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ZrO_2-induced d–d spatial coordination effects of Ru single-atom catalysts to boost the oxygen evolution reaction

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Proton exchange membrane water electrolysis (PEMWE) is a leading strategy for producing green hydrogen from intermittent renewable energy. However, the high anodic energy barrier of the oxygen evolution reaction (OER), in a strongly acidic and highly oxidative operating environment, poses severe challenges for catalyst design. Herein, based on a unique d–d spatial coordination design, tetragonal zirconia-supported Ru single-atom catalysts (Ru-RSZ) were synthesized, which exhibited an overpotential as low as 208 mV and a mass activity of 1452.61 A g_{Ru}^{-1} @ 1.51 V. Remarkably, these catalysts were stably operated for 500 h. X-ray absorption spectroscopy (XAS) and high-angle annular dark-field (HAADF) imaging demonstrated that Ru is atomically dispersed at Zr lattice sites in ZrO_2, and the point-group symmetry of the Ru atom changes from D_{2h} in RuO_2 to D_{2d}. Density functional theory (DFT) calculations elucidated that the d-band center of Ru atoms was lowered by d–d spatial coordination effects, which weakened the strong adsorption of oxygen at Ru sites, eventually reducing the activation barrier of the OER rate-determining step. This work paves a new avenue to design high-efficiency and stable catalysts for hydrogen production.

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Introduction

Against the backdrop of advancing green, low-carbon development and the global energy transition, hydrogen production from water electrolysis has emerged as a cornerstone technology for building the future energy system.[1–4] Proton exchange membrane water electrolysis (PEMWE) has garnered significant attention due to its higher current density, rapid kinetics and higher stack efficiency (70–77%) in contrast to alkaline water electrolysis.[5,6] However, the oxygen evolution reaction (OER) of PEMWE systems involves complex multi-step proton-coupled electron transfer processes and demonstrates sluggish kinetics, which significantly limit the overall efficiency of water electrolysis.[7,8] Furthermore, protonation and solvation effects in acidic media pose substantial challenges to the stability of anode catalysts.[9] Currently, only iridium-based oxides are widely used as OER catalysts, but the disadvantages of high-cost and scarcity severely limit their large-scale applications.[10,11] To address these challenges, extensive research has focused on finding alternative catalysts, with cost-effective (10 times cheaper than iridium)[12] and Earth-abundant[13] ruthenium (Ru) emerging as a promising iridium substitute owing to its comparable catalytic activity.[14–16] Nevertheless, the durability of ruthenium oxides remains limited and insufficient to meet the long-term operational requirements of commercial-scale PEMWE systems.[17] Moreover, as a noble metal, ruthenium still entails substantial cost.[18] To satisfy the commercial demands of PEMWE for industrial hydrogen production, it is imperative to develop low-cost Ru electrocatalysts with high activity and long-term stability.

Nowadays, the development of Ru-based electrocatalysts primarily encompasses doping and defect engineering, interface engineering, hybridized orbital engineering, *etc.*[16,19,20] Among these, orbital coupling between RuO_2 and heteroatom dopants has demonstrated pronounced enhancement and stabilization of active sites.[21] For example, Pb doping produces Pb–O–Ru 6s–2p–4d orbital hybridization that increases the energy required to remove lattice oxygen, thereby suppressing excessive oxidation of Ru.[22] Similarly, unique lanthanide dopants induce f–p–d gradient orbital coupling that can modify adsorption energies of reaction intermediates and inhibit involvement of lattice oxygen, thus preventing over-oxidation of Ru.[23] However, Ru–M orbital coupling mediated by O bridges is weakened by the presence of O 2p orbitals. Moreover, studies of dopant-induced orbital coupling based on the rutile structure have frequently neglected the strong influence of local atomic coordination, although some studies have compared the OER performance of Ru located at sites of different symmetries in other structures such as pyrochlore[24] and perovskites.[25,26]

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Investigations specifically addressing how crystal-structure-driven differences alter orbital coupling remain scarce. More importantly, substantial amounts of Ru catalysts are still required in doped RuO_2 systems, which does not satisfy the low-cost requirement of industrial hydrogen production.

In this work, an acid-resistant oxide, ZrO_2, was adopted as the support to provide Ru atoms with a distinctive atomic coordination geometry ($P4_2/nmc$).[27] A Ru single-atom catalyst supported on ZrO_2 (Ru-RSZ) was synthesized *via* a hydrothermal method. X-ray diffraction (XRD) and Raman characterization indicate that introduction of Ru stabilizes the tetragonal phase of ZrO_2. Further high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) and X-ray absorption spectroscopy (XAS) analyses reveal that Ru occupies Zr lattice sites, with site symmetry transformed from D_{2h} in RuO_2 to D_{2d} in ZrO_2. Density functional theory (DFT) calculations reveal that the unique d–d interactions in Ru-RSZ furnish direct bonding, substantially lowering the Ru 4d-band center, suppressing strong adsorption of oxygen intermediates on Ru, reducing reaction barriers, and concurrently weakening Ru–O covalency to inhibit participation of lattice oxygen, thereby enhancing structural stability. The synthesized Ru-RSZ catalyst exhibits an overpotential reduced to 208 mV at a Ru loading of only 43.9 μg_{Ru} cm^{-2}, and chronopotentiometry at a current density of 10 mA cm^{-2} shows that the catalyst remains stable for 500 h. Moreover, oxygen vacancies present in Ru-RSZ further reinforce the d–d interactions of Ru–Zr, contributing to the catalyst's activity and stability. This work provides an effective strategy for developing high-efficiency and low-cost electrocatalysts for industrial hydrogen production.

