

## EDGE ARTICLE

Cite this: *Chem. Sci.*, 2025, 16, 1837

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## Asymmetric Rh–O–Co bridge sites enable superior bifunctional catalysis for hydrazine-assisted hydrogen production†

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Hydrazine-assisted water splitting is a promising strategy for energy-efficient hydrogen production, yet challenges remain in developing effective catalysts that can concurrently catalyze both the hydrogen evolution reaction (HER) and hydrazine oxidation reaction (HzOR) in acidic media. Herein, we report an effective bifunctional catalyst consisting of Rh clusters anchored on Co<sub>3</sub>O<sub>4</sub> branched nanosheets (Rh-Co<sub>3</sub>O<sub>4</sub> BNSs) synthesized via an innovative arginine-induced strategy. The Rh-Co<sub>3</sub>O<sub>4</sub> BNSs exhibit unique Rh–O–Co interfacial sites that facilitate charge redistribution between Rh clusters and the Co<sub>3</sub>O<sub>4</sub> substrate, thereby optimizing their valence electronic structures. When the current density reaches 10 mA cm<sup>−2</sup>, the Rh-Co<sub>3</sub>O<sub>4</sub> BNSs require working potentials of only 32 mV for the HER and 0.26 V for the HzOR, far surpassing commercial Pt/C. Furthermore, the Rh-Co<sub>3</sub>O<sub>4</sub> BNSs can work efficiently for hydrazine-assisted water electrolysis with a low voltage of 0.34 V at 10 mA cm<sup>−2</sup> and excellent stability. Theoretical calculations reveal that the optimized valence electronic structure within interfacial Rh–O–Co sites not only reduces the adsorption energy barrier of Co<sub>3</sub>O<sub>4</sub> for H\* in the HER; but also optimizes the hydrazine adsorption in the HzOR and lowers the free energy change in the potential-determining step, where the facilitated dehydrogenation is observed in *in situ* Raman spectra. This work provides a viable approach for designing efficient bifunctional catalysts for future hydrazine-assisted hydrogen production.

Received 4th November 2024  
Accepted 16th December 2024

DOI: 10.1039/d4sc07442d

rsc.li/chemical-science

## Introduction

Hydrogen (H<sub>2</sub>) is regarded as a promising clean energy carrier to replace conventional fossil fuels due to its high energy density and sustainability.<sup>1–4</sup> Consequently, substantial research efforts have been focused on the production of high-purity hydrogen through electrochemical overall water splitting (OWS), owing to its environmental friendliness and zero carbon emission in the cathodic hydrogen evolution reaction (HER).<sup>5–7</sup> However, the sluggish kinetics and high theoretical potential of the anodic oxygen evolution reaction (OER, 1.23 V vs. RHE) require a cell voltage exceeding 1.5 V to drive the OWS process, which hinders the large-scale application.<sup>8,9</sup> To address this obstacle, several more favorable small-molecule oxidation reactions (*e.g.*, tetrahydroisoquinoline oxidation,<sup>10,11</sup> urea oxidation,<sup>12,13</sup> and

hydrazine oxidation<sup>14,15</sup>) have been proposed as alternatives to the OER. Among these, an overall hydrazine splitting (OHZS) system, which integrates the hydrazine oxidation reaction (HzOR) with a low thermodynamic voltage (−0.23 V vs. RHE, pH = 0) and HER, offers an advantageous strategy for green hydrogen production.<sup>16,17</sup> Within such a system, the generation of N<sub>2</sub> as the sole byproduct from the HzOR mitigates the risk associated with explosive H<sub>2</sub>/O<sub>2</sub> mixtures produced by conventional OWS.<sup>18</sup>

