and d), resulting in enhanced activity. Furthermore, the authors loaded Pd- $\text{La}_2\text{O}_3$  on chitosan-functionalized carbon nanotubes and obtained a better performance than that with Pd- $\text{La}_2\text{O}_3$ /C. In addition, a 3D core-shell nanocatalyst of  $\text{Au}@\text{CeO}_2@\text{Pt}/\text{C}$  for the MOR was obtained by Dao *et al.*<sup>130</sup> through a facile hydrothermal route. The as-prepared catalyst showed much higher activity ( $\text{MA} = 1360 \text{ mA mg}_{\text{Pt}}^{-1}$ ) and durability than that of commercial Pt/C ( $\text{MA} = 670 \text{ mA mg}_{\text{Pt}}^{-1}$ ) and  $\text{CeO}_2@\text{Pt}/\text{C}$  ( $\text{MA} = 920 \text{ mA mg}_{\text{Pt}}^{-1}$ ) owing

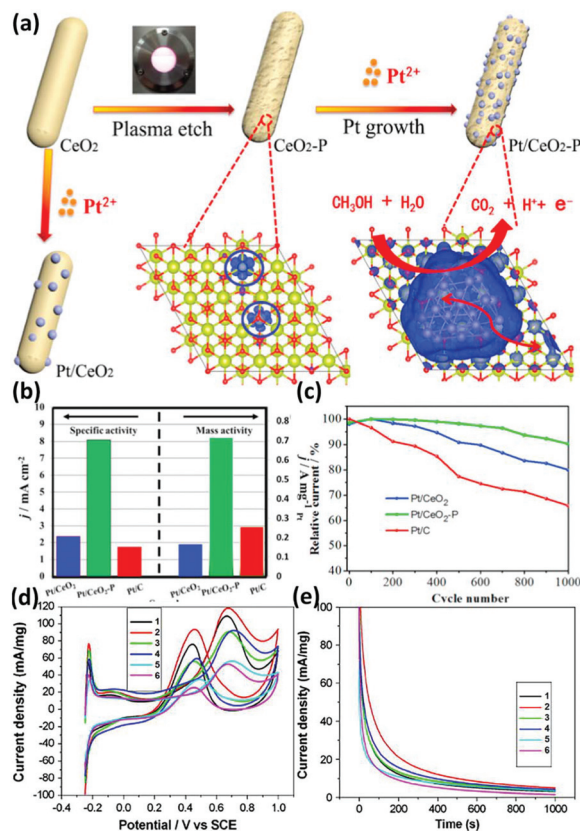




**Fig. 20** (a) TEM image of Pd-L<sub>2</sub>O<sub>3</sub>/C. (b) Cyclic voltammograms of Pd/C and Pd-L<sub>2</sub>O<sub>3</sub>/C in 1 M KOH + 1 M CH<sub>3</sub>OH. XPS spectra of Pd 3d for (c) Pd/C and (d) Pd-L<sub>2</sub>O<sub>3</sub>/C. Adapted with permission from ref. 129 Copyright 2019, Elsevier. (e) Schematic illustration of the possible mechanism of Au@CeO<sub>2</sub>@Pt/C for the MOR. Adapted with permission from ref. 130. Copyright 2019, Royal Society of Chemistry.

to the electronic and synergistic effects among Au, CeO<sub>2</sub> and Pt, which could easily remove the poisoner of CO intermediates (Fig. 20e).