Results and discussion

Material design and theoretical calculation

To validate the feasibility of the design strategy, DFT calculations were conducted to systematically compare the electronic structure and stability of the ZrO_2-supported Ru catalyst (denoted as Ru-RSZ) and commercial RuO_2 (Fig. 1a). Quantitative analysis of the intermetallic interactions provides direct evidence for the support stabilization effect: the integrated crystal orbital Hamilton population (ICOHP) for the Ru–Zr pair in Ru-RSZ is −0.001 eV, indicating a weak net bonding interaction.[15] In contrast, the ICOHP for the Ru–Ru pair in RuO_2 is +0.048 eV revealing a net antibonding interaction. Similarly, when Zr occupies the Ru sites in RuO_2 with D_{2h} symmetry, a net antibonding interaction (ICOHP = +0.021 eV) is also observed (Fig. S1). The direct d–d interaction between Zr and Ru not only reinforces the lattice framework but also markedly alters the 4d orbital distribution at Ru sites (Fig. 1b). Projected density of states (PDOS) and electronic band structure analyses (Fig. 1c and S2) reveal that the d-band center of the Ru 4d orbitals in Ru-RSZ shifts downward and farther from the Fermi level compared to that in com-RuO_2.[22] This modulation in the electronic structure suggests a weakened adsorption strength for oxygen evolution reaction intermediates, which is anticipated to mitigate the catalytic activity limitation inherent to conventional RuO_2 caused by the over-binding of intermediates, thereby enhancing the intrinsic activity.[28] Furthermore, the altered coordination environment induces a further separation between the Ru 4d and O 2p bands, characterized by a downward shift of both band centers, resulting in an enlarged characteristic band gap (ε_{d-p}) of 2.91 eV for Ru-RSZ compared to

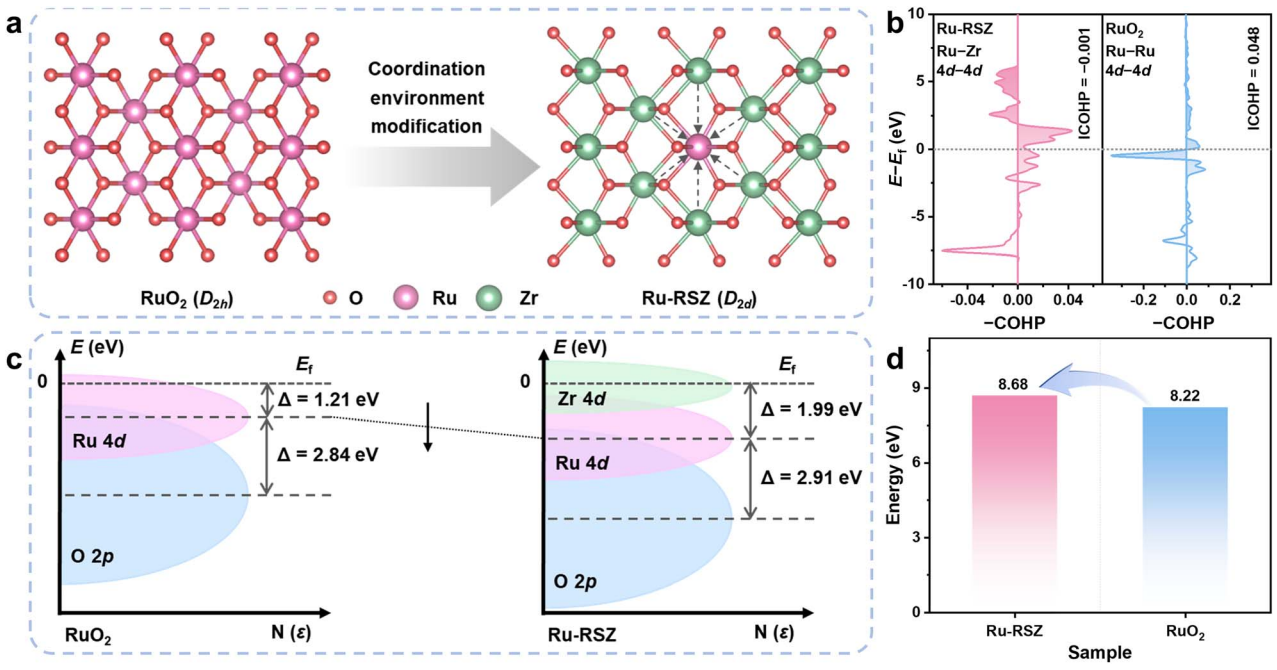

Fig. 1 (a) Schematic diagram of the design strategy for modifying the coordination environment of Ru. (b) Calculated COHP of Ru-RSZ and RuO_2. (c) Schematic diagram of the band structure for Ru-RSZ and ZrO_2. (d) Ru vacancy formation energy of Ru-RSZ and RuO_2.

2.84 eV for RuO_2. This enlarged band gap indicates a reduced degree of covalent hybridization in the Ru–O bonds within Ru-RSZ, an electronic feature that contributes to suppressing the over-oxidation and dissolution of ruthenium under operational conditions, thereby enhancing the electrochemical stability of the catalyst.[29] The obviously increased Ru vacancy formation energy (Fig. 1d) in Ru-RSZ further corroborates, from a thermodynamic perspective, the superior stabilization effect exerted by the ZrO_2 support on the ruthenium active sites.[20,30]

Material characterization and the coordination environment

Ru-RSZ was synthesized *via* the co-precipitation method (Fig. S3). The resulting precipitate was then subjected to hydrothermal treatment at 200 °C for 12 hours, followed by centrifugation and drying to obtain Ru-RSZ powder. The XRD pattern confirms the presence of a tetragonal ZrO_2 phase (JCPDS 01-070-7300) in Ru-RSZ (Fig. 2a). No detectable peaks corresponding to Ru were observed, indicating that the lattice structure of ZrO_2 remains intact after Ru introduction (Fig. S4).[31] Notably, the XRD pattern of Ru-RSZ shifts slightly to higher diffraction angles compared to that of ZrO_2 (Fig. S5), indicating a decrease in the Ru-RSZ lattice constant owing to a smaller Ru atomic radius.[32] After the introduction of Ru, the peaks associated with the monoclinic phase of ZrO_2 were no longer detected, suggesting that Ru promotes the stabilization of the tetragonal phase. Raman spectroscopy (Fig. S6) confirmed the presence of the tetragonal ZrO_2 phase (t-ZrO_2) in the Ru-RSZ sample, with characteristic peaks at 284, 457 and 645 cm^{-1}.[33,34] No peaks from the monoclinic phase were observed. This result was in accordance with the above XRD

