Strategies for the design of ruthenium-based electrocatalysts toward acidic oxygen evolution reaction

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Polymer electrolyte membrane water electrolyzers (PEMWEs) driven by renewable electricity are deemed to be a promising technology toward green hydrogen production, where anodic oxygen evolution reaction (OER) is one of the main obstacles that impede the practical application of PEMWEs. The strongly acidic environment and greatly oxidative working conditions make the development of highly active and stable electrocatalysts toward OER extremely challenging. Ruthenium (Ru)-based materials as acidic OER catalysts possess a number of advantages including high activity and the lowest price among the precious metal family, while their long-term durability is far from satisfactory. To date, effective efforts have been made to improve the durability of Ru species to balance activity and stability. In this review, the recent progress in the development of Ru-based catalysts for enhanced acidic OER performance is summarized, expecting to offer guidance for exploring highly active and stable Ru-based catalysts. The fundamental understanding of the relationship between OER mechanism and activity as well as stability of Ru-based catalysts is discussed. Then, experimental attempts to improve the acidic OER performance of Ru-based catalysts are reviewed. Finally, the challenges and perspectives for future studies of Ru-based catalysts for acidic OER are also proposed.

Broader context
Polymer electrolyte membrane water electrolyzers (PEMWEs) have been deemed to be one of the promising techniques to produce renewable hydrogen. The strong corrosive condition and high operating potential lead to serious challenges for the development of significantly active and durable catalysts toward anodic oxygen evolution reaction (OER). Catalysts based on ruthenium (Ru), which is the cheapest noble metal, can deliver high activity for the acidic OER. Nevertheless, the lack of reasonable durability of Ru-based catalysts for acidic OER prevents them from further large-scale applications. Within this scenario, a comprehensive discussion of the fundamental understanding of the relationship between OER mechanism and activity as well as stability of Ru-based catalysts is provided. Second, recent progress in the development of Ru-based catalysts for acidic OER is reviewed with an emphasis on the underlying structure-performance relationships. Last, the remaining challenges and personal perspectives for future studies on Ru-based OER catalysts are proposed to realize the commercialization of electrochemical water splitting.

1. Introduction
The excessive use of fossil fuels brings about not only resource exhaustion, but also severe environmental issues, such as the greenhouse effect, air contamination, and so on, which are badly in need of storage and conversion technologies for renewable energy.1–4 Green hydrogen, continuously produced by electrochemical water splitting coupled with renewable electricity, is regarded as a potential energy carrier.5–7 Alkaline water electrolyzer (AWE) technology was industrialized for the first time in the 1920s, and then gradually developed into a matured commercial application technology.8,9 However, AWE is subject to high ohmic losses, low working pressure, slow kinetics, and low operating current density.10 These shortcomings were not resolved until the proposal of the concept of solid polymer electrolytes by Grubb.11 Polymer electrolyte membrane water electrolyzers (PEMWEs) can operate with a larger power input range due to the high proton conductivity and lower
Electrochemical water splitting consists of an anodic oxygen evolution reaction (OER) and a cathodic hydrogen evolution reaction (HER). The cathodic HER is a two-electron reaction, and is one of the simplest electrochemical reactions and is relatively effortless to achieve. However, the anodic OER is a complex multi-step reaction and involves four-electron transfer, leading to a much higher energy expenditure to surmount the kinetic barrier than HER. To date, substantial OER catalysis, including alloys, metal oxides, pyrochlores, and perovskites, have been developed to improve anodic electrode kinetics and stability. However, on account of the thermodynamic unsteadiness of non-noble metal elements under harsh acidic OER operation conditions, the most promising acidic OER catalysts are restricted to precious metals at the present stage. As forecasted by the theoretical volcano maps, ruthenium (Ru)-based and iridium (Ir)-based compounds are currently considered the most advanced OER catalysts under strong acidic environments. Note that Ir-based oxides are the most promising candidates to reach the stability standard of PEMWE equipment, owing to their superior acid resistance and oxidation resistance. Nevertheless, because of the extremely scarce feature of Ir, more than 40 years of global Ir production is required to scale up PEMWE to the terawatt-level. As the cheapest member of the Pt-related precious metal family, more abundant Ru-based materials deliver relatively superior OER mass activities compared with Ir-related catalysts. A variety of strategies, including surface engineering, alloy engineering, and single atom engineering, have been exploited to construct advanced Ru-related OER catalysts. Satisfyingly, an extremely low overpotential of ~150 mV at 10 mA cm⁻² current density can be achieved under strong acidic electrolytes. Unfortunately, the over-oxidation of RuO₂ to soluble RuO₄ species would inevitably occur under the highly oxidizing voltage and strong acidic medium, which calls into question the durability of Ru-related catalysts and leaves the infinite possibility for improvement (Fig. 1).

To date, the dynamic dissolution process of Ru-related acidic OER catalysts has been extensively studied. More importantly, diverse in situ/operando means, including operando X-ray absorption spectroscopy (XAS), in situ ATR-SEIRAS, in situ X-ray photoelectron spectroscopy (XPS), in situ Raman, and isotope labeling measurements, have been adopted to explore the dissolution behavior of Ru-related derivatives during the acidic OER process. Moreover, theoretical calculations (DFT) have been conducted to simulate the reaction behavior and process of Ru-related species during the acidic OER process. These results not only confirm existing theories but also offer new insights into the durability of Ru-related OER catalysts in acidic electrolytes. Despite these achievements, available measures to increase the stability of Ru-related OER catalysts while maintaining their high activity are still relatively limited. Several excellent reviews on similar topics have been published in recent years, while a comprehensive systematic review of engineering strategies for Ru-related acidic OER electrocatalysts and their corresponding
2. Mechanistic studies on Ru-based OER electrocatalysts

Generally speaking, the overall electrocatalytic performances of Ru-based catalysts include activity and stability, which are closely related to the reaction mechanisms. To better analyze the relationship between reaction mechanisms and activity or stability, we summarize them separately.

2.1 The relationship between reaction mechanisms and activity

Analogous to other electrochemical reactions, the adsorption energy of reaction intermediates can also be applied to describe the OER activity. In 2007, the oxygen adsorption energy ($\Delta G_{\text{O}}$) was first applied to define the electrocatalytic activity of an OER catalyst by Rossmeisl et al. They observed that the binding energy of the relevant OER intermediates on the surfaces of a catalyst (i.e., OH*, O*, OOH*) follows a linear relationship. In other words, the binding energy fluctuation of one oxygen-related reaction intermediate could lead to the binding energy fluctuation of other oxygen-related reaction intermediates, which will inevitably impede optimizing the activity of a catalyst via only improving one reaction step. Fig. 2a shows the theoretical activity of OER as a linear function of the oxygen binding energy ($O^*$), indicating optimal adsorption energy corresponding to the best OER activity and conforming to the above-discussed linear scaling relationship. Rossmel et al. further identified the linear scaling relationship between the adsorption energy of HOO* and HO* with an approximately constant, which can in reverse define the lowest theoretical activity of an OER catalyst. As presented in Fig. 2b, the relationship between OER activity and the standard free energy of $\Delta G_{\text{O}}^\circ - \Delta G_{\text{OOH}}^\circ$ presented a volcano tendency. As a result, the volcano map indicated that an excellent OER electrocatalyst should have moderate bonding energies with the oxygen-related reaction intermediates.

In spite of the restrictions of the linear scaling relationship on enhancing the activity of catalysts to reach the thermodynamic potential limitation of the OER, Halck et al. broke the linear correlation of the adsorption energies by embellishing the oxide surface. Conventionally, the coordinatively unsaturated sites (cus) were considered as the active center for the OER. Nevertheless, they found that a dopant like Co or Ni atom located in the bridge site can activate the commonly inactive oxygen atom at the top as a proton donor or receiver, thus lowering the OER overpotential of RuO$_2$ [Fig. 2c]. According to theoretical analysis, the proton donor–acceptor functionality would not only function as a hydrogen acceptor from Ru–OH or Ru–OOH intermediates to reduce their energy state, but also affect the reaction activity at the cus. More importantly, the additional parameter only influenced two of the three oxygen-related reaction intermediates, thus breaking the linear scaling relationship. Besides, Liu et al. found that the bridging O atom could serve as a proton-acceptor functionality even on pure RuO$_2$, and the H$_2$O tended to attack the aggregation of two surface O groups during the O–O bond formation stage (Fig. 2d and e). Furthermore, Chen et al. proved that the electronic structures of bridging oxygen atom sites as proton receivers at the surface of RuO$_2$ played a significant role in the OER activity, which could be adjusted by the introduction of foreign metal atoms (Fig. 2f). Therefore, these theoretical works have pointed out guidelines for the rational design of significantly active Ru-related OER catalysts.