When rare earth oxides are used as a support in the MOR, efforts must be made to improve their conductivity. For example, CeO<sub>2</sub> nanorod-supported Pt catalysts were prepared by Tao *et al.*<sup>131</sup> and used for the MOR. They used plasma etching of the CeO<sub>2</sub> nanorods to modify the surface structure of the CeO<sub>2</sub> support (denoted as CeO<sub>2</sub>-P), and used the untreated CeO<sub>2</sub> as a comparison sample (Fig. 21a). The authors found that the abundant oxygen vacancies in Pt/CeO<sub>2</sub>-P played a significant role in the enhanced activity (MA = 714 mA mg<sub>Pt</sub><sup>-1</sup>) and stability compared with the sample without plasma etching (MA = 164 mA mg<sub>Pt</sub><sup>-1</sup>) (Fig. 21b and c), which influenced the interactions between Pt and CeO<sub>2</sub> and enriched the electronic density of Pt, resulting in the enhanced conductivity of CeO<sub>2</sub> and MOR activity. As another example, Tang *et al.*<sup>133</sup> combined the rare earth oxides of Pr and Ce with carbon black to support Pt species for the MOR. They found that the introduction of Pr<sub>2</sub>O<sub>3</sub> and CeO<sub>2</sub> significantly improved the catalytic performance (Fig. 21d and e), and the ratio of Pr/Ce had a crucial effect on the activity. According to their observations, Pt/Pr<sub>1</sub>Ce<sub>1</sub>O<sub>2</sub>-C exhibited the highest activity (SA = 118.3 mA cm<sup>-2</sup>) and best stability among the samples. The



**Fig. 21** (a) Schematic illustration of the mechanism of the Pt/CeO<sub>2</sub> catalyst for the MOR. (b) Mass activity and specific activity for the MOR. (c) Stability test for the MOR. Adapted with permission from ref. 131. Copyright 2018, Elsevier. (d) Cyclic voltammograms and (e) chronoamperometry curves at 0.65 V (vs. SCE) for Pt/C and Pt/RE-C catalysts: Sample 1, Pt/Pr<sub>3</sub>Ce<sub>1</sub>O<sub>2</sub>-C; Sample 2, Pt/Pr<sub>1</sub>Ce<sub>1</sub>O<sub>2</sub>-C; Sample 3, Pt/Pr<sub>1</sub>Ce<sub>3</sub>O<sub>2</sub>-C; Sample 4, Pt<sub>3</sub>/PrO<sub>x</sub>-C; Sample 5, Pt<sub>3</sub>/CeO<sub>x</sub>-C; and Sample 6, Pt/C. Adapted with permission from ref. 133. Copyright 2008, Elsevier.

abundant surface oxygen-containing species as well as the high oxygen mobility derived from Pr<sub>2</sub>O<sub>3</sub> and CeO<sub>2</sub> contributed to the enhanced CO-tolerance and catalytic performance.

In summary, although rare earth oxide nanomaterials have poor conductivity, which limits their activity for the MOR, they are widely used as a promotor or support for the rational engineering of their structures in the MOR since they can enrich the electronic density and improve the CO tolerance through electronic and synergistic effects.

## 5. Summary and perspective

In this review, we introduced the structural features of the rare earth oxides and summarized the engineering of rare earth oxide nanomaterials with well-defined structures mainly considering their morphology. Then we chose some representative C1 chemical reactions including CO oxidation, water gas-shift reaction, CO<sub>2</sub> hydrogenation reaction, methane oxidation reaction and methanol oxidation reaction to summarize the struc-

Table 1 The synthesis and applications of rare earth oxide-based nanocatalysts for some C1 chemical reactions