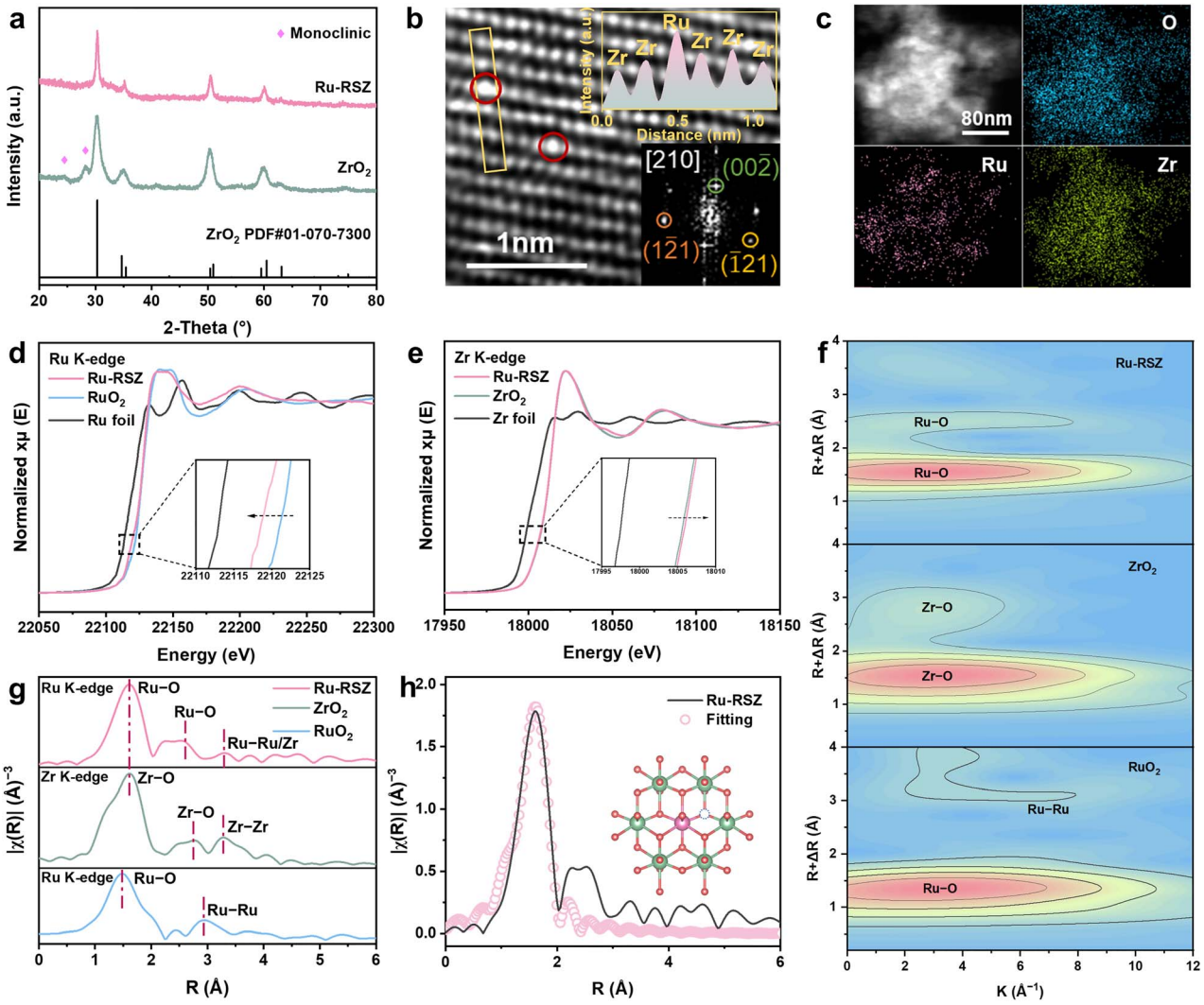

Fig. 2 (a) XRD patterns of Ru-RSZ and ZrO_2. (b) HAADF-STEM and corresponding FFT image (inset) of Ru-RSZ along the [210] orientation with the *Z*-contrast intensity line profile extracted from the marked area. The bright spots highlighted by red circles correspond to isolated Ru atoms occupying Zr lattice sites. (c) HAADF-STEM image and corresponding EDS mapping of Ru-RSZ. (d) Normalized Ru K-edge XANES spectra of Ru-RSZ, RuO_2, and Ru foil. (e) Normalized Zr K-edge XANES spectra of Ru-RSZ, ZrO_2 and Zr foil. (f) Wavelet-transformed k^3-weighted EXAFS signals of RSZ, ZrO_2 and RuO_2. (g) Fourier transform *R*-space of the experimental EXAFS signal collected at the Ru K-edge for Ru-RSZ and RuO_2, and the Zr K-edge for ZrO_2. (h) *R*-Space fitting results of Ru K-edge XAFS spectra of Ru-RSZ.

results. Furthermore, two Raman bands corresponding to the tetragonal phase over the Ru-RSZ sample were blue-shifted, suggesting a strong metal–support interaction between Ru and ZrO_2.[35,36]

To investigate the morphology and distribution of Ru atoms in Ru-RSZ, scanning electron microscopy (SEM) and spherical aberration-corrected HAADF-STEM imaging (Fig. 2b) were performed.[37] SEM and STEM images of Ru-RSZ reveal a morphology similar to that of ZrO_2, with both materials consisting of nanoparticles approximately 8 nm in diameter (Fig. S7). The *Z*-contrast image acquired by HAADF-STEM (Fig. 2b), its Fast Fourier Transform (FFT) (inset) and the corresponding *Z*-contrast intensity profile show Ru (highlighted) randomly dispersed on Zr lattice sites in ZrO_2 projected along the [210] crystallographic direction. STEM-energy-dispersive spectroscopy (STEM-EDS) mapping (Fig. 2c, S8 and Table S1) indicates uniform distribution of Ru, Zr, and O in Ru-RSZ with no obvious segregation (Ru atom percentage of metallic elements in Ru-RSZ is $\approx$10.8 at%).