In addition, note that catalytic descriptors are important means to analyze the relationship between catalytic behavior and the catalysts, which can also unscramble the activity tendency and find more highly active catalysts. For example, the d-band theory has become a widely used tool to analyze and forecast the relationship between the electronic properties and activity of catalysts since it was proposed by Hammer and Nørskov. Henceforward this theory has been extensively applied to describe bond formation on the surface of catalysts with the diverse filling of the d band. In terms of the interaction between adsorbates and the surface of catalysts, the coupling to a broad metal band will result in broadened and lowered electronic states of the adsorbate (Fig. 3a). Generally...
speaking, the farther the d states are away from the Fermi level, the higher energy is for the antibonding states and the stronger binding energy is between the adsorbate and the surface of catalysts. Moreover, the d-band center position could be adjusted by embellishing the electronic properties of catalysts via diverse ways (doping, alloying, strain engineering, etc.), which can realize the optimal interaction between adsorbrates and catalysts to improve OER performance. Yang et al. revealed that the distance between the d-band center and the Fermi level was larger than RuO$_2$ when Cu was doped into RuO$_2$. This result showed the lowered antibonding energy states and the weakened interaction between adsorbed O species and Ru (Fig. 3b). Later, the O 2p band center theory was also established. As shown in Fig. 3c, the d band broke up into two $e_g$ states at the higher energy level while it broke up into three $t_{2g}$ states at the lower energy level in the field of octahedral coordination. There is a strong overlap between $e_g$ doublets and O 2p orbitals, which will produce $\sigma$-bonding and $\pi^*$-antibonding states. However, there was a weak overlap between the $t_{2g}$ triplets and the O 2p orbital, which will generate $\pi$-bonds and $\pi^*$-antibonds. Owing to the translational symmetry of the unit cell, the molecular orbitals turned into bands in oxide crystals, which were expressed as the metal d band and the O 2p band. The bonds formed from the hybridization of metal d bands and O 2p bands could be easily tuned by tuning the electronic properties of catalysts. Our group has investigated the function between OER activity and composition for Cu$_x$Ru$_y$O$_{12}$ catalysts via the O 2p band center theory. It can be concluded by the theoretical study that when the O 2p bands were far away from the Fermi level in comparison to the Ru 4d bands, the lattice oxygen was greatly limited and the OER mechanism tended to the adsorbate evolution mechanism (AEM). In contrast, when the O 2p band center got close to the Ru 4d orbital center, the lattice oxygen at the catalyst surface was more likely to take part in the reaction and the OER mechanism was inclined to the lattice oxygen evolution mechanism (LOM) (Fig. 3d). The obvious correlation between the computed relative OER over-potentials ($\eta_{\text{LOM}} - \eta_{\text{AEM}}$) and the difference value between O 2p and Ru 4d-band centers ($\epsilon_{\text{O2p}} - \epsilon_{\text{Ru4d}}$) indicated that the switching between the OER mechanism can be tuned by the amount of Cu or Ni (Fig. 3e).

Over the past decade, beyond d-band and O 2p center theories, extensive works have been done to establish catalytic descriptors to explore the optimal catalysts, including $e_g$ orbital occupancy, metal-oxygen covalency, average O-2p-state energy, coordinatively unsaturated metal cation, and so on. What calls for special attention is that every above-mentioned descriptor has its limited application domain, and more new effective descriptors need to be established to analyze the Ru-related catalysts. Very recently, Ge et al. reported that the Ru charge was defined as a descriptor to describe the overall performance of Ru-related catalysts (Fig. 3f). Moreover, they have managed to regulate the OER mechanism (AEM or LOM) and precisely control the activity and stability under the AEM by changing...
the chelating atoms around the RuO₆ species in MRuOₓ solid solution.

2.2 The relationship between reaction mechanism and stability

Ru-related materials are widely considered to be extremely unstable when acting as OER catalysts in a strongly acidic medium. During the same OER process, RuO₂ will dissolve severely under high overpotential owing to its serious overoxidation, while the dissolution rate of Ru is severalfold quicker than Ru-related oxides. Over the years, extensive efforts have been made to grasp and understand the degradation mechanism of Ru-related catalysts in the OER, universally attributing to the generation of unstable RuO₄ species via the participation of lattice oxygen (Fig. 4a). Moreover, the formation and exfoliation of RuO₄ species from the electrode can be quantitatively detected by using inductively coupled plasma-mass spectrometry; meanwhile, the presence of ruthenium oxy...
species in the electrolyte can also be identified by using in situ reflection spectroscopy.\textsuperscript{86} In addition, Klyukin et al. revealed that the launch of OER and dissolution occurred synchronously for RuO\textsubscript{2}, suggesting that the dissolution was caused by OER (Fig. 4b).\textsuperscript{87} It is worth noting that though the dissolved RuO\textsubscript{4} species can be relieved via redeposition in the reaction process as presented in Fig. 4a, the durability of Ru-based catalysts would be still greatly deteriorated.

Furthermore, the durability of Ru-related catalysts is closely related to the OER mechanisms.\textsuperscript{15,88,89} Over the years, different OER mechanisms in acidic electrolytes have been proposed to uncover the OER process, which is aimed to offer directions for the construction of advanced OER catalysts. Generally, the two most credible hypotheses are known as AEM and LOM in accordance with the origin of the produced O\textsubscript{2} molecule.\textsuperscript{90–92} For the AEM in acidic media, all the oxygen atoms in the produced O\textsubscript{2} molecules are derived from the adsorbed water, and such an OER process is made up of four synchronous proton–electron transfer procedures as presented in Fig. 4c. In terms of the LOM, it involves the surface lattice oxygen redox. That is, the excited lattice oxygen atoms in catalysts will take part in the water oxidation steps, and finally the oxygen atoms in the generated O\textsubscript{2} derive from both adsorbed water and the lattice of Ru-based catalysts as shown in Fig. 4d. Excitingly, the formation of the O−O bond is not accompanied by the generation of Ru−OOH, and therefore breaks the scaling relationships.\textsuperscript{62,93,94} Significantly, the surface of Ru-related catalysts via the AEM process is deemed to be stable with only valence variation of the active sites, while the surface is unstable through the LOM process with the generation of activated lattice oxygen.\textsuperscript{95} This result is due to the rate of oxygen vacancy (O\textsubscript{v}) formation being generally faster than that of O\textsubscript{v} refilling during the LOM process. Meanwhile, the exfoliation of adjacent cations would occur on the surface of catalysts to achieve the compensated charge balance.\textsuperscript{12} Such results can be confirmed by the higher dissolution rate of electrochemically produced RuO\textsubscript{2} with enriched defects than that of thermally formed RuO\textsubscript{2}.\textsuperscript{96} Nonetheless, whether the involvement of lattice oxygen indeed brings about inferior durability for Ru-based catalysts remains open. On the contrary, Tian et al. reported a Co-doped RuO\textsubscript{2} catalyst with enriched oxygen vacancies with an ultra-high acidic OER performance obeying the LOM mechanism. Moreover, they thought that the greatly enhanced durability of Co-doped RuO\textsubscript{2} was closely related to the LOM pathway, and the over-oxidation of Ru to dissolved RuO\textsubscript{4} species was due to the participation of the oxygen vacancy (Fig. 4e).\textsuperscript{97}

Based on the AEM mechanism, the binding energy of different reaction intermediates is linearly correlated by the so-called scaling relationships, thus resulting in a smallest theoretical overpotential of 0.37 V, which essentially limits catalytic activity.\textsuperscript{98} In order to avoid the limitation of the theoretical overpotential in the AEM and the poor stability due to the participation of oxygen vacancies in the LOM, Lin et al. reported an advanced acidic OER catalyst with atomically dispersed Ru on γ-MnO\textsubscript{2}, involving only *O and *OH species serving as intermediates and allowing the O−O radical to produce O\textsubscript{2} without the formation of oxygen vacancies (Fig. 4f).\textsuperscript{99} Beyond expectation, such a Ru-based catalyst can exhibit superior activity as low as 161 mV at 10 mA cm\textsuperscript{2} and remarkable durability without overpotential variation over 200 h. All in all, enhancing stability without sacrificing activity needs reducing the bulk oxygen diffusion rate and surface exchange kinetics whether following the LOM or bypassing the AEM and LOM.

Fig. 4 (a) Model for the oxygen evolution and corrosion on Ru and RuO\textsubscript{2} electrodes.\textsuperscript{85} (b) Schematic representation of the found coupling between corrosion and oxygen evolution reaction for the RuO\textsubscript{2}(110) surface.\textsuperscript{87} (c) The adsorbate evolution mechanism (AEM). (d) The lattice oxygen evolution mechanism (LOM). (e) The free energy diagrams of the two mechanisms of LOM and AEM for Co-doped RuO\textsubscript{2}.\textsuperscript{97} (f) O−O radical coupling promoted by symmetric dual active sites.\textsuperscript{99}
3. Attempts to enhance the OER performance of Ru-based electrocatalysts

To date, various Ru-related materials have been explored for enhanced acidic OER performance. Table 1 presents a representative list of the reported Ru-based acidic OER catalysts. This section provides a review of the progress in Ru-based materials, including metallic Ru, Ru-based oxides, and Ru-based oxometallates, toward acidic OER and highlights the mechanism of improved performance.