In terms of the HzOR, the multi-step reaction pathway in acidic media includes the adsorption of N<sub>2</sub>H<sub>x</sub> intermediates, successive intermediate dehydrogenation, and final nitrogen desorption (N<sub>2</sub>H<sub>5</sub><sup>+</sup> ⇌ N<sub>2</sub> + 5H<sup>+</sup> + 4e<sup>−</sup>). However, since the catalytic process of the HzOR involves the coupling of 2p orbitals of N-containing intermediates and d orbitals of metal sites, the interaction strength of p–d coupling largely inhibits reactant transformation, which may result in a high activation energy barrier.<sup>19</sup> Moreover, the challenge of activating the N–H bond also limits the kinetics of the dehydrogenation process. At present, pioneering studies in the HzOR converge on the use of 3d transition metals, particularly the modulation for Co-based materials.<sup>20,21</sup> For example, Xia *et al.* demonstrated that tuning the electronic structure of ordered Co<sub>3</sub>Ta leads to exceptional electrocatalytic activity for the HzOR, where the Co–Ta bridge

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† Electronic supplementary information (ESI) available. See DOI: <https://doi.org/10.1039/d4sc07442d>

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acts as the most active site.<sup>22</sup> Wang *et al.* revealed that the Ni(Co)-Ru-P interfacial sites on Ru<sub>1</sub>-NiCoP could effectively lower the vacant d-band center of NiCoP, which strengthens \*N<sub>2</sub>H<sub>2</sub> adsorption and decreases the reaction energy barrier, thereby significantly improving HzOR activity.<sup>23</sup> These findings indicate that the formation of distinctive bridges between Co-based materials and other transition metals has the potential to optimize the d-band center of the Co site, thus enhancing its adsorption capacity for nitrogen-containing intermediates.<sup>24,25</sup> Furthermore, the selection of suitable coupling species to accelerate the dehydrogenation of continuous intermediates in the HzOR while reducing the free energy of hydrogen adsorption ( $\Delta G_{H^*}$ ) in the HER is of paramount importance for the development of efficient HzOR/HER bifunctional catalysts. According to Trassati's volcano diagram, the Rh is located near the apex, suggesting that Rh has a desirable  $\Delta G_{H^*}$ , and is promising to serve as the active site for the HER on coupling with Co-based materials.<sup>26,27</sup> As a result, the introduction of Rh can not only modulate the d-band center of Co-based materials, but is also promising to accelerate the dehydrogenation reaction kinetics by serving as an active site for N-H bond activation, thereby enhancing intermediate adsorption during the HzOR and lowering the reaction energy barriers. Nevertheless, further investigation is needed to elucidate the mode of interaction between Co-based hosts and Rh species, and to determine whether this interaction can achieve the predicted bifunctional activity and stability under acidic conditions.

Herein, we present a novel arginine-induced synthesis approach for the fabrication of Co<sub>3</sub>O<sub>4</sub> branched nanosheets uniformly anchored with Rh clusters (Rh-Co<sub>3</sub>O<sub>4</sub> BNSSs). Using this catalyst as a model, we systematically investigated the role of the interaction mode between Co<sub>3</sub>O<sub>4</sub> and Rh in modulating the catalytic activities of both the HzOR and HER under acidic conditions. X-ray absorption spectroscopy (XAS) and X-ray photoelectron spectroscopy (XPS) analyses demonstrated that the Rh-O-Co asymmetric unit induces charge redistribution, effectively modulating the electronic states of both Rh and Co. Electrochemical tests demonstrate that Rh-Co<sub>3</sub>O<sub>4</sub> BNSSs exhibit exceptional bifunctional activity and stability for the HER and HzOR under highly acidic conditions. Specifically, the Rh-Co<sub>3</sub>O<sub>4</sub> BNSSs require working potentials of only 32 mV for the HER and 0.26 V for the HzOR to achieve 10 mA cm<sup>-2</sup>, far surpassing the performance of commercial Pt/C. When applied in a hydrazine-assisted water electrolysis system, the Rh-Co<sub>3</sub>O<sub>4</sub> BNSSs achieve a cell voltage of 0.34 V at 10 mA cm<sup>-2</sup> and maintain excellent stability over 20 h. Density functional theory (DFT) calculations elucidate that the coupling between Rh and Co<sub>3</sub>O<sub>4</sub> leads to electronic redistribution through the asymmetric Rh-O-Co bridge, which not only reduces the adsorption energy barrier of Co<sub>3</sub>O<sub>4</sub> for H\* in the HER, but also optimizes the hydrazine adsorption of N-containing intermediates in the HzOR. With the construction of a Rh-O-Co bridge, the potential-determining step of N<sub>2</sub>H<sub>4</sub>\* → N<sub>2</sub>H<sub>3</sub>\* is shifted to N<sub>2</sub>H<sub>2</sub>\* → N<sub>2</sub>H<sub>1</sub>\*, which facilitated dehydrogenation with a lower free energy change. *In situ* Raman spectroscopy during the HzOR process confirms that the introduction of Rh into Co<sub>3</sub>O<sub>4</sub> BNSSs enhances the adsorption of \*N<sub>2</sub>H<sub>4</sub> and promotes the low-potential driving of