| Catalyst   | Synthetic route                 | Application                               | Conditions  | Performance   | Key factors in catalysis                                    | Ref. |
|--|---------------------------------|---|---|---|---|------|
| Ln-Doped CeO <sub>2</sub> nanowires (Ln = La-Lu)                           | Hydrothermal method             | CO oxidation reaction                     | 1% CO-20% O <sub>2</sub> -He<br>Total speed: 40 mL min <sup>-1</sup>  | TOF at 200 °C = $5.4 \times 10^{-4}$ s <sup>-1</sup>  | Doping effect   | 35   |
| Pr <sub>6</sub> O <sub>11</sub>  | Hard template method            | CO oxidation reaction                     | 1% CO-20% O <sub>2</sub> -N <sub>2</sub><br>SV = 10 000 mL g <sup>-1</sup> h <sup>-1</sup>                                      | T <sub>50</sub> = 305 °C  | Surface area  | 75   |
| Tb <sub>4</sub> O <sub>7</sub>   | Hard template method            | CO oxidation reaction                     | 1% CO-20% O <sub>2</sub> -N <sub>2</sub><br>SV = 10 000 mL g <sup>-1</sup> h <sup>-1</sup>                                      | T <sub>50</sub> = 360 °C  | Oxygen vacancy<br>Surface area                              | 75   |
| PtO <sub>x</sub> nanoclusters/<br>CeO <sub>2</sub>                         | Hydrothermal method             | CO oxidation reaction                     | 13.3% CO-33.3% O <sub>2</sub> -<br>53.3% He<br>Total speed: 15 mL min <sup>-1</sup>   | TOF at 50 °C = $1.3 \times 10^{-2}$ s <sup>-1</sup>   | Oxygen vacancy<br>Suitable Pt-O<br>coordination number      | 77   |
| Au/Pr <sub>6</sub> O <sub>11</sub> nanorods                                | Hydrothermal method             | CO oxidation reaction                     | 1% CO-Air<br>Total speed: 33.6 mL min <sup>-1</sup>   | T <sub>100</sub> = 140 °C   | Synergistic effect  | 78   |
| Ag/Pr <sub>6</sub> O <sub>11</sub> nanorods                                | Hydrothermal method             | CO oxidation reaction                     | 1% CO-20% O <sub>2</sub> -Ar<br>Total speed: 50 mL min <sup>-1</sup>  | T <sub>100</sub> = 210 °C   | Surface area<br>Oxygen vacancy                              | 79   |
| Au/CeO <sub>2</sub> nanorods   | Hydrothermal method             | WGS                                       | 2% CO-10% H <sub>2</sub> O-He<br>Total speed: 70 mL min <sup>-1</sup>   | T <sub>50</sub> ~ 190 °C  | Plane effect  | 87   |
| Au nanoclusters/<br>CeO <sub>2</sub>                                       | Hydrothermal method             | WGS                                       | 2% CO-12% H <sub>2</sub> O-N <sub>2</sub><br>Total speed: 30 mL min <sup>-1</sup>   | Rate at 200 °C ~ $5.0 \times 10^2$ mol g <sub>Au</sub> <sup>-1</sup> s <sup>-1</sup>  | Bridged -OH and Au <sup>δ+</sup>                            | 15   |
| Pt/Ce <sub>0.6</sub> Y <sub>0.4</sub> O <sub>2</sub>                       | Sol-gel method                  | WGS                                       | 5% CO-15% H <sub>2</sub> O-N <sub>2</sub><br>WHSV = 30 000 mL g <sub>cat</sub> <sup>-1</sup> h <sup>-1</sup>                    | TOF at 250 °C = 0.55 s <sup>-1</sup>  | Reducibility of the support                                 | 86   |
| Au/La <sub>2</sub> O <sub>3</sub>  | Hydrolysis method               | WGS                                       | 10% CO-3% H <sub>2</sub> O-He   | T <sub>50</sub> ~ 375 °C  | Oxidation state of Au                                       | 13   |