3.1 Optimization of metallic Ru

To improve the overall OER catalytic performance of Ru metals in acidic media, efficient strategies need to be adopted to increase their accessible active sites and resistance to corrosion, such as facet engineering, strain engineering, alloying engineering, synergistic effects, and single atom engineering.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Catalysts</th>
<th>Electrolyte</th>
<th>Overpotential (mV) at 10 mA cm²</th>
<th>Tafel slope (mV dec⁻¹)</th>
<th>Stability</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metallic Ru</td>
<td>Faceted Ru branched nanoparticles</td>
<td>0.1 M HClO₄</td>
<td>180</td>
<td>52</td>
<td>4 h@10 mA cm⁻²</td>
<td>100</td>
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<td></td>
<td>L-Ru</td>
<td>0.5 M H₂SO₄</td>
<td>202</td>
<td>69.6</td>
<td>10 h@10 mA cm⁻²</td>
<td>103</td>
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<td></td>
<td>Co-RuIr</td>
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<td>235</td>
<td>66.9</td>
<td>25 h@10 mA cm⁻²</td>
<td>42</td>
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<tr>
<td></td>
<td>RuMn</td>
<td>0.5 M H₂SO₄</td>
<td>223</td>
<td>45</td>
<td>40 h@10 mA cm⁻²</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>Ru@CoNc</td>
<td>0.5 M H₂SO₄</td>
<td>205</td>
<td>—</td>
<td>—</td>
<td>111</td>
</tr>
<tr>
<td></td>
<td>Ni-cluster-Ru NWS</td>
<td>0.5 M H₂SO₄</td>
<td>201</td>
<td>47.2</td>
<td>3000 cycles</td>
<td>112</td>
</tr>
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<td></td>
<td>Ru/RuS₂</td>
<td>0.5 M H₂SO₄</td>
<td>282</td>
<td>69.1</td>
<td>24 h@10 mA cm⁻²</td>
<td>113</td>
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<td></td>
<td>Ru/IrO₂</td>
<td>0.5 M H₂SO₄</td>
<td>226</td>
<td>51</td>
<td>—</td>
<td>114</td>
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<tr>
<td></td>
<td>Ru/MoO(S)₂</td>
<td>0.5 M H₂SO₄</td>
<td>267</td>
<td>52.6</td>
<td>30 h@1.5 V vs. RHE</td>
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<td></td>
<td>Ru–N–C</td>
<td>0.5 M H₂SO₄</td>
<td>232</td>
<td>—</td>
<td>20 h@10 mA cm⁻²</td>
<td>119</td>
</tr>
<tr>
<td></td>
<td>Ru/Co-N–C</td>
<td>0.5 M H₂SO₄</td>
<td>161</td>
<td>29.4</td>
<td>200 h@10 mA cm⁻²</td>
<td>99</td>
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<tr>
<td></td>
<td>Ru/Pt/Cu</td>
<td>0.1 M HClO₄</td>
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<td>—</td>
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<td>RuO₂ NNS</td>
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<td>38.2</td>
<td>20000 s@10 mA cm⁻²</td>
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<td>UFD–RuO₂/CC</td>
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<td>36.9</td>
<td>20 h@1.42 V vs. RHE</td>
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<td>Ru–UO–67–bpydc</td>
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<td>RuO₂–WC NPs</td>
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<td>Ru@V–RuO₂/C HMS</td>
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<td>176</td>
<td>45.6</td>
<td>10K cycles</td>
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<td>RuN₅/C/G–250</td>
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<td>24 h@10 mA cm⁻²</td>
<td>126</td>
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<tr>
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<td>RuO₂/D–TiO₂</td>
<td>0.5 M H₂SO₄</td>
<td>180</td>
<td>43</td>
<td>—</td>
<td>127</td>
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<td></td>
<td>RuO₂/(Co,Mn)₃O₄</td>
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<td>270</td>
<td>77</td>
<td>24 h@10 mA cm⁻²</td>
<td>128</td>
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<tr>
<td></td>
<td>Au@Pt@RuO₂ nanowires</td>
<td>0.1 M HClO₄</td>
<td>215</td>
<td>65.5</td>
<td>40 h@10 mA cm⁻²</td>
<td>129</td>
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<tr>
<td></td>
<td>a/RuO₂</td>
<td>0.5 M HClO₄</td>
<td>205</td>
<td>48.6</td>
<td>60 h@10 mA cm⁻²</td>
<td>49</td>
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<td></td>
<td>Rh–RuO₂</td>
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<td>151</td>
<td>45.8</td>
<td>700 h@50 mA cm⁻²</td>
<td>56</td>
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<tr>
<td></td>
<td>RuO₂@RuO₂</td>
<td>0.1 M HClO₄</td>
<td>190</td>
<td>45.5</td>
<td>200 h@10 mA cm⁻²</td>
<td>51</td>
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<tr>
<td></td>
<td>75–H–RuO₂</td>
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<td>71</td>
<td>20 h@10 mA cm⁻²</td>
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<td>B–RuO₂</td>
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<td>55</td>
<td>12 h@10 mA cm⁻²</td>
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<td>Si–RuO₂@C</td>
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<td>100 h@10 mA cm⁻²</td>
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<td></td>
<td>SS Pt–RuO₂ HMNs</td>
<td>0.5 M H₂SO₄</td>
<td>228</td>
<td>51</td>
<td>100 h@10 mA cm⁻²</td>
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<td></td>
<td>S–RuFeO₂</td>
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<td>40</td>
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<td>133</td>
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<tr>
<td></td>
<td>RuO₁₂–ZnO₁₂O₄–δ</td>
<td>0.5 M H₂SO₄</td>
<td>190</td>
<td>42</td>
<td>50 h@10 mA cm⁻²</td>
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<td></td>
<td>SnRuO₂</td>
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<td>194</td>
<td>38.2</td>
<td>100 h@250 mA cm⁻²</td>
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<td></td>
<td>Li₅S₂RuO₃</td>
<td>0.5 M H₂SO₄</td>
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<td>70 h@10 mA cm⁻²</td>
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<td></td>
<td>Y₂RuO₇–δ</td>
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<td>190</td>
<td>55</td>
<td>8 h@1 mA cm⁻²</td>
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<td></td>
<td>Mo–YRO</td>
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<td>240</td>
<td>40.45</td>
<td>30 h@10 mA cm⁻²</td>
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<tr>
<td></td>
<td>Sr₂[Ru₂O₅Ir₂O₅]₄</td>
<td>0.1 M HClO₄</td>
<td>8.06 mA cm⁻² @ 1.55 V vs. RHE</td>
<td>47</td>
<td>24 h@10 mA cm⁻²</td>
<td>161</td>
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<td>SrRu₀.₅Ir₅.₅O₃</td>
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<td>183</td>
<td>35</td>
<td>50 h@10 mA cm⁻²</td>
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<td>Sr₁₀Na₁₀RuO₃</td>
<td>0.1 M HClO₄</td>
<td>170</td>
<td>—</td>
<td>—</td>
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<tr>
<td></td>
<td>CaCu/RuO₂₂</td>
<td>0.5 M H₂SO₄</td>
<td>171</td>
<td>40</td>
<td>24 h@10 mA cm⁻²</td>
<td>138</td>
</tr>
<tr>
<td></td>
<td>Ru chalcogenides/boride</td>
<td>0.5 M H₂SO₄</td>
<td>245</td>
<td>—</td>
<td>—</td>
<td>164</td>
</tr>
<tr>
<td></td>
<td>RuTe₅ PNRs</td>
<td>0.5 M H₂SO₄</td>
<td>223</td>
<td>39.8</td>
<td>10 h@10 mA cm⁻²</td>
<td>165</td>
</tr>
</tbody>
</table>

**Facet engineering.** Note that the crystallographic orientations are closely related to the exposed accessible active sites, atomic arrangement, defects, etc., which strongly influence the catalytic performances. For instance, Powerprijt et al. reported that Ru-branched nanoparticles possessed controllable surface facets with different catalytic performances. Detailedly, they prepared polycrystalline Ru nanoparticles by using a mass of dodecylamine surfactant and Ru branches with low-index facets exposed by using a small amount of dodecylamine surfactant (Fig. 5a). Interestingly, the faceted Ru nanoparticles delivered much superior activity and stability compared with polycrystalline Ru nanoparticles (Fig. 5b), which was because the dissolution of Ru was suppressed on the low-index facets. In addition, it has been demonstrated that Ru with a face-centered cubic (fcc) structure is attractive for many reactions; nevertheless, it is difficult to be synthesized by traditional strategies due to its specific surface free energies. As a breakthrough, Zhao et al. successfully prepared fcc Ru...
nanoparticles with controlled (111) facets by using the seed-mediated growth with Rh cubes as seeds (Fig. 5c).41 Furthermore, the obtained Ru nanocrystals showed higher thermal stability and 4.4-fold specific activity compared with hcp-Ru nanoparticles for OER (Fig. 5d). Thus, facet engineering was demonstrated to be an effective strategy to design advanced Ru-based catalysts with controllable crystallinity and surface configuration.