The electronic structure of Ru-RSZ was further characterized by using X-ray photoelectron spectroscopy (XPS) and XAS. The full XPS spectra of Ru-RSZ, RuO_2 and ZrO_2 are presented in Fig. S9. X-ray absorption near-edge spectroscopy (XANES) of the Ru K-edge reveals a shift of the absorption edge to lower energy in Ru-RSZ compared to RuO_2, suggesting a decrease in the Ru valence state (Fig. 2d). The Zr K-edge XANES spectra indicate a near-edge absorption energy slightly higher than that of ZrO_2 (Fig. 2e). The Zr 3d XPS spectrum (Fig. S10) of Ru-RSZ exhibits a discernible binding energy upshift of approximately 0.14 eV and 0.2 eV for the Zr $3d_{5/2}$ and Zr $3d_{3/2}$ peaks, respectively, compared to ZrO_2, suggesting a relatively higher oxidation state of Zr in Ru-RSZ, which agrees well with the XANES analysis results.[38,39] Meanwhile, the deconvolution of the Ru 3p XPS spectrum (Fig. S11 and Table S2) indicates that the proportion of Ru^{III} in Ru-RSZ is 74%, significantly higher than that in RuO_2 (26%).[40] This higher ratio suggests electron transfer from the ZrO_2 support to Ru, leading to a reorganization of its local electronic structure, a conclusion further supported by the distinct negative shift in the Ru 3p binding energy peaks. The pre-reduction effect of Zr on Ru can effectively prevent the excessive oxidative dissolution of Ru during the OER process, thereby enhancing its stability.[41]

Wavelet Transform Extended X-ray Absorption Fine Structure (WT-EXAFS) indicates that the coordination environment of Ru in Ru-RSZ is the same as that of the Zr sites in ZrO_2 (featuring two Ru/Zr–O coordination bonds),[20] distinct from that in RuO_2 (which exhibits Ru–O and Ru–Ru coordination bonds) (Fig. 2f). Concurrently, Ru K-edge EXAFS reveals Ru–O and Ru–Ru/Zr scattering peaks in Ru-RSZ at approximately 1.6 Å, 2.8 Å, and 3.2 Å. Zr K-edge EXAFS likewise shows Zr–O and Zr–Zr scattering peaks in Ru-RSZ at 1.6 Å, 2.7 Å, and 3.2 Å, demonstrating that Ru and Zr occupy the same metal sites in the Ru/Zr oxide phase, with a symmetry change from D_{2h} to D_{2d} (Fig. 2g, S12 and S13). In addition, EXAFS fitting results (Fig. 2h and Table S3) indicate a Ru–O coordination number of 7.4 in Ru-RSZ, evidencing a significant presence of oxygen vacancies.[16] Furthermore, the O 1s peak (Fig. S14) of Ru-RSZ is deconvoluted into three peaks at 529.6, 530.7, and 532.7 eV, corresponding to the lattice oxygen (O_L), surface oxygen vacancies (O_V) and surface oxygen adsorbates (O_{ads}), respectively.[42,43] The peak fitting results of the O 1s XPS spectra (Table S4) indicate that the proportion of oxygen vacancies in Ru-RSZ is 43%, significantly higher than the 29% observed in ZrO_2, suggesting a significant increase after Ru introduction. This finding is further corroborated by electron paramagnetic resonance (EPR) measurements (Fig. S15), which reveal a characteristic signal at $g = 2.005$ for Ru-RSZ (Fig. S15), corresponding to unpaired electrons trapped at oxygen vacancies, in good agreement with the XPS O 1s analysis.[29]

Electrochemical performance in acidic electrolytes

The OER performance of Ru-RSZ, ZrO_2 and RuO_2 catalysts was evaluated in a three-electrode system using 0.5 M H_2SO_4 as the electrolyte. Linear sweep voltammetry (LSV) and corresponding Tafel analysis (Fig. 3a and b) demonstrated that the Ru-RSZ catalyst exhibits outstanding electrocatalytic activity, requiring an overpotential (η) of only 208 mV to achieve a current density of 10 mA cm^{-2} along with a Tafel slope of 62.15 mV dec^{-1}. These values are substantially lower than those of RuO_2 (265 mV and 71.97 mV dec^{-1}, respectively), while the ZrO_2 support showed negligible OER activity. Notably, the Ru specific mass activity (Fig. 3cand S16) of the Ru-RSZ catalyst was calculated to be as high as 1452.61 A $g_{Ru}{}^{-1}$ at $\eta = 1.51$ V, which is more than 40.1 times higher than that of RuO_2 (36.21 A $g_{Ru}{}^{-1}$ at 1.51 V). To further evaluate the intrinsic activity of the Ru species, the turnover frequency (TOF) was calculated and plotted against the overpotential (Fig. S17). The calculated TOF value for Ru-RSZ reached 0.38 s^{-1} at an overpotential of 1.51 V, representing a 38-fold enhancement over that of RuO_2 (0.01 s^{-1}). Double-layer capacitance (C_{dl}) was measured to determine the electrochemical active surface area (ECSA) for evaluating the OER performance (Fig. 3d, S18 and Table S5). Ru-RSZ demonstrates the highest C_{dl} of 13.67 mF cm^{-2} and ECSA (390.57 cm^2), values approximately 1.43 times greater than those of RuO_2 (9.56 mF cm^{-2} and 273.14 cm^2, respectively). This indicates a significantly increased number of available active sites in Ru-RSZ, which effectively enhances its OER performance. Additionally, the OER activity normalized to the electrochemical surface area of Ru-RSZ and RuO_2 was also calculated (Fig. S19). The ECSA-normalized mass activity of Ru-RSZ reached 0.16 mA cm^{-2} at 1.51 V (*vs.* RHE), which is 3.2 times higher than that of RuO_2 (0.05 mA cm^{-2}), further demonstrating its superior intrinsic OER catalytic activity.