| Au/La <sub>2</sub> O <sub>3</sub> SO <sub>4</sub>                          | Surfactant-assisted technique   | WGS                                       | 10% CO-3% H <sub>2</sub> O-He   | T <sub>50</sub> ~ 350 °C  | Oxidation state of Au                                       | 13   |
| CuO/CeO <sub>2</sub> -La <sub>2</sub> O <sub>3</sub>                       | Co-precipitation method         | WGS                                       | 5% CO-30% H <sub>2</sub> -6%<br>CO <sub>2</sub> -50% H <sub>2</sub> O-N <sub>2</sub><br>Total speed: 207.4 mL min <sup>-1</sup> | T <sub>90</sub> ~ 225 °C  | Oxidation state of Cu and oxygen<br>vacancy                 | 88   |
| Cu/CeO <sub>2</sub> nanorods   | Hydrothermal method             | RWGS                                      | 10% CO <sub>2</sub> -50% H <sub>2</sub> -He<br>Total speed: 20 mL min <sup>-1</sup>   | Rate at 250 °C = 1.8 μmol g <sub>cat</sub> <sup>-1</sup> s <sup>-1</sup>  | CeO <sub>2</sub> (110) facets                               | 94   |
| Ni/La <sub>2</sub> O <sub>3</sub>  | Sol-gel method                  | RWGS                                      | 50% CO <sub>2</sub> -50% H <sub>2</sub><br>Total speed: 20 mL min <sup>-1</sup>   | ~100 °C; CO <sub>2</sub> conversion = 51.0%;<br>CO yield = 39.1%  | Ni dispersion and SMSI                                      | 95   |
| Ru nanoclusters/<br>CeO <sub>2</sub>                                       | Hydrothermal method             | CO <sub>2</sub> methanation               | 5% CO <sub>2</sub> -20% H <sub>2</sub> -He<br>Total speed: 40 mL min <sup>-1</sup>  | TOF at 190 °C = $7.4 \times 10^{-3}$ s <sup>-1</sup><br>Selectivity ~100%   | SMSI and H-spillover  | 96   |
| Ni-Sm <sub>2</sub> O <sub>3</sub>  | Sol-gel method                  | CO <sub>2</sub> methanation               | 10% CO <sub>2</sub> -40% H <sub>2</sub> -Ar<br>Total speed: 50 mL min <sup>-1</sup>   | T <sub>100</sub> ~ 100 °C<br>Selectivity ~100%  | Smaller size and more perimeter<br>sites                    | 97   |
| Co/Gd <sub>2</sub> O <sub>3</sub>  | Impregnation method             | CO <sub>2</sub> methanation               | 10% CO <sub>2</sub> -90% H <sub>2</sub><br>Total speed: 75 mL min <sup>-1</sup>   | TOF at 300 °C = 1.3 min <sup>-1</sup><br>Selectivity ~80%   | Reducibility  | 98   |
| Cu/La <sub>2</sub> O <sub>3</sub> CO <sub>3</sub> nanorods                 | Deposition-precipitation method | CO <sub>2</sub> hydrogenation to methanol | 24% CO <sub>2</sub> -72% H <sub>2</sub> -N <sub>2</sub> 3.0 MPa   | TOF at 240 °C = $7.0 \times 10^{-3}$ s <sup>-1</sup>  | Cu <sup>δ+</sup> and enhanced CO <sub>2</sub><br>adsorption | 103  |
| La <sub>2</sub> O <sub>3</sub> doped CuO/<br>ZnO/ZrO <sub>2</sub>          | Co-precipitation method         | CO <sub>2</sub> hydrogenation to methanol | 25% CO <sub>2</sub> -75% H <sub>2</sub> 3.0 MPa   | Selectivity = 92.5%<br>CH <sub>3</sub> OH productivity at 230 °C =<br>2.7 mol kg <sub>cat</sub> <sup>-1</sup> h <sup>-1</sup> | Oxygen vacancy  | 104  |
| La <sub>2</sub> O <sub>3</sub> -CuO/ZnO/<br>Al <sub>2</sub> O <sub>3</sub> | Co-precipitation method         | CO <sub>2</sub> hydrogenation to methanol | 10% CO <sub>2</sub> -90% H <sub>2</sub><br>Total speed: 50 mL min <sup>-1</sup>   | Selectivity = 49.8%<br>210 °C; CH <sub>3</sub> OH yield = 0.9%; selectivity<br>~40%   | Enhanced adsorption of CO <sub>2</sub>                      | 105  |