**Strain engineering.** The strain effect is mainly beneficial to optimize the overall electrocatalytic performance of catalysts, owing to its well-adjusted electronic properties for catalysts and optimization of the binding energies for adsorbates.101–103 For example, Ru nanoparticles with enriched grain boundaries coupled with compressive strain were synthesized successfully via using the laser-ablation-in-liquid technique by Wang et al. (Fig. 5e).103 The as-obtained sample as an OER catalyst showed a low overpotential of 202 mV at 10 mA cm$^{-2}$ in acidic media and superior durability for 10 h compared with commercial RuO$_2$ (305 mV@10 mA cm$^{-2}$, less than 6 h). From the experimental analysis and theoretical calculations, the compressive strain induced by grain boundaries promoted the reduction of the d-band center and the binding energy of reaction intermediates, thus enhancing the electrocatalytic activity (Fig. 5f). Furthermore, the low d-band center caused by strain engineering would lead to the additional repulsion of oxygen-related species, improving the surface oxidation resistance of Ru nanoparticles to enhance their stability. Such engineering has become an effective tool to improve the performances of various electrocatalysts. Of note, at present, there are limited studies of strain engineering on Ru metal, which remains a very worthy direction for us to study.

**Alloying engineering.** Alloying with foreign metal elements is proven to be an effective means to improve the catalytic properties owing to the lattice parameter mismatch, adjustment of the coordination environment, and charge redistributions.42,104–106 It has been confirmed that the drastic dissolution of Ru leads to much inferior stability for Ru metals during the acidic OER process, which can be enhanced by alloying the heterometal elements. For example, Forgie et al. have investigated the OER activity of seven binary Ru-based alloys. The experiment results showed that Ru–Cu, Ru–Ir, and Ru–Co alloys were hexagonal and cubic mixed phase and all their activity was improved, owing to the chemisorption energy modulation of oxygen caused by the secondary metal component.104 Further, Danilovic et al. reported an advanced Ru$_{0.5}$Ir$_{0.5}$ alloy with balanced activity and stability in an acidic medium via a surface segregation method to atomically tailor the near-surface composition (inset in Fig. 6a).105 As shown in Fig. 6a, the excellent stability was attributed to the generation of the Ir-skeleton layer by thermal annealing, resulting in the suppressed dissolution of Ru atoms during the acidic OER process. Jiang et al. fabricated an atomic equidistributed Ru$_{0.5}$Ir$_{0.5}$ alloy catalyst, exhibiting great catalytic performances when acting as an OER catalyst in acidic media.106 They found that the charge redistribution on the surface of the catalyst was promoted by the weak electronic coupling between Ru and Ir, resulting in Ru serving as the active site to enhance catalytic activity. Moreover, the atomic equidistribution in the alloy contributed to oxygen species occupying the vacancy formed from Ru leaching, while the oxygen species can bind well the adjacent Ir atoms. This result led to the formation of an Ir-protective skeleton to significantly suppress the further
dissolution of Ru atoms, thus ensuring the excellent stability of the Ru0.5Ir0.5 alloy catalyst.

Except for the Ir-armour structures, the introduction of nonprecious transition metals is able to not only further improve catalytic activity but also greatly reduce the consumption of noble metals. For instance, Shan et al. reported a Co-RuIr catalyst with a small overpotential of 235 mV at 10 mA cm⁻² for OER in acidic media, much superior to that of RuIr (344 mV), which was due to the increased concentration of O¹⁻ species caused by the dealloying of the Co element, greatly enhancing OER catalytic activity.²⁴ In addition, Ni-RuIr and Fe-RuIr electrocatalysts were also prepared to build the composition–activity relationship, showing that both OH⁻ desorption peak positions and OER activity are linear with the intensity of O¹⁻ species (Fig. 6c), which suggested that the concentration of oxygen species predicted the trend of OER activity.

Notably, although dealloying–caused surface reconstruction will complicate the reaction sites, it can be a win–win situation in terms of increased overall catalytic performance if utilized properly. For example, An et al. reported that a series of Ru-based alloys were prepared by doping with Mn, Zn, Cr, and Co and then subjected to dealloying treatment by the CV cycle test.¹⁰⁷ Thereinto, RuMn showed superior anti-corrosion and anti-oxidation properties during the acidic OER process while other Ru-based alloys dissolved quickly in the process of dealloying treatment (Fig. 6d). This was because there was a controllable surface reconstruction process during the continuous CV cycle test along with the leaching of Mn species and the formation of an amorphous RuOₓ surface. Theoretical calculations indicated that the strong binding energy of Ru in the RuMn alloy could cause a highly stable structure (Fig. 6e). More attractively, the RuMn alloy catalyst exhibited a very competitive stability over 720 h at 10 mA cm⁻² (Fig. 6f).

In addition, alloying engineering coupled with other strategies can further significantly improve the catalytic performance of Ru-related catalysts. For example, Huang’s group reported channel-enriched RuCu nanosheets as acidic OER catalysts with enhanced electrochemical performance (Fig. 6g).¹⁰⁸ DFT calculations indicated that the channel-enriched structures...
could not only activate the electron on the catalyst surface, but also lead to obvious lattice distortion around the channel area, thus greatly reducing the energy consumption of bond-dissociation for intermediates during the acidic OER process (Fig. 6h). They also reported Mn-doped ultrathin Ru nanosheet branches as a significantly active and stable catalyst toward acidic water splitting.109 Xu et al. reported an OER catalyst comprising atomic-step enriched RuIr nanoparticles supported on the novel MOF-derived carbon (Fig. 6i), delivering a low overpotential of 223 mV and remarkable durability without notable degradation up to 40 h at 10 mA cm\(^{-2}\) in an acidic electrolyte.110 Detailed experimental characterization coupled with theoretical calculations indicated that a strong chemical bond was formed between the pyrrolic-N sites on the skeleton and RuIr nanocrystals to provide a good solubility resistance during the acidic OER. Meanwhile, the unique atomic steps could fully expose the active sites and optimize the rate-determining step of OER, thus improving the catalytic activity. All in all, alloying engineering can enhance both activity and stability of Ru-based metal catalysts via the effective optimization of the electronic structure.

**Synergistic effects.** When the metallic Ru is coupled with other materials to form heterostructured catalysts, there will be synergistic effects in the new effective heterostructured catalysts, which can greatly increase the electrocatalytic activity and stability of Ru-based catalysts.111–114 For instance, Zhu et al. reported diluted Ni nanocluster-decorated Ru nanowires (Fig. 7a), showing high catalytic performances when explored as an acidic OER electrocatalyst. Experimental data and DFT calculations indicated that the robust interaction between the Ni nanocluster and the Ru surface can not only maintain the high electrical activity of the Ni 3d bands (Fig. 7b), but also accelerate electron transfer and enhance the durability. Mu et al. reported a heterostructured Ru/RuS\(_2\) nanosheet that was synthesized through an isochronous reduction-sulphuration way (Fig. 7c). When used as an acidic OER catalyst, such material exhibited a low overpotential of 201 mV at 10 mA cm\(^{-2}\) and superior durability without obvious activity change after
successive 3000 CV tests. Theoretical calculations indicated that the heterostructure with higher density states at the Fermi level ensured quick electron transfer during the OER process (Fig. 7d). Moreover, there was a strong charge redistribution at the interfaces (Fig. 7e), which greatly modulated the adsorption behavior of key intermediates, hence ensuring the favorable OER kinetics on heterostructures.

Among the various heterostructures, the core–shell structure can protect the core from oxidation and corrosion more effectively, guaranteeing higher stability. Recently, Shan and co-workers reported a core–shell heterostructured OER catalyst composed of a partially oxidized Ir shell and a greatly disordered and strained Ru core (Ru@IrOx) that displayed an overpotential of 282 mV at 10 mA cm−2 and good stability over 24 h under acidic conditions, much superior to that of RuIr oxide alloy (RuIrOx) nanocrystals (Fig. 7f).113 They found that the charge was greatly redistributed at the Ru-core and IrOx-shell interface, which increased the valence state of Ir and reduced the valence state of Ru to form favorable surface chemical states, therefore increasing the catalytic activity. Also, the improved stability was due to the synergistic effect from the unique core–shell heterojunction as well as induced charge redistributions (Fig. 7g). DETA and HAADF-STEM images of Ru@IrOx after the test indicated that the stable chemical states contributed to preventing the generation of dissolvable high-valence intermediate species and the core–shell nanostructure protected active Ru sites from loss in acidic media. In addition to the protection of the Ir-based shell, Ru encapsulated by a transition metal-based shell is demonstrated to be a cheap and effective strategy to design highly advanced Ru-based catalysts. Mu’s group designed and prepared a core–shell structured catalyst Ru@MoO(S)x (Fig. 7h and i), which displayed a high catalytic performance in the acidic OER process, owing to not only Ru acting as a highly active site but also due to it being protected by the MoO(S)x shell.114 Therefore, designing heterostructures can not only achieve improved stability through strong interactions at the heterogeneous interfaces and also through the good protection from the stable enclosure.