Electrochemical impedance spectroscopy (EIS) is a powerful technique to examine the electrical charge transfer behavior across interfaces and phases in electrochemical systems.[44] The EIS measurements (Fig. 3e) revealed well-defined semicircular Nyquist plots for Ru-RSZ, RuO_2, and ZrO_2.[45] Among these, Ru-RSZ exhibited a semicircle with a notably smaller radius compared to RuO_2 and ZrO_2. The fitting results (Table S6) indicated a significantly lower charge-transfer resistance (R_{ct}) and more efficient electron transfer across the electrode/electrolyte interface. The stability of Ru-RSZ was evaluated by

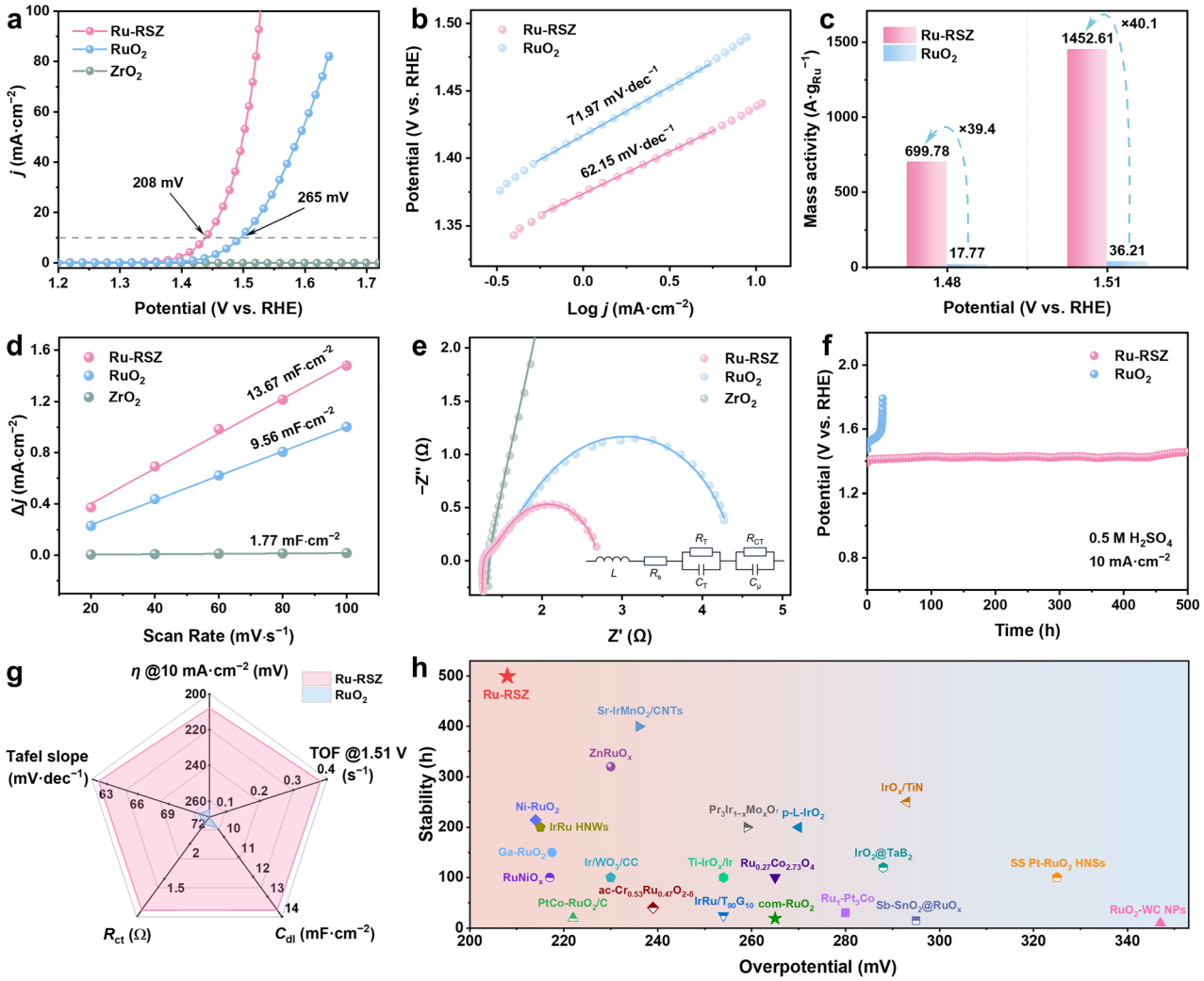

Fig. 3 Electrocatalytic OER performance evaluation in 0.5 M H_2SO_4 electrolyte. (a) LSV polarization curves and (b) Tafel plots of Ru-RSZ and RuO_2. (c) Ru mass activities of Ru-RSZ and RuO_2 at 1.48 and 1.51 V *vs.* RHE. (d) C_{dl} plots and (e) Nyquist plots of Ru-RSZ, ZrO_2 and RuO_2 derived from CV curves. (f) Chronopotentiometry test at 10 mA cm^{-2} of electrocatalysts. (g) Summary of some major OER performance metrics of Ru-RSZ and RuO_2. (h) Comparison of the overpotential and stability of Ru-RSZ with previously reported OER electrocatalysts in acidic electrolyte.