Table 1 (Contd.)

| Catalyst  | Synthetic route                                     | Application  | Conditions  | Performance   | Key factors in catalysis  | Ref.                     |
|---|---|--|---|---|---|--------------------------|
| La-Nd-PdO/Al <sub>2</sub> O <sub>3</sub>  | Impregnation method                                 | Methane combustion reaction                                | 1% CH <sub>4</sub> /Ar  | TOF at 850 °C = 4.8 mol g <sup>-1</sup> s <sup>-1</sup>   | Stabilizing Pd species  | 113                      |
| La-Nd-PdO/<br>ZrO <sub>2</sub> -Al <sub>2</sub> O <sub>3</sub><br>Pd-CeO <sub>2</sub> | Impregnation method<br>Ball milling method          | Methane combustion reaction<br>Methane combustion reaction | 1% CH <sub>4</sub> /Ar  | Rate at 800 °C = 6.9 × 10 <sup>2</sup> μmol g <sup>-1</sup> s <sup>-1</sup>   | Stabilizing Pd species  | 114                      |
| NiO-Gd <sub>2</sub> O <sub>3</sub>  | Controlled oxidation of the intermetallic compounds | Methane combustion reaction                                | 0.5% CH <sub>4</sub> -2% O <sub>2</sub> -He<br>GHSV = 200 000 h <sup>-1</sup>   | T <sub>50</sub> ~ 350 °C  | Structural effect   | 115                      |
| Ni/Y <sub>2</sub> O <sub>3</sub>  | Precipitation method                                | Partial oxidation of methane                               | 28% CH <sub>4</sub> -14% O <sub>2</sub> -N <sub>2</sub><br>GHSV = 8500 mL g <sup>-1</sup> h <sup>-1</sup><br>66.7% CH <sub>4</sub> -33.3% O <sub>2</sub><br>Total speed: 165 mL min <sup>-1</sup> | T <sub>50</sub> ~ 625 °C  | Synergistic effect  | 116                      |
| Pt/Gd <sub>2</sub> O <sub>3</sub>   | Impregnation method                                 | Partial oxidation of methane                               | 64% CH <sub>4</sub> -36% O <sub>2</sub><br>SV = 5 × 10 <sup>5</sup> mL g <sup>-1</sup> h <sup>-1</sup>  | CH <sub>4</sub> conversion at 700 °C ~ 82%; CO and H <sub>2</sub> selectivity at 700 °C ~ 90%   | Basic sites and reducible oxygen  | 117                      |
| Pd/Sm <sub>2</sub> O <sub>3</sub>   | Impregnation method                                 | Partial oxidation of methane                               | 64% CH <sub>4</sub> -36% O <sub>2</sub><br>SV = 5 × 10 <sup>5</sup> mL g <sup>-1</sup> h <sup>-1</sup>  | CO productivity at 700 °C = 9.5 mol g <sup>-1</sup> h <sup>-1</sup>   | Basic sites   | 121                      |
| Pd-Y <sub>2</sub> O <sub>3</sub> /C   | Microwave-assisted reduction                        | MOR  | 1 M CH <sub>3</sub> OH + 0.5 M KOH  | CO productivity at 700 °C = 7.9 mol g <sup>-1</sup> h <sup>-1</sup>   | Basic sites   | 121                      |
| Pd-La <sub>2</sub> O <sub>3</sub> /C<br>Au@CeO <sub>2</sub> @Pt                       | Reduction reaction<br>Hydrothermal method           | MOR<br>MOR   | 1 M CH <sub>3</sub> OH + 1 M KOH<br>1 M CH <sub>3</sub> OH + 0.25 M H <sub>2</sub> SO <sub>4</sub>  | ECOA = 70 m <sup>2</sup> g <sup>-1</sup><br>SA: 145 mA cm <sup>-2</sup><br>SA: 1.8 mA cm <sup>-2</sup><br>ECOA = 80 m <sup>2</sup> g <sup>-1</sup><br>MA: 1360 mA mg <sub>Pt</sub> <sup>-1</sup><br>MA: 714 mA mg <sub>Pt</sub> <sup>-1</sup> | Enhanced ECSA and synergistic effect<br>Metallic Pd<br>Electronic, bifunctional and synergistic effects<br>Oxygen vacancy | 126<br>129<br>130<br>131 |
| Pt/CeO <sub>2</sub>   | Hydrothermal method<br>etch                         | MOR  | 1 M CH <sub>3</sub> OH + 0.5 M H <sub>2</sub> SO <sub>4</sub>   |   |   |                          |
| Pt/Pt <sub>1</sub> Ce <sub>1</sub> O <sub>2</sub> -C                                  | Precipitation method                                | MOR  | 0.5 M CH <sub>3</sub> OH + 0.5 M H <sub>2</sub> SO <sub>4</sub>   | SA: 118.3 mA cm <sup>-2</sup>   | Surface oxygen-containing species and oxygen mobility   | 133                      |