**Single atom engineering.** To date, single atom catalysts have sparked great attention in various electrochemical reactions, which is attributed to their nearly 100% atomic utilization and subtle electron properties.115 Nevertheless, the strong surface free energy of SACs leads to poor stability especially under acidic conditions, calling for suitable substrates and appropriate strategies to perfectly anchor the isolated atoms and produce stabilized configurations. As a response, numerous synthetic ways such as defect engineering, metal–support interplay, heteroatom tethering, etc. have been explored and various supports including carbon materials, transition metal oxides, and so forth have also been put into use.116,117

Recently, Cao and co-workers reported atomically dispersed Ru1-N4 moieties immobilized on a N-carbon substrate (Ru-N-C). When Ru-N-C was used as an acidic OER catalyst, it showed a low overpotential of 267 mV at 10 mA cm−2 with persistent and stable working over 30 h.118 They found that there was reversible dynamic adsorption/desorption of a single oxygen atom on the Ru1-N4 sites with the formation of O-Ru1-N4, and the generation of a higher valence state of Ru during the in situ operation through operando XAS and SR-FTIR (Fig. 8a and b). DFT results indicated that more charge donations occurred from the Ru 4d state to the N 2p state, further suggesting that the formation of O-Ru1-N4 sites contributed to OER activity and stability (Fig. 8c). Further, Rong et al. regulated the electronic structure and catalytic performances of the atomically anchored Ru active sites by the introduction of another atomically dispersed Co site (Fig. 8d).119 Namely, they prepared atomical Ru and Co dual-sites dispersed on N-carbon (Ru/Co-N-C), exhibiting a small overpotential of 232 mV and remarkable stability over 20 h with stable activity for OER at 10 mA cm−2 in an acidic medium. DFT calculations demonstrated that the incorporation of Co-N4 sites into Ru/Co-N-C not only significantly tuned the electronic properties of Ru sites through increasing Ru–O covalency but also promoted the electron transfer from C/N atoms to Ru. Therefore, the binding energy of reaction intermediates was greatly optimized to enhance OER activity and the electron around Ru-N4 was well redistributed to enhance the resistance to corrosion of Ru/Co-N-C (Fig. 8e and f).

Note that although the carbon skeleton contributes to anchoring and protecting single atoms from unwanted agglomeration, the thermodynamical property of carbon materials under oxidation potential is not stable, which will result in the configuration damage of single atoms.30 Fortunately, it has been demonstrated that Sb/Ti/Sn/Ge/Mo/W-based oxides possess strong resistance to oxidation and dissolution in the acidic OER process.120 Moreover, γ-MnO2 can work as an acidic OER catalyst over 8000 h, though tested under low current density, making it act as a potential acid-resistant support.121 If the Ru atoms can be coupled well with these acid-stable supports, it will not only reduce the consumption of Ru elements but also improve the stability of single atom Ru-related catalysts. For example, Lin et al. reported an advanced OER catalyst with Ru atom chains anchored on γ-MnO2 (Ru/MnO2) through a cation exchange method.99 Time-dependent elemental analysis revealed that the in situ dynamic cation exchange reaction occurred during the OER process. This dynamic reaction not only led to the formation of Ru atom arrays but also preserved the catalyst from metal-leaching-induced dissolution (Fig. 8g). Owing to the shorter interatomic Ru–Ru distance in Ru/MnO2, such catalyst followed the oxide path mechanism to ensure high activity as discussed above in Fig. 4f. As a consequence, Ru/MnO2 displayed an overpotential as low as 161 mV at 10 mA cm−2 and excellent long-term stability of more than 200 h under acidic OER conditions.

Other than noble transition metal oxides, noble metal-based skeletons are also promising supports to atomically anchor and disperse Ru atoms, except for the limitation of high price. Yao et al. reported a group of PtCux/Pt skin core–shell structures with embedded Ru atoms on account of the epitaxial growth of nano-island formation of PtCu, from the Cu
In situ XAFS measurements indicated that the valence state of Ru$_1$ was almost unchanged during the OER process. During the acid etching and electrochemical leaching process, the gradual release of compressive strain in comparison to pristine Pt was conducive to increasing the Ru d-band center to approach the Fermi level, resulting in the well-optimized oxygen adsorption energy ($E_O$), which ultimately leads to an inverse volcano-type relationship between the OER activity and the lattice constant (Fig. 8h and i). As a result, the best Ru$_1$-Pt$_3$Cu catalyst displayed an overpotential of 220 mV at 10 mA cm$^{-2}$ and remarkable long-term stability, much better than that of commercial RuO$_2$. The enhanced stability was attributed to the occurrence of electron transfer from Pt to Ru as revealed by in situ XANES, which protected the Ru atoms from overoxidation and accompanying dissolution. Thus, single-atom engineering can not only reduce the consumption of precious Ru metal, but also endow single Ru atoms with unique coordination environments to ensure their superior overall acidic OER performances.

3.2 Optimization of Ru-based oxides

Strategies for improved performance of Ru-based oxides including morphology control, heterostructure construction, doping, substituting, and so forth have been confirmed to be effective. Morphology control. Reducing particle size or nanosheet thickness is an effective strategy to increase the specific surface area, thus fully exposing active sites, while the structural defects will inevitably come along. For example, Zhao et al. have synthesized ultra-thin RuO$_2$ nanosheets with a thickness of 1–2 nm and with enriched Ru vacancy defects (RuO$_2$ NSs) via a molten salt method (Fig. 9a and b). The obtained RuO$_2$ NSs showed a lower overpotential of 199 mV at 10 mA cm$^{-2}$ and...
much higher specific and mass activities at 230 mV compared with the commercial RuO₂. DFT calculations revealed that the existence of Ru vacancies on the surface of RuO₂ NSs remarkably reduced the energy consumption in the transformation of key reaction intermediates, hence significantly improving the catalytic activity (Fig. 9c). In addition, Paoli et al. have investigated the relationship between mass activity and particle size of RuO₂ by using mass-selected nanoparticles, revealing that the particle size of RuO₂ at about 3–5 nm displayed the optimum mass activity (Fig. 9d). Combining the advantages of structure engineering and defect engineering, ultrafine defective RuO₂ nanoparticles with an average grain diameter of about 5 nm on carbon cloth were prepared, exhibiting a low overpotential of 179 mV at 10 mA cm⁻² and a well-maintained activity for 20 h for acidic OER. Theoretical calculations indicated that the presence of oxygen vacancies not only produced abundant active sites in RuO₂, but also optimized the electronic properties of unsaturated five-coordinated sites adjacent to oxygen

Fig. 9  (a) STEM images of RuO₂ NSs at a lower magnification. (b) Atomic STEM images of RuO₂ NSs. (c) Two-dimensional volcano plot constructed using the descriptors of ΔG_O₂*/C₀ and ΔG_OOH*/C₀. (d) OER mass activities of different thermally oxidized RuO₂ particle masses. (e) The top view of the defective RuO₂ structure. (f) The calculated free-energy profiles of OER on the (a) Ru0, (b) Ru1, and (c) Ru2 sites. (g) Scheme of the preparation of the Ru-UIO-67-bpydc catalyst. (h) The stability of the Ru intermediate in the MOF-anchored Ru oxide during the acidic OER by the LOM pathway. (i) Schematic illustration of the intermediate model in CV peaks with and without TMA⁺. (j) Gibbs free energy illustration by Ru-UIO-67-bpydc and RuO₂ catalysts during the OER process by the AEM or LOM pathway. (k) Schematic molecular orbital energy diagram for Ru-UIO-67-bpydc and RuO₂ toward the acidic OER.
vacancies, thus enhancing the catalytic activity (Fig. 9e and f). Of note, the different optimal nanoparticle size may be due to the preparation techniques and coordination environments. If the size of Ru oxides can be downsized to the atomic level, the catalytic performances will be significantly improved, due to the maximized atom utilization efficiency and unique electronic structure. Very recently, Yao et al. prepared an acidic OER catalyst of atomically dispersed Ru oxide on UiO-67-bpydc (Ru-UiO-67-bpydc) with robust Ru–N bonds through an effective metal-organic framework anchored strategy (Fig. 9g).54 They thought that the sturdy coordinating pyridine ligands and the strong interaction between Ru oxide and the metal-organic framework could induce the motivated LOM pathway and stabilize the dissolvable high-valence oxygen-vacancy intermediates simultaneously, thus leading to the synchronously improved overall catalytic performance of Ru oxides (Fig. 9h). As a consequence, Ru-UiO-67-bpydc displayed a low overpotential of 200 mV and excellent stability without activity and structure degeneration over 115 h at 10 mA cm\(^{-2}\) under acidic conditions. The experimental results confirmed that the lattice oxygen was involved in the OER process via the LOM pathway (Fig. 9i and j). DFT calculations indicated that the robust Ru–N bonds led to the Ru d-band center far away from the Fermi level but the O 2p-band center close to the Fermi level, definitely enhancing the catalytic performances of Ru oxides (Fig. 9k). Therefore, an important way to improve the catalytic performance of Ru-based oxides is to design the structure of nano-materials reasonably, so as to realize effective utilization of precious metals.