the rapid dehydrogenation process. This work presents a promising strategy for the development of highly efficient bifunctional catalysts aimed at advancing hydrazine-assisted hydrogen production under acidic conditions.

## Results and discussion

### Synthesis and characterization

The synthesis of Rh clusters anchored on Co<sub>3</sub>O<sub>4</sub> branched nanosheets (Rh-Co<sub>3</sub>O<sub>4</sub> BNSSs) is schematically illustrated in Fig. 1a. First, the Co<sub>3</sub>O<sub>4</sub> BNSSs were obtained by a facile hydrothermal treatment of arginine and Co<sup>2+</sup> salt in a mixed ethanol and water solution. Then, the as-prepared Co<sub>3</sub>O<sub>4</sub> BNSSs were transferred to ethylene glycol containing RhCl<sub>3</sub> aqueous solution for the reflux treatment to obtain the Rh-Co<sub>3</sub>O<sub>4</sub> BNSSs. Arginine has both unique groups of guanidino and carboxyl, which makes it easy to bind with Co<sup>2+</sup> cations through the coordination interaction, thereby allowing the synthesis of Co<sub>3</sub>O<sub>4</sub> BNSSs to be kinetically controlled.<sup>28</sup> The coordination between arginine and Co<sup>2+</sup> cations is confirmed by using the ultraviolet and visible spectroscopy (UV-vis) spectra (Fig. 1b), where the absorption peak of Co<sup>2+</sup> aqueous solution shows a significant blue shift after the introduction of arginine. The Fourier transform infrared (FTIR) spectrum of arginine-Co(NO<sub>3</sub>)<sub>2</sub> shows a distinct multi-peak overlapping phenomenon between -OH and -NH<sub>2</sub> vibrational peaks compared with that of arginine, indicating the coordination between Co<sup>2+</sup> and arginine. The crystal structures of Co<sub>3</sub>O<sub>4</sub> BNSSs and Rh-Co<sub>3</sub>O<sub>4</sub> BNSSs were characterized by X-ray diffraction (XRD) analysis. All the diffraction peaks of both samples are in good agreement with the standard pattern of the spinal Co<sub>3</sub>O<sub>4</sub> phase (JCPDS no. 42-1467), and no Rh-related peaks were detected in Rh-Co<sub>3</sub>O<sub>4</sub> BNSSs (Fig. 1c), indicating a high Rh dispersion with small particle sizes.<sup>24,29</sup> The electron paramagnetic resonance (EPR) spectra show that both samples possess strong EPR signals at *g* = 2.003 (Fig. 1d), which are assigned to oxygen vacancies.<sup>30,31</sup> Note that the density of oxygen vacancies of Rh-Co<sub>3</sub>O<sub>4</sub> BNSSs increase significantly compared with that of Co<sub>3</sub>O<sub>4</sub> BNSSs, which indicates a strong interaction between Rh sites and the Co<sub>3</sub>O<sub>4</sub> support.<sup>32</sup> The vacancies increase the disorder of the crystal, as verified by Raman spectra, where the peaks of Rh-Co<sub>3</sub>O<sub>4</sub> BNSSs show a significant redshift compared to those of Co<sub>3</sub>O<sub>4</sub> BNSSs (Fig. S2†), especially the A<sub>1g</sub> peak located at 678 cm<sup>-1</sup>.