chronopotentiometry (CP) at a constant current density of 10 mA cm^{-2} (Fig. 3f). Compared to the commercial RuO_2 catalyst, Ru-RSZ exhibited excellent stability, retaining most of its potential over a 500-hour period, with some cases even showing a slight performance enhancement as indicated by a decrease in the overpotential. Post-reaction characterization (Fig. S20) confirmed that the crystal structure and atomic dispersion of Ru remained intact, further supporting the structural robustness of the catalyst. With regard to the OER, Ru-RSZ outperformed RuO_2 across all five considered dimensions (Fig. 3g and Table S7). The outstanding activity and stability of Ru-RSZ significantly exceed those of previously reported noble metal electrocatalysts in acidic electrolytes (Fig. 3h and Table S8).

Insights into the OER catalytic mechanism

To elucidate the regulatory mechanism of oxygen vacancies on the electronic structure of catalytic sites, systematic DFT calculations were conducted on Ru-RSZ-O_V, Ru-RSZ, and RuO_2. Structural optimization (Fig. 4a) reveals that the formation of an oxygen vacancy induces notable local structural relaxation, reducing the distance between Ru and the adjacent Zr atom from 3.98 Å (Ru-RSZ) to 2.87 Å (Ru-RSZ-O_V), thereby creating favorable geometric conditions for interatomic orbital interactions.[22] Charge density difference and Bader charge analyses (Fig. 4b and Table S9) collectively unveil the charge redistribution triggered by the oxygen vacancies, with pronounced electron accumulation observed in the Ru–Zr bridging region, preliminarily indicating enhanced d–d orbital interaction.[46] The Bader charge on the Ru atom in Ru-RSZ-O_V decreases to +0.3099|*e*|, lower than its value of +0.8249|*e*| in Ru-RSZ, while the charge on the adjacent Zr atom also decreases from +1.6345|*e*| to +1.5131|*e*|, suggesting weakened electron localization and enhanced covalency.[47] Notably, the Bader charge of Ru in Ru-RSZ-O_V is lower than that of Ru in RuO_2 (+1.4893|*e*|), while the charge of its Zr is higher than that of Zr in ZrO_2

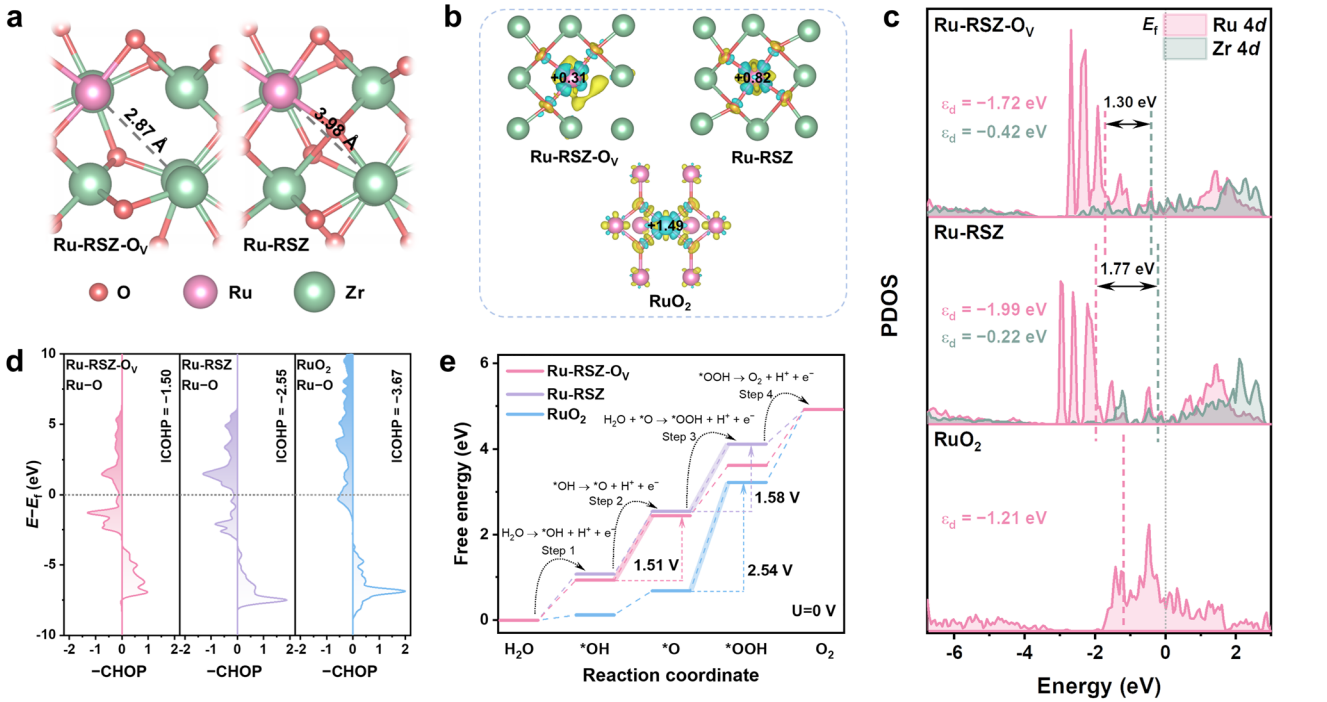

Fig. 4 Theoretical simulation and analysis. (a) Comparison of Ru–Zr atomic distances in Ru-RSZ-O_V (left) and Ru-RSZ (right). (b) Differential charge density and Bader charge calculation of Ru-RSZ-O_V, Ru-RSZ and RuO_2 (yellow indicates charge accumulation, while blue indicates charge depletion). (c) The PDOS of Ru 4d and Zr 4d for Ru-RSZ-O_V, Ru-RSZ and RuO_2. (d) Calculated COHP of Ru-RSZ-O_V, Ru-RSZ and RuO_2. (e) Gibbs free energy diagrams *via* the AEM pathway on the Ru site at $U = 0$ V for Ru-RSZ-O_V, Ru-RSZ and RuO_2.