**Heterostructure.** Constructing heterogeneous structures has been demonstrated to be an effective strategy to not only promote electron redistribution but also induce synergistic effects at the interface, so as to realize enhanced catalytic performance for acidic OER. For example, Sun et al. developed an advanced OER catalyst of WC-supported RuO\(_2\) nanoparticles (RuO\(_2\)-WC NPs) with strong catalyst–support interaction (Fig. 10a), showing a high mass activity of 1430 A g\(_{\text{Ru}}\)^{-1}, which greatly exceeded that of commercial RuO\(_2\).124 DFT calculations confirmed that the robust catalyst–support interaction at the interface between RuO\(_2\) and WC promoted the electron transfer from W atoms to Ru atoms, resulting in an electron accumulation region around the Ru site. Meanwhile, the WC support optimized the binding energy of reaction intermediates on Ru sites to break the reaction barrier, thus enhancing the catalytic activity of RuO\(_2\)-WC NPs (Fig. 10b). Li et al. reported a core-shell heterostructure composed of oxygen defect-engineered RuO\(_2\) sub-nanometer skin on the Ru core (Ru@V-RuO\(_2\)/C HMS, Fig. 10c).125 There was a robust strain effect at the interfaces to accelerate the reaction kinetics and increase additional active sites (Fig. 10d). DFT calculations indicated that the core–shell heterostructure induced a lower d-band center and a smaller electron transfer between the catalyst surface and *O\(_2*\), hence reducing the adsorption energy of oxygen-related intermediates to enhance OER activity (Fig. 10e). Moreover, the elevated p-band center caused by the core–shell heterostructure suppressed the reaction activity of lattice oxygen, contributing to the improved structural stability during the OER process. Accordingly, Ru@V-RuO\(_2\)/C HMS displayed an ultrasmall overpotential of 176 mV at 10 mA cm\(^{-2}\) and a slight change of activity in the accelerated decay test with the curve after 5k cycles for OER in 0.5 M H\(_2\)SO\(_4\). In addition, the Ru-based oxide–support interaction on RuNi\(_3\)@G-250 (Fig. 10f),126 RuO\(_2\)/D-TiO\(_2\) (Fig. 11g),127 RuO\(_2\)/(Co,Mn)\(_2\)O\(_4\) (Fig. 10h),128 and Au@Pt@RuO\(_2\) (Fig. 10i)129 was also demonstrated to be an effective strategy to optimize electron redistribution and enhance catalytic performances for acidic OER. In a word, heterogeneous structures can accumulate charge at the interface, which can endow rapid electron conduction ability and optimize the adsorption strength of oxygen evolution intermediates, so as to improve the catalytic activity of Ru-based oxides.

In addition to the strategies discussed above, another effective strategy is incorporating foreign metal atoms, such as alkali metals (Li,45 Na,49 etc.), transition metals (Ti,130 Cr,131 Mn,132 Fe,133 Ni,55 Co,134 Cu,135 Zn,136 etc.), main group metals (Mg,137 Ca,138 Sr,139 etc.), noble metals (Pt,140 Rh,56 Ir,141 etc.), acid-insoluble metals (Sn,82 Pb,142 etc.), and rare earth metals (La,143 Ce,144 Y,145 Er,146 etc.), and non-metallic elements (H,147 C,148 B,149 S,150 Se,151 Si,152 etc.) with Ru through doping and substitution or forming Ru-related pyrochlores and perovskites to greatly enhance the OER performances (Fig. 11). This part will be divided into the following aspects: cation doping, anion codoping, anion and cation codoping, and solid solution oxides.

**Cation doping.** Doping and substitution of foreign cations in Ru-based oxides have been proven to be pleiotropic ways to regulate structural and electronic structures with flexible composition and structure modulations. For example, our group reported a Na-doped and oxygen vacancy enriched amorphous/crystalline RuO\(_2\) (a/c-RuO\(_2\)), exhibiting an excellent activity of 205 mV and superior stability in continuously catalyzing OER for 60 h with no activity degeneration over 60 h at 10 mA cm\(^{-2}\) in an acidic medium.49 Operando XAS results indicated that the obtained a/c-RuO\(_2\) possessed flexible structural distortions and redox reaction of Ru, which greatly enhanced the resistance to overoxidation and dissolution in the OER process (Fig. 12a). Theoretical calculations revealed that the incorporation of Na and oxygen vacancies induced the Ru d-band center far away from the Fermi level, which optimized the adsorption energy between reaction intermediates and the catalyst surface, thus reducing the reaction energy barrier for the OER (Fig. 12b). Wu et al. reported a Ni-doped RuO\(_2\) (Ni-RuO\(_2\)) catalyst, which acted as an OER catalyst in PEM water electrolysis, showing much remarkable stability over 1000 h at 200 mA cm\(^{-2}\).55 Operando tests coupled with DFT studies confirmed that the introduction of Ni not only significantly stabilized the RuO\(_2\) lattice but also greatly avoided the dissolution of surface Ru and subsurface oxygen for enhanced OER stability. By means of heteroatom doping, such as Na,49 Ni,55 Ti,130 etc., the d-band center can be kept far away from the Fermi level and the lattice oxygen can be suppressed to obey the AEM mechanism, thus improving both catalytic activity and stability.
Unusually, Wang et al. recently reported an OER catalyst of Rh-doped RuO$_2$ on graphene (Rh-RuO$_2$/G), whose OER mechanism followed the lattice oxygen mediated mechanism-oxygen vacancy site mechanism (LOM-OVSM). As a result, Rh-RuO$_2$/G delivered an ultralow overpotential of 161 mV at 10 mA cm$^{-2}$ and remarkable long-term durability without obvious activity change over 700 h at 50 mA cm$^{-2}$. Experimental characterization analysis coupled with DFT calculations confirmed that the emerging oxygen species during the OER process were reversible, which greatly improved both intrinsic activity and crystal structure stability (Fig. 12c and d). DFT calculations indicated that the oxygen vacancies coupled with Ru–O–Rh active sites...
made Rh-RuO$_2$/G follow the LOM-OVSM. In addition, the generation of *O on Ru–O–Rh active sites was the rate-determining step of Rh-RuO$_2$/G, which broke the barrier limitation (*OOH) of the AEM (Fig. 12e).

In addition to regulating the reaction mechanism, the electron transport form can also be adjusted to improve the overall catalytic performance. Very recently, Jin et al. found that the electron accepting–donating process in Re-doped RuO$_2$ (Re$_{0.06}$Ru$_{0.94}$O$_2$) was dynamic, completely different from the traditional static electron redistribution caused by the dopant, which significantly improved both activity and stability. Operando XAS characterization indicated that the electron transfer between Re and Ru sites was highly correlated to the operating potential along with dynamic role change of the Re site (Fig. 12f). As detailedly shown in Fig. 12g, the Re sites accept electrons from Ru sites at the on-site potential to enhance the catalytic activity of Ru sites. In contrast, the electrons are transferred from Re atoms to Ru sites at a large overpotential to avoid the overoxidation of Ru and boost the stability of Ru sites. Moreover, in situ characterization and DFT calculations confirmed that the unique dynamic electron transfer promoted the transformation of the reaction pathway on Re$_{0.06}$Ru$_{0.94}$O$_2$ from LOM to AEM and optimized the binding energies of reaction intermediates, thus increasing catalytic performances (Fig. 12h). Moreover, aberration-corrected HAADF-STEM images and XAFS measurements of Re$_{0.06}$Ru$_{0.94}$O$_2$ after OER indicated that there was no aggregation or reconstruction of Re single atoms and no change of the valence state and coordination environment of Ru and Re atoms after the OER process. Thus, cation doping is demonstrated to be an effective way to optimize the electronic structures of Ru-based oxides to regulate the OER pathway.