Transmission electron microscopy (TEM) characterization shows that the Co<sub>3</sub>O<sub>4</sub> BNSSs present a branched nanosheet structure with a lateral width of about 150 nm (Fig. 2a and S3†), which is further verified by scanning electron microscopy (SEM) images (Fig. S4†). The atomic force microscopy (AFM) image reveals a uniform height distribution of Co<sub>3</sub>O<sub>4</sub> BNSSs with an average thickness of about 2.40 nm (Fig. S5†). The formation of the branched nanosheet structure is strongly dependent on the appropriate concentration of arginine. Without arginine or with an excess amount, the Co<sub>3</sub>O<sub>4</sub> substrate exhibits a non-uniform nanosheet morphology lacking any branches (Fig. S6†). Furthermore, the substrate prepared in water exhibits a nano-needle structure (Fig. S7†), indicating that ethanol is also conducive to the formation of nanosheets. After the deposition

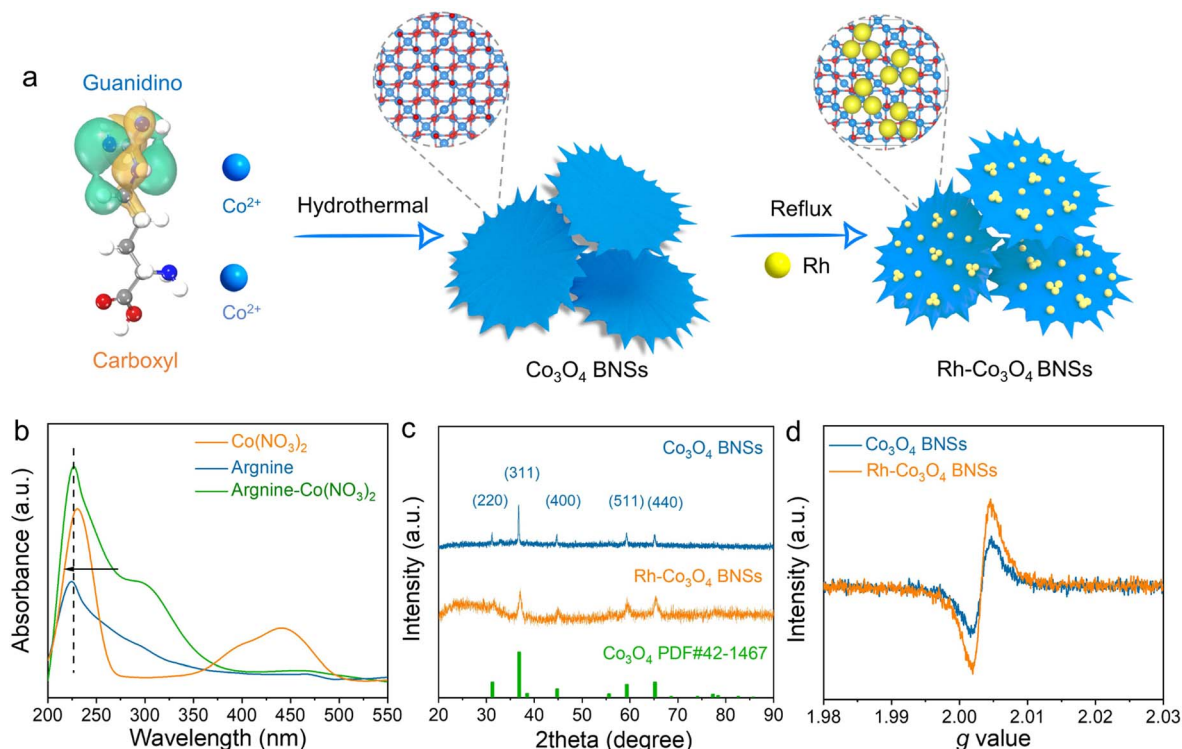


Fig. 1 (a) Schematic illustration of the preparation of Rh- $\text{Co}_3\text{O}_4$  BNSs; (b) UV-vis absorption spectra of  $\text{Co}(\text{NO}_3)_2$ , arginine and arginine- $\text{Co}(\text{NO}_3)_2$  aqueous solution; (c) XRD patterns of  $\text{Co}_3\text{O}_4$  BNSs and Rh- $\text{Co}_3\text{O}_4$  BNSs; (d) EPR spectra of  $\text{Co}_3\text{O}_4$  BNSs and Rh- $\text{Co}_3\text{O}_4$  BNSs.