(+1.2822|e|), providing clear evidence for electron transfer from Zr to Ru, aligning with the valence state trend measured by XAS, jointly confirming the metal–support electronic synergy.

In-depth analysis of the electronic structure shows that the PDOS (Fig. 4c) of the Ru-4d and Zr-4d orbitals in Ru-RSZ-O_V exhibits significantly enhanced peak overlap and hybridization near the Fermi level, confirming the effective promotion of d–d orbital coupling between Ru and Zr by the oxygen vacancies.[48] Furthermore, the separation between their d-band centers contracts from 1.77 eV in Ru-RSZ to 1.30 eV in Ru-RSZ-Ov, implying a reduced average energy difference and closer spatial distribution between the Ru-4d and Zr-4d orbitals, which further supports the conclusion of enhanced d–d orbital coupling. This coupling drives electron transfer from Zr to Ru, resulting in a moderate upshift of the Ru d-band center (from −1.99 eV to −1.72 eV) and a concomitant downshift of the Zr d-band center (from −0.42 eV to −0.22 eV) in Ru-RSZ-O_V, a theoretically calculated charge redistribution that is consistent with the XAS analysis. The moderate upshift of the Ru d-band center facilitates the optimization of its adsorption free energy for OER intermediates, thereby enhancing the intrinsic activity.[49] Concurrently, its energy level remains substantially lower than that of RuO_2 (−1.21 eV), which is beneficial for suppressing the over-oxidation of Ru and consequently improving the electrochemical stability.

Direct evidence for chemical bond strengthening is provided by ICOHP analysis. The ICOHP value for the Ru–Zr atomic pair (Fig. S21) decreases significantly from −0.001 eV in Ru-RSZ to −0.089 eV in Ru-RSZ-O_V, demonstrating a significant enhancement of the Ru–Zr bond induced by the oxygen vacancies. Simultaneously, analysis of the Ru site reveals that the ICOHP value (Fig. 5d) for the Ru–O bond in Ru-RSZ-Ov exhibits a less negative value (−1.50 eV) compared to those in Ru-RSZ (−2.55 eV) and RuO_2 (−3.067 eV), indicating a weakened covalent character. This attenuation is attributed to the Ru–Zr d–d orbital coupling, which effectively modulates the adsorption strength of oxygenated intermediates on the Ru active sites, thereby optimizing the reaction kinetics of the OER. Furthermore, pH-dependent and tetramethylammonium cation (TMA^+) probing measurements were further used to demonstrate the restricted lattice oxygen activity in Ru-RSZ (Fig. S22–24). According to the calculated proton reaction orders ($\rho = \partial\log(j)/\partial$pH), RuO_2 shows significant pH-dependent ($\rho = -0.165$) OER activity, whereas Ru-RSZ reflects a pH-independent ($\rho = -0.076$) characteristic in which the current density nearly remains constant as the pH value changes. This result indicates that the degree of non-equilibrium proton–electron coupling transfer of Ru-RSZ has decreased.[23] Moreover, the addition of TMA^+ in 0.5 M H_2SO_4 does not affect the OER activity of Ru-RSZ, whereas a clear inhibition is observed for RuO_2, indicating that the amount of *OO intermediates produced by Ru-RSZ is lower, demonstrating that the extent of lattice oxygen involvement in the OER process is reduced and the stability of the lattice structure has been optimized.[50] Gibbs free energy calculations (Fig. 5e, S25 and S26) demonstrate that the adsorption energies of Ru-RSZ-O_V for all OER intermediates lie between those of Ru-