### Anion doping

In addition to cation doping, anion doping is demonstrated to be an effective strategy to improve the performance of RuO$_2$. For example, He et al. successfully introduced the hydrogen binding modes into the RuO$_2$ lattice, which induced the electronic interaction between Ru and O atoms and promoted the formation of hydrogen bonds, ensuring the
obtained catalyst with a low overpotential of 200 mV at 10 mA cm\(^{-2}\) (Fig. 13a).\(^{147}\) Liu \textit{et al.} developed a boron-doped RuO\(_2\) (B-RuO\(_2\)) with an overpotential of 200 mV and remarkable durability over 12 h at 10 mA cm\(^{-2}\).\(^{149}\) DFT calculations indicated that the B dopant weakened the interaction between Ru atoms and O atoms to lift up the d-band center, thus increasing the binding energy between reaction intermediates and Ru sites (Fig. 13b). This coupled with advanced characterization revealed that the formed unusual B–O covalent bonding activated the bridge Ru site (Ru-bri site) to act as an active site, leading to fully exposed active sites, which greatly enhanced the catalytic activity of B-RuO\(_2\) (Fig. 13c). In addition, Liu \textit{et al.} prepared carbon-coated Si-doped RuO\(_x\) particles (Si-RuO\(_x@C\)) from a nano-organic cage. When Si-RuO\(_x@C\) was used as an OER catalyst, it showed a low overpotential of 220 mV at 10 mA cm\(^{-2}\), remarkable durability for 100 hours, and stable CV energy after operating for 27 000 cycles in an acid electrolyte.\(^{152}\) Theoretical calculations revealed that the Si dopant not only optimized the binding energy of oxygen-related intermediates but also served as an electron receiver from Ru to enhance the resistance to overoxidation, thus improving both activity and stability (Fig. 13d). Although great enhancements of activity and stability are achieved by using anion doping, the change of the doped anion atoms during the OER process requires further detailed research.

Anion and cation codoping. In addition, co-doping with both cation and anion elements can also greatly enhance both catalytic activity and stability. For instance, Wang \textit{et al.} reported a single-site Pt-doped RuO\(_2\) with interstitial C (SS Pt-RuO\(_2\) HNSs), delivering a low overpotential of 228 mV and a stable overpotential over 100 hours at 10 mA cm\(^{-2}\) toward acidic OER (Fig. 13e).\(^{153}\) Experimental characterization indicated that the bond lengths of Ru–O and Pt–O were simultaneously elongated by the interstitial C, and the electron distribution on RuO\(_2\) was effectively optimized by the introduction of single-site Pt (Fig. 13f). DFT calculations confirmed that the strong synergy not only greatly increased the dissociation energy of *O species but also significantly reduced the energy barriers for OER, thus readily enhancing both catalytic activity and stability of SS Pt-RuO\(_2\) HNSs (Fig. 13e).\(^{153}\) Xue \textit{et al.} reported that codoping with the sulfate anion and Fe cation in RuO\(_2\) (S-RuFeO\(_x\)) effectively enhanced the catalytic performances for acidic OER.\(^{133}\) Detailed experiments revealed that the binding energy of the *OO–H intermediate was reduced by the doping of the sulfate anion and the deprotonation of H\(_2\)O was boosted by the doping of the Fe cation, thus promoting the catalytic activity of S-
RuFeO$_x$ (Fig. 13h). Moreover, the sulfate anion dopant prevented lattice oxygen well, hence enhancing the stability of S-RuFeO$_x$. Consequently, the obtained S-RuFeO$_x$ displayed a superior activity with an overpotential of 187 mV at 10 mA cm$^{-2}$ and good stability during the 50 h of the chronopotentiometry test at 1 mA cm$^{-2}$.

**Solid solution oxides.** Doping with foreign atoms can produce a kind of unique polymetallic oxide: solid solution oxides with RuO$_2$ as a solid solvent. Recently, our group developed an oxygen-vacancy-enriched Ru–Zn solid solution oxide (Ru$_{0.85}$Zn$_{0.15}$O$_2$) via a molten salt method. Based on the detailed structural characterization and analysis, we safely inferred that the obtained Ru$_{0.85}$Zn$_{0.15}$O$_2$ was constituted by tetragonally distorted RuO$_6$ and ZnO$_6$ octahedra with oxygen vacancies adjacent to Zn atoms as shown in Fig. 14a. In the solid solution, the existence of Zn atoms and oxygen vacancies not only reduced the Ru valence state, but also promoted the Ru d-band center far away from the Fermi level, resulting in a weaker free energy barrier for OER (Fig. 14b). Moreover, robust Zn-O-Ru local structures were formed to prevent Ru atoms from overoxidation and dissolution during the OER process, thus enhancing structural stability (Fig. 14c). As a result, the Ru$_{0.85}$Zn$_{0.15}$O$_2$ solid solution oxide showed a low overpotential of 190 mV and long-term stability with negligible activity degeneration over 50 h at 10 mA cm$^{-2}$ towards acidic OER. In addition, tuning the chelating elements around RuO$_6$ in solid solution oxides with controllable M–O–Ru (M = Ce, Sn, Ru, Cr) could precisely regulate the OER mechanism (Fig. 14c).

![Fig. 14](https://example.com/fig14.png)
2360 A gRu−1 at 1.48 V and superior long-term stability with small activity variation under 100 mA cm−². Other Ru-based solid solution oxides with the chelating elements adjacent to RuO6 like Cr-Ru solid solution oxide131 and Mn-Ru solid solution oxide132 have also been investigated for improved performance for acidic OER.

Different from the previously reported solid solution with the Ru cations replaced by foreign atoms, a unique Li0.52RuO2 solid solution oxide with Li ions intercalated into the octahedral interstices composed of six adjacent O atoms was synthesized by Qin et al. via the electrochemical lithiation process (Fig. 14f and g).45 The Li ions intercalated into the lattice interstices induced the electron redistribution and local lattice distortion of RuO2, reducing the valence state of Ru with the generation of the robust Li–O–Ru local structure, which prevented the dissolution of Ru and improved the stability. Note that the surface structural distortion caused by intrinsic lattice strain could motivate the dangling O atom surrounding the Ru active site to act as a proton receiver, which effectively anchored the OOH* to greatly improve the catalytic activity of Li0.52RuO2 solid solution oxide for acidic OER (Fig. 14h and i). The constructed Li0.52RuO2 delivered a record activity of 156 mV at 10 mA cm−² and good stability with persistent operation for 70 h without obvious overpotential change. All in all, the Ru-based solid solution oxides, whether the M intercalates into the octahedral interstices or substitutes the position of Ru, deliver improved catalytic performance through the formation of unique M–O–Ru bonds.

3.3 Optimization of Ru-based oxometallates

Ru-based oxometallates, including pyrochlore- and perovskite-type ruthenates, have attracted widespread attention with their low Ru content and remarkable catalytic performances in acidic OER. The most effective strategy to improve the performance of pyrochlore- and perovskite-type ruthenates is substitution.

To expand acid-stable Ru-based catalysts with high activity for OER, Kim et al. produced a pyrochlore yttrium ruthenate (Y2RuO7-d) by the sol–gel method, showing a low onset overpotential of 190 mV and high stability over 8 h at 1 mA cm−² under acidic conditions.154 The overall enhanced catalytic performance was due to the lowered Ru valence state and the reduced overlapped energy band center between Ru 4d and O 2p bands (Fig. 15a and b). Moreover, the superior structural stability of Y2RuO7-d during the acidic OER process was confirmed by the XPS, XAS and PXRD results. Recently, Hubert et al. prepared a series of A3Ru2O7 (A = Y, Nd, Gd, Bi) as acidic OER catalysts and investigated the relationships between A-site elements and both the activity and stability.144 They found that the initial OER activity of A3Ru2O7 was higher than that of RuO2, which was attributed to the elongated Ru–O bond length and the reduced binding energy between the Ru 4d and O 2p bands (Fig. 15c and d). Moreover, the property of the A-site element had a great impact on the Ru dissolution rates during the OER process, which was consistent with theoretical Pourbaix analysis, suggesting that such A3Ru2O7 pyrochlores were thermodynamically unstable towards OER in acidic media (Fig. 15e). Theoretical activity predictions indicated that the OER activity was highly related to A-site cation leaching, revealing that A-site cation leaching fully exposed highly oxidized Ru sites to improve activity. Note that, all A3Ru2O7 catalysts were proven to possess superior activity and stability than RuO2, although not without dissolution.

To improve the catalytic performance of A3Ru2O7 pyrochlore, the substitution of A or Ru with foreign elements has been demonstrated to be an effective strategy. For instance, Kim et al. reported a Y1.8M0.2Ru2O7-d porous pyrochlore oxide with partial substitution by Y3+ on the B-site (Fig. 15f), exhibiting a higher activity compared with Y2RuO7-d and RuO2 references (Fig. 15g) for acidic OER.155 The enhanced activity was due to both a high surface area and an optimized energy band structure caused by the B-site substitution. Feng and co-workers constructed an A-site substituted Y1.85Zn0.15Ru2O7-d catalyst with a highly active and stable performance for acidic OER, which was attributed to the optimized electronic structure induced by the partial substitution of Y3+ ions with Zn2+ ions.156 Later, Kuznetsov et al. developed a group of A-site substituted Y1.8M0.2Ru2O7-d (M = Cu, Co, Ni, Fe, Y) with controllable oxygen vacancy concentration and demonstrated that the OER activity is highly correlated to oxygen vacancy concentration.157 DFT calculations revealed that the enhanced activity along with increased oxygen vacancy concentration led to the lowered binding energy of the M–O band, which was scaling with the enthalpy of generation (ΔHoxide) of the respective MOx species and the overlap between the M d orbitals and O 2p orbitals (Fig. 15h and i).