of Rh species, the Rh- $\text{Co}_3\text{O}_4$  BNSs still retain the structure and morphology integrity of the branched nanosheet (Fig. 2b and S8†). The magnified TEM image shows that the Rh nanoparticles are uniformly dispersed on the surface of  $\text{Co}_3\text{O}_4$  BNSs with an ultrasmall particle size of about 1.60 nm (Fig. 2c). To further clarify the atomic structure of Rh species on the  $\text{Co}_3\text{O}_4$  substrate, aberration-corrected high-angle annular dark-field scanning TEM (HAADF-STEM) was carried out. As shown in Fig. 2d and e, many bright speckles appear on the surface of  $\text{Co}_3\text{O}_4$  BNSs, which are considered to be Rh cluster sites. From the high-resolution HAADF-STEM image (Fig. 2f), the lattice spacings of 0.219 nm and 0.214 nm correspond to the (111) and (400) planes of Rh and  $\text{Co}_3\text{O}_4$ , respectively. The energy dispersive X-ray (EDX) element mapping images of Rh- $\text{Co}_3\text{O}_4$  BNSs show that the Rh signals are uniformly distributed on  $\text{Co}_3\text{O}_4$  BNSs without obvious segregation (Fig. 2g and S9†). The mass loading of Rh on Rh- $\text{Co}_3\text{O}_4$  BNSs is about 15.1 wt%, determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES). By varying the addition of  $\text{RhCl}_3$ , other Rh- $\text{Co}_3\text{O}_4$  BNSs with different Rh loadings of 7.9 wt% and 31.7 wt% could be obtained, which exhibit a similar crystal structure and morphology to that of Rh- $\text{Co}_3\text{O}_4$  BNSs (Fig. S10 and S11†). The pure Rh sample was also synthesized for comparison (Fig. S12†).

X-ray photoelectron spectroscopy (XPS) was performed to understand the surface chemical and electronic states of Rh- $\text{Co}_3\text{O}_4$  BNSs. The survey XPS spectrum shows the existence of Rh, Co and O elements on the surface of Rh- $\text{Co}_3\text{O}_4$  BNSs (Fig.

S13†). For the high-resolution Rh 3d spectrum (Fig. 3a), the intense peaks observed at 306.9 and 311.7 eV are attributed to metallic  $\text{Rh}^0$  species, while the peaks centered at 308.0/313.2 and 309.7/314.7 eV respectively correspond to  $\text{Rh}^+$  and  $\text{Rh}^{3+}$ .<sup>33</sup> The geometric areas of the  $\text{Rh}^+$  and  $\text{Rh}^{3+}$  peaks obviously increase when compared with pure Rh, indicating that the Rh species within Rh- $\text{Co}_3\text{O}_4$  BNSs has a higher oxidation state. The Co 2p spectrum of Rh- $\text{Co}_3\text{O}_4$  BNSs (Fig. 3b) corresponds to spin-orbit splitting into  $2p_{1/2}$  (781.0) and  $2p_{3/2}$  (796.2 eV), where the peaks at 781.0 and 797.2 eV are assigned to  $\text{Co}^{3+}$  species and the peaks at 784.4 and 801.6 eV correspond to  $\text{Co}^{2+}$  species.<sup>34,35</sup> It is worth noting that the binding energies of Rh 3d and Co 2p spectra in Rh- $\text{Co}_3\text{O}_4$  BNSs exhibit a positive shift of about 0.23 eV and 0.65 eV compared to those in pure Rh and  $\text{Co}_3\text{O}_4$  BNSs, respectively. This shift indicates a strong interaction between Rh and the  $\text{Co}_3\text{O}_4$  support, leading to the charge redistribution. In the high-resolution O 1s spectra (Fig. S14†), the peaks of O1 at 530.4 eV and O3 at 532.6 eV are attributed to the metal-oxygen bond and surface-adsorbed water molecule, while the O2 peak at 531.3 eV is caused by oxygen vacancies.<sup>36,37</sup> Compared to  $\text{Co}_3\text{O}_4$  BNSs, the O2 peak area in Rh- $\text{Co}_3\text{O}_4$  BNSs shows a significant increase, suggesting an increase in oxygen vacancies of Rh- $\text{Co}_3\text{O}_4$  BNSs. X-ray absorption spectroscopy (XAS) was conducted with the aim of distinguishing the electronic structure and the coordination environment of Rh and Co in Rh- $\text{Co}_3\text{O}_4$  BNSs. As shown by the normalized Co K-edge X-ray absorption near-edge structure (XANES), the Rh- $\text{Co}_3\text{O}_4$  BNSs exhibit a lower energy compared with the  $\text{Co}_3\text{O}_4$  reference