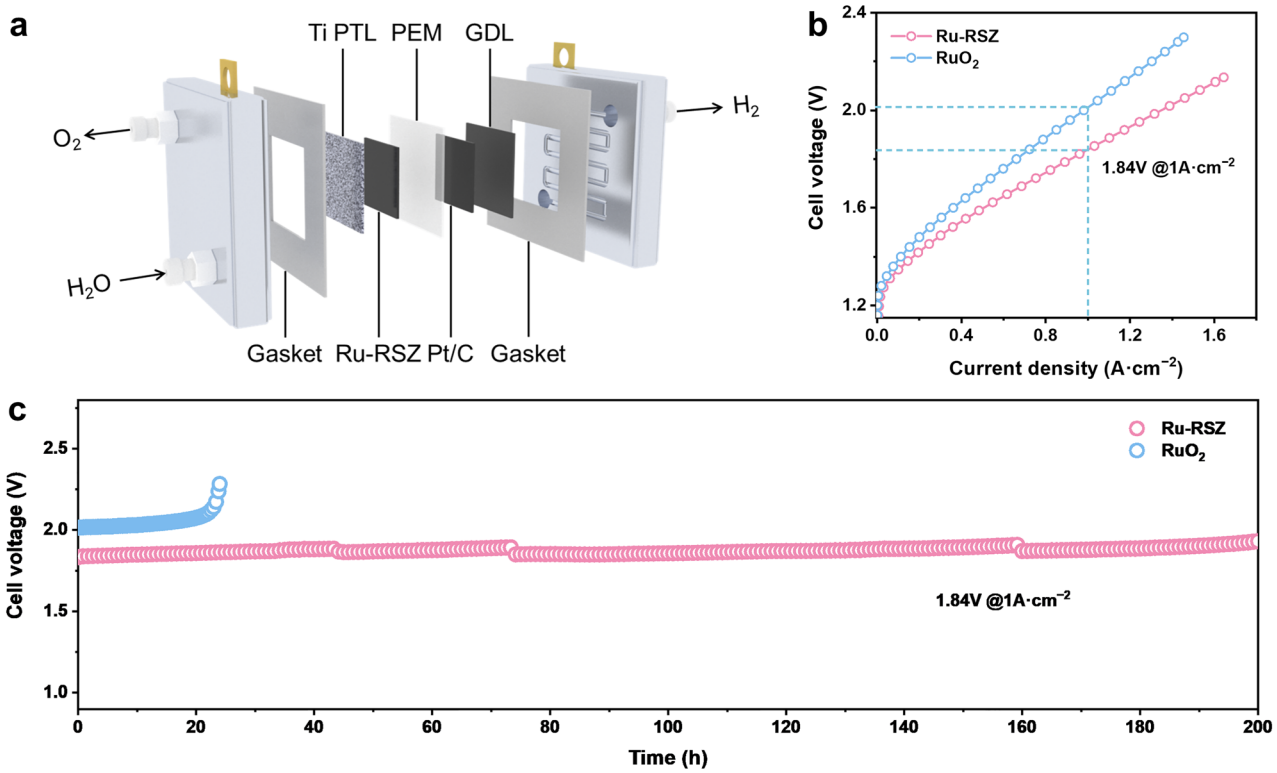

Fig. 5 (a) Schematic diagram of the PEM electrolyzer using Ru-RSZ as the anode electrocatalyst. (b) Polarization curves of PEMWE employing Ru-RSZ and RuO_2 as the anodic electrocatalyst. (c) Chronopotentiometry curve of Ru-RSZ and RuO_2 in a PEMWE electrolyzer at 1 A cm^{-2}.

RSZ and RuO_2, achieving a more balanced adsorption strength.[51] Concurrently, the rate-determining step (RDS) energy barrier for Ru-RSZ-O_V is the lowest (1.51 eV, *OH → *O + $H^+ + e^-$) among the studied catalysts, being lower than those for Ru-RSZ (1.58 eV, H_2O + *O → *OOH + $H^+ + e^-$) and RuO_2 (2.41 eV). The change in the RDS coupled with the significant reduction in the energy barrier collectively contributes to the enhanced OER activity.[30] The vacancy formation energy calculations (Fig. S27) indicate that the Ru vacancy formation energy in Ru-RSZ-O_V (8.94 eV) is higher than those in RuO_2 (8.22 eV) and Ru-RSZ (8.68 eV), suggesting greater resistance of the Ru species to dissolution, which further corroborates, from a thermodynamic perspective, the crucial role of d–d orbital coupling in enhancing OER stability.

PEMWE performance evaluation

To further verify the performance of Ru-RSZ for practical applications in water electrolysis, a membrane electrode assembly was constructed utilizing a Nafion 211 membrane with Ru-RSZ as the anode catalyst and commercial Pt/C as the cathode catalyst, respectively (Fig. 5a). The mass loading of Ru in the anode of the PEMWE tests is 175.7 μg_{Ru} cm^{-2}. The polarization curve (without *iR* compensation) confirms the superior catalytic activity of Ru-RSZ compared to commercial RuO_2. Specifically, the Ru-RSZ-based PEMWE electrolyzer delivers a current density of 1 A cm^{-2} at a cell voltage of 1.84 V, which is 180 mV lower than the voltage required by commercial RuO_2 (Fig. 5b).[11,52] Furthermore, the long-term stability of the PEMWE with the Ru-RSZ anode was evaluated by the CP test at a constant current density of 1 A cm^{-2} (Fig. 5c). The result indicates that the cell voltage remained stable throughout the 200-hour test period, with no significant increase observed. These results strongly confirm that the electronic regulation of Ru by the ZrO_2 support could enhance both the catalytic activity and stability of Ru-RSZ, demonstrating significant potential for practical application in PEMWE.

Conclusions

In summary, this work reports the synthesis of a Ru electrocatalyst anchored on a zirconia support (Ru-RSZ), wherein the electronic structure of the Ru active sites is precisely modulated through the establishment of Ru–Zr 4d–4d coupling *via* oxygen vacancy generation, leading to substantially improved activity and stability for acidic OER. The successful stabilization of the tetragonal ZrO_2 phase upon Ru incorporation was confirmed by XRD and Raman spectroscopy, while the formation of oxygen vacancies induced by Ru doping was evidenced by XAS and XPS analyses. DFT calculations provide a mechanistic foundation, showing that the coupling redistributes electron density and weakens the binding strength of oxygen intermediates, thereby optimizing the reaction kinetics. The optimized Ru-RSZ electrode delivers a low overpotential of 208 mV at 10 mA cm^{-2} and a mass activity (1452.61 A g_{Ru}^{-1} @ 1.51 V) 40.1 times greater than that of commercial RuO_2. Its practical viability is further

demonstrated in a PEMWE cell, achieving 1.84 V at 1 A cm^{-2} with stable operation for >200 h. Consequently, this work presents a rational and effective strategy for the development of efficient and durable Ru-based electrocatalysts for practical renewable energy conversion technologies.

Author contributions

D. Yu conceived the project, performed all the electrochemical measurements, and wrote the initial draft of the manuscript. H. Zhao and Y. Zhang reviewed and edited the manuscript. B. Liu, D. Li, and J. Yu provided useful discussions and insights. X. Li and S. Liu contributed to the interpretation of the experimental results. Z. Li and P. Gao supervised the research. All authors contributed to the manuscript.

Conflicts of interest

The authors declare no competing financial interest.

Data availability

The data supporting the findings of this article are available within the paper and the supplementary information (SI). Supplementary information is available. See DOI: https://doi.org/10.1039/d6sc01575a.

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