In addition to substitutional strategies for regulating electronic properties, the surface manipulation strategy is also proven to be an effective strategy for regulating the electronic properties of A3Ru2O7 pyrochlore. Very recently, Liu et al. implanted MoOx species on Y2RuO7-d to generate Mo–O–Ru micro-interfaces with accelerated electron transfer, which resulted in rearrangement of the Ru 4d orbital alignment and elimination of the bandgap.158 In addition, the implanted MoOx could not only compress the bond length of the Ru–O band and expand the Ru–O–Ru bond angle with moderate distortion of RuO6, but could also act as an electron receiver to induce more electronegative surfaces and prevent metal ions from dissolution, hence enhancing both OER activity and stability (Fig. 15j and k). Consequently, the obtained heterogeneous catalyst delivered an improved activity with an overpotential of 240 mV at 10 mA cm−² and enhanced stability over 30 h relative to Y2RuO7-d (Fig. 15l).

As for perovskite-type ruthenates (ARuO3), a thin film of SrRuO3 OER catalyst with a very remarkable activity (1.33 V vs. RHE at 0.1 mA cm−²) under alkaline conditions has been reported (Fig. 16a).159 Nevertheless, the activity was completely degraded after only two cycles, which was due to not only the overoxidation of Ru under high voltages, but also the structure collapse of the perovskite starting at the Sr dissolution (Fig. 16a and b).159,160 To overcome the lack of superior durability of Ru-related perovskites especially in acidic electrolytes, a series of B-site mixed Sr2(Ru1-xIrx)O4 were prepared and proven to
display an optimal current density of 8.06 mA cm\(^{-2}\) at 1.55 V and good stability over 24 h at 10 mA cm\(^{-2}\) towards acidic OER (Fig. 16c), owing to the generation of enriched hydroxyl groups and the broadened Ru 4d band through the metal substitution.\(^{161}\) In the same year, Xia \textit{et al.} reported a B-site mixed SrRu\(_{0.5}\)Ir\(_{0.5}\)O\(_3\) double perovskite with a strong electronic synergistic effect between Ir and Ru (Fig. 16d).\(^{162}\) When used as an acidic OER catalyst, it showed a low overpotential of...
185 mV at 10 mA cm$^{-2}$ and stable stability for over 50 h. In addition to B-site substitution, A-site-substituted ruthenium perovskite Sr$_{0.95}$Na$_{0.05}$RuO$_3$ was also found to be an enhanced acidic OER catalyst by Na$^+$ doping in the Sr$^{2+}$ position. Such perovskite catalysts showed an ultralow overpotential of only 120 mV at 0.5 mA cm$^{-2}$ and improved structural stability (Fig. 16e), which was attributed to lower surface energy and higher dissolution potentials induced by Na-doping in the A-site (Fig. 16f). The HRTEM/digital diffraction pattern, STEM-HAADF micrographs with the line scans, and XPS results indicated that Na$^+$ doping suppressed the dissolution of Sr and Ru and increased the structural stability, not generating the different phases, such as RuO$_x$, during the OER. In general, metal substitutions can effectively regulate the electronic properties of perovskite-type ruthenates to greatly improve their catalytic performances. Furthermore, a quadruple perovskite oxide CaCu$_3$Ru$_4$O$_{12}$ (Fig. 16g) was reported to deliver an ultrasmall overpotential of 171 mV at 10 mA cm$^{-2}$ and much better stability compared to RuO$_2$ for acidic OER (Fig. 16h and i), which was due to a lower Ru 4d-band center in CaCu$_3$Ru$_4$O$_{12}$ relative to RuO$_2$. These studies have indeed confirmed the role of electronic property tuning in achieving improved electrocatalytic performances and offered direction to the rational design of advanced Ru-based electrocatalysts.

Apart from the three types of Ru-based catalysts (Ru-based metal, oxides, and oxometallates) mentioned above, there are some other types of Ru-based catalysts, such as Ru chalcogenides (RuTe$_2$) and Ru boride (RuB$_4$), used for acidic OER. Although their stability is far from satisfaction, these advanced works are still great breakthroughs in the expansion of Ru-based acidic OER electrocatalysts.

4. Conclusions and perspectives

All in all, the four-electron transfer OER process on the surface of Ru-related catalysts is along with the redox of Ru or O sites,
in which the Ru element may dissolve under high overpotential and strong acidic conditions due to its severe overoxidation accompanied by the formation of the unstable and soluble RuO$_4$ species. Despite these drawbacks, Ru-based materials are still proven to be promising potential candidates for PEM anodic catalysts if the stability can be greatly enhanced. To date, Ru-based materials have been extensively studied to develop highly active and stable catalysts toward acidic OER. Thereinto, the effective and universal strategy to improve stability without sacrificing activity is to reduce the bulk oxygen diffusion rate and surface exchange kinetics of Ru-based catalysts whether following any reaction mechanisms. This review provides an overview of the recent advanced progress in Ru-related acidic OER catalysts, including metallic Ru, Ru-based oxides, and oxometallate-type ruthenates, and categorically summarizes the optimizing strategy to improve both stability and activity. Of note, most of the summarized strategies are applied to regulate the electronic structure to enhance the catalytic performances of Ru-based catalysts. Despite great progress, there remains a wide gap between experimental research and practical requirements. To further promote the development of Ru-based catalysts, many issues are still needed to be studied in depth.

**Design of Ru-based materials**

For the future development of highly active and stable Ru-related catalysts for acidic OER, heteroatom doping engineering on RuO$_2$ may be one of the promising and effective strategies. Of note, the previous studies involving heteroatom doped RuO$_2$ catalysts generally discuss the effect of doping engineering on electronic properties. However, the impact of structure engineering, such as specific microstructure, specific exposed facet, etc., on Ru-based oxides is rarely considered. Therefore, developing heteroatom doped RuO$_2$ with a designed microstructure might be a resultful strategy. In addition, in view of the low reserves of Ru, atomically dispersed Ru atoms on an acid-stable non-noble metal oxide-based support (SA Ru/MO) is an ideal choice, which can not only reduce the consumption of noble metals but also construct unique geometric structures to enhance the stability of Ru-based catalysts. Nevertheless, mismatch in ionic radius, crystal structures, and electronegativity of different MOs makes the synthesis of SA Ru/MO significantly challenging. Consequently, new and effective synthetic methodologies to design advanced atomically dispersed Ru-based catalysts are needed to be explored. Furthermore, high-throughput theoretical calculations are recommended to screen advanced Ru-based catalysts for acidic OER.

**Evaluation of the reaction process**

Theoretical studies and various descriptors have been demonstrated to be effective tools for designing advanced Ru-based catalysts toward acidic OER. Of note, current theoretical calculations are usually based on simplified models without considering practical factors to simulate the complicated actual catalysts and reaction processes, which can only afford limited information to direct the development of Ru-based catalysts. Therefore, more actual factors should be taken into consideration, such as the actual catalyst model, surface thickness, pH, external electric field, the catalyst-electrolyte interface, etc., thus uncovering a more realistic reaction process. In addition, current descriptors generally describe the bulk properties of Ru-based catalysts, being in inconformity with the viewpoint of actual reactions that occurred on the catalyst surface. Consequently, establishing a more precise descriptor should be based on the elaborate surface properties of Ru-based catalysts, and be further verified by abundant experimental evidence. More importantly, the actual active sites should be accurately identified, owing to the possible structure and/or phase reconstruction during the acidic OER process. To detailively investigate the real active sites, some advanced in situ/operando XRD/XAS/Raman and isotope labeling techniques are needed to investigate the structural and electronic variation of Ru-based catalysts during the acidic OER process.

**Evaluation of PEMWE**

To promote the scalable application of PEMWE, the gap between laboratory studies and the typical industrial requirement (operating over 1 A cm$^{-2}$ current density for over 10 years under 80 °C) should be plugged. Satisfactorily, Wen et al. recently prepared a Ni-stabilized RuO$_2$ (Ni-RuO$_2$) as the anode catalyst of PEMWE, displaying >1000 h stability at 200 mA cm$^{-2}$. Further, Shi et al. constructed a SnRuO$_4$ solid solution oxide as an anode catalyst of PEMWE, showing a remarkable performance of working for 1300 h under 1 A cm$^{-2}$ at 50 °C. Although these designed catalysts do not meet the industrial requirement, they make the Ru-based catalysts a step closer to industrial application. More highly stable Ru-based catalysts with high activity are needed to be produced to satisfy the actual application in PEMWEs. Note that, the OER performance trends of catalysts might be different between the experimental method and industrial PEMWE. Moreover, the complex assembly process of the PEMWE cell may lead to certain deviations, which will result in some misleading information. Therefore, a standard protocol for not only evaluation (activity and stability) of anode catalysts in PEMWE under actual operating conditions but also PEMWE cell assembly should be established.

**Conflicts of interest**

The authors declare no competing interests.

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References

Review


J. Li, Nanomicro Lett., 2022, 14, 112.


| 164 | J. Wang, L. Han, B. Huang, Q. Shao, H. L. Xin and X. Huang, *Nat. Commun.*, 2019, 10, 5692. |