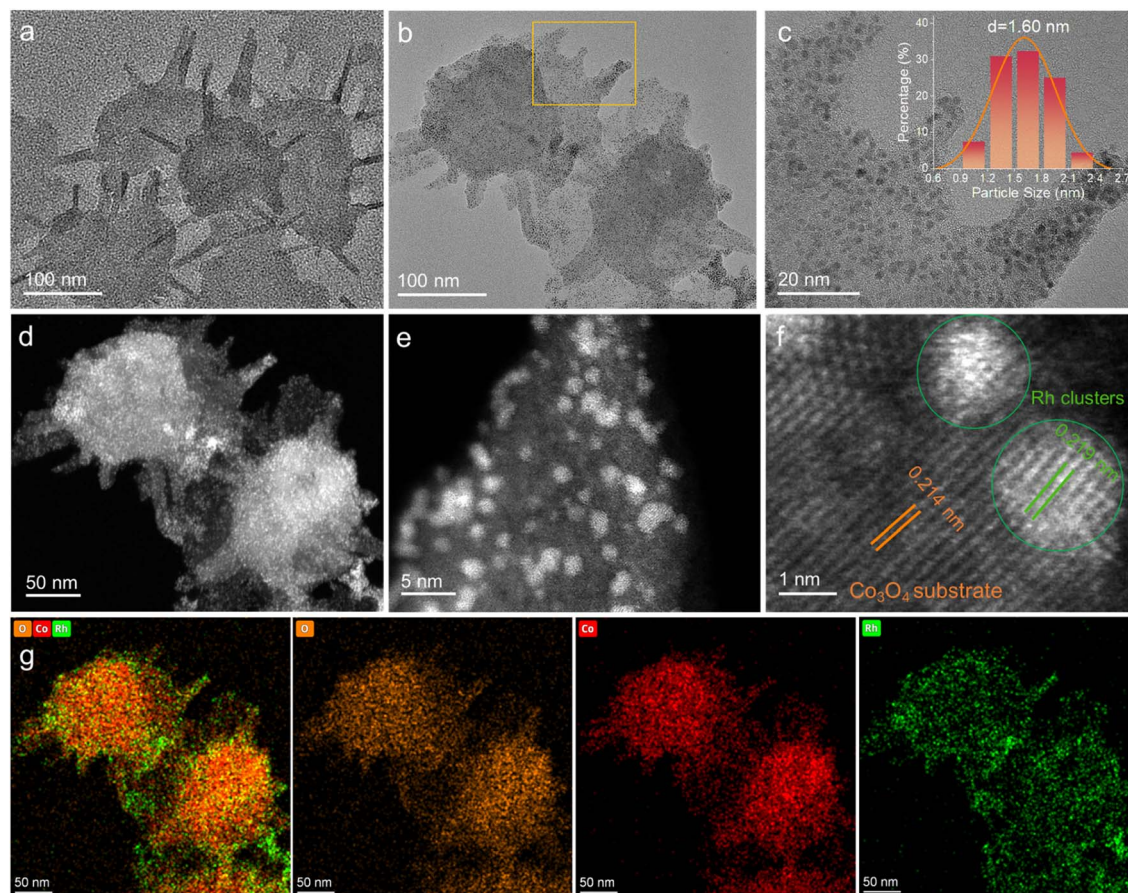


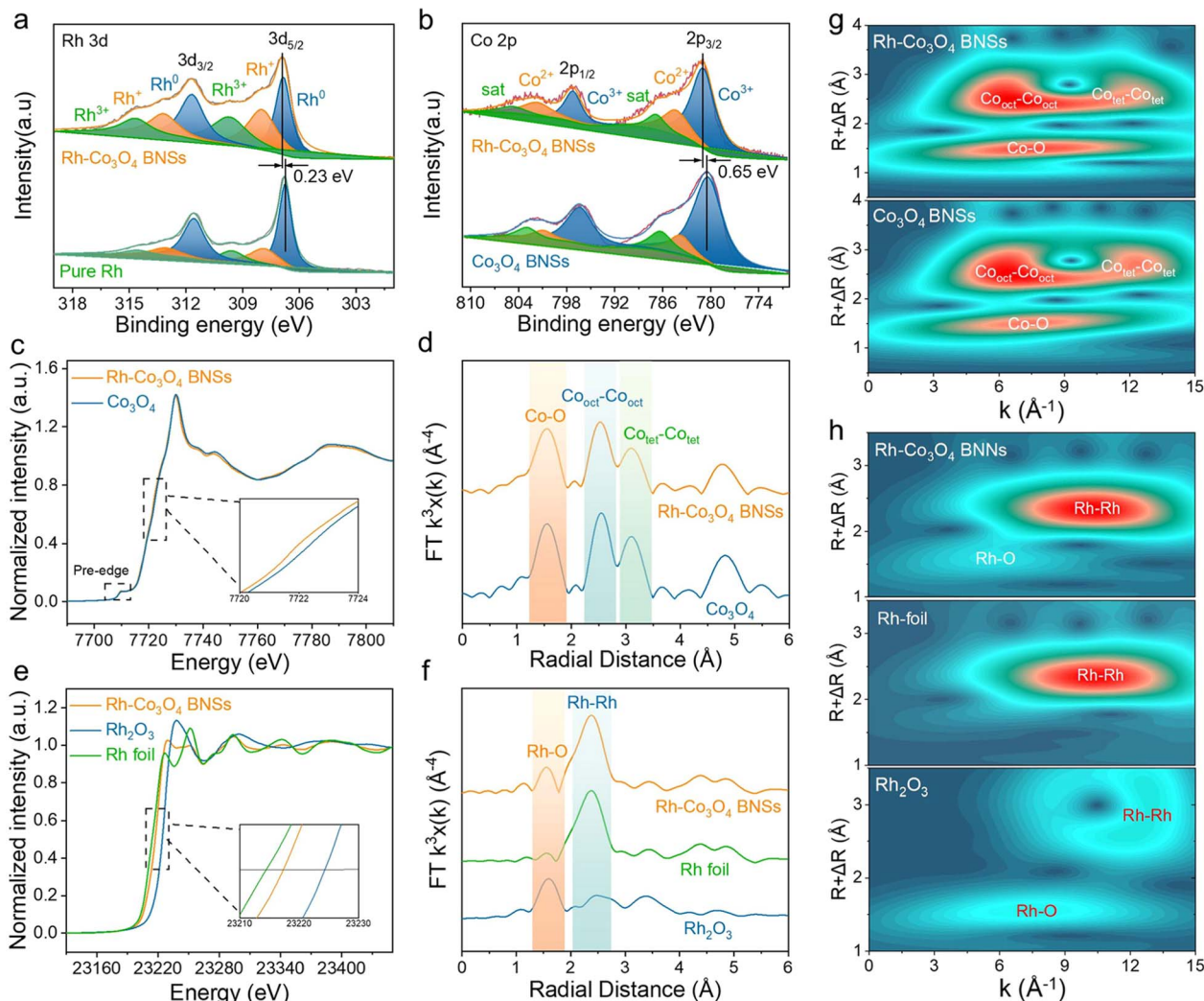
Fig. 2 (a) TEM image of Co<sub>3</sub>O<sub>4</sub> BNSs; (b) and (c) TEM images of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs with different resolutions, the inset of (c) shows the corresponding particle-size distribution; (d)–(f) AC-HAADF-STEM image of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs; (g) EDX element mapping images of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs.