ture-function correlation of rare earth oxide-based nanomaterials applied in catalytic applications. We also presented the reported works in Table 1, including their preparation methods and catalytic properties. In summary, the role of well-defined rare earth oxide-based catalysts in C1 chemical reactions mainly involves three aspects: (1) providing stable sites for the loading and dispersion of other metal catalysts, (2) providing strong metal support interaction and enhancing the electron density of the metal loading, and (3) providing sites for the adsorption and activation of small molecules such as H<sub>2</sub>O, O<sub>2</sub> and CO<sub>2</sub>. There is no doubt that rare earth oxide-based catalysts play a significant role in C1 chemical reactions, but there are also many problems that need to be solved.

Firstly, optimized synthesis strategies still need to be developed for the large-scale and low-cost production of rare earth oxide materials with high performances. Based on the current developed synthetic routes, on the one hand, methods such as thermal decomposition and precipitation are low-cost and efficient, but they are not suitable for designing and obtaining nanostructures with a specific morphology, which may result in desirable properties. On the other hand, routes such as the hydrothermal and sol-gel methods are suitable for the preparation of functional nanomaterials, but they cannot guarantee their large production and low cost. Besides, the role of rare earth oxides themselves in the catalytic reaction needs a deeper and clearer understanding. Many reported works have demonstrated that rare earth oxides exhibit catalytic activity for C1 chemical reactions. However, when the rare earth oxides are used as a support to form composite materials with other metal or metal oxides, it is not clear if they only work as support or they also provide active sites. In addition, the defects in rare-earth oxides also play a crucial role in C1 chemical reactions, such as stabilizing the active metal loading, providing sites for the adsorption of reactant molecules such as H<sub>2</sub>O and CO<sub>2</sub>, and promoting the electron transfer between the support and active metals, especially oxygen defects. However, other defects such as dislocation and grain boundaries in rare earth oxides are rarely discussed in C1 chemical reactions, and thus more research is needed to fill this blank. Furthermore, most of the characterizations of rare earth oxide-based catalysts are restricted to the *ex situ* level. Nevertheless, the surface structure of the catalyst always changes in the reaction process, and there are many intermediate species generated that disappear and cannot be observed by *ex situ* techniques. Consequently, *in situ/operando* characterizations combined with theoretical simulation need to be performed to uncover the real reaction mechanism behind the catalytic reaction. Finally, to date, most of the research on rare earth oxide-based catalysts for C1 chemical reactions has focused on CeO<sub>2</sub>, but the catalytic properties of other rare earth oxides need to be explored to obtain more novel catalysts with high performances. Also, the powerful function of computational simulation in explaining and predicting the catalytic properties of rare earth oxides should be noted. There is also a problem that most computational works on rare earth oxides are based on CeO<sub>2</sub> nanomaterials. However, using theoretical computation



to predict properties may result in the development of more non-ceria rare earth oxides nanostructures with high catalytic performances. We believe that all of these problems will be addressed in the future, and rare earth oxide-based nanomaterials will shine brightly at the stage of catalytic applications in C1 chemical reactions.

## Conflicts of interest

There are no conflicts to declare.

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