(Fig. 3c), indicating a slight decrease in the average valence state of Co species in Co<sub>3</sub>O<sub>4</sub> after the introduction of Rh. The Co K-edge Fourier-transformed extended X-ray absorption fine structure (FT-EXAFS) of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs is similar to that of Co<sub>3</sub>O<sub>4</sub> (Fig. 3d), with three distinct peaks identified as Co–O, octahedral Co–Co and tetrahedral Co–Co bonds, respectively.<sup>38,39</sup> Fig. 3e depicts the normalized XANES spectra for the Rh K-edge of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs and standard samples. The Rh K-edge absorption edge for Rh-Co<sub>3</sub>O<sub>4</sub> BNSs is located between that of Rh foil and Rh<sub>2</sub>O<sub>3</sub>, with a greater proximity to the line of Rh. The Rh valence of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs was quantitatively measured by using the adsorption energy ( $E_0$ ) to be +0.51 (Fig. S15†). This fact proves that the coupling of Rh and Co<sub>3</sub>O<sub>4</sub> leads to the transfer of electrons from the Rh sites to the Co sites *via* the bridged O atoms. Furthermore, the presence of O as Lewis acids, while exhibiting a weaker metal-electron withdrawing effect than O atoms, also facilitates electron donation by Rh.<sup>40,41</sup> The information derived from Rh EXAFS shows that the Rh-Co<sub>3</sub>O<sub>4</sub> BNS sample exhibits a strong Rh–Rh peak and a more pronounced weak Rh–O peak relative to the Rh foil (Fig. 3f), implying the existence of Rh–O–Co bridging sites between the Rh clusters and the Co<sub>3</sub>O<sub>4</sub> BNSs.<sup>42,43</sup> Consistent results were observed from the wavelet transform (WT) analyses of the Rh-Co<sub>3</sub>O<sub>4</sub> BNS spectrum. The oscillation of the WT spectrum of Rh-

Co<sub>3</sub>O<sub>4</sub> BNSs is similar to that of pristine Co<sub>3</sub>O<sub>4</sub>, suggesting their similar spinel structure (Fig. 3g). In addition, the Rh–O scattering of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs ( $R = 1.61 \text{ \AA}$ ,  $k = 5.65 \text{ \AA}^{-1}$ ) are quite different from those of Rh–O scattering in Rh<sub>2</sub>O<sub>3</sub> ( $R = 1.55 \text{ \AA}$ ,  $k = 7.40 \text{ \AA}^{-1}$ ), which further demonstrates the presence of asymmetric Rh–O–Co bridging sites rather than pure Rh–O bridging sites in the Rh-Co<sub>3</sub>O<sub>4</sub> BNSs (Fig. 3h).

### Electrocatalytic performance towards the HER

The HER performance of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs was evaluated in 0.5 M H<sub>2</sub>SO<sub>4</sub> electrolyte using a typical three-electrode setup, where Co<sub>3</sub>O<sub>4</sub> BNSs, pure Rh, and commercial Pt/C catalysts were also measured under the same conditions for comparison. Fig. 4a shows the HER polarization curves of the catalysts. The Rh-Co<sub>3</sub>O<sub>4</sub> BNSs require remarkably low overpotentials of 32 mV and 56 mV to achieve current densities of 10 mA cm<sup>−2</sup> ( $E_{50}$ ) and 50 mA cm<sup>−2</sup> ( $E_{50}$ ), respectively (Fig. 4a). These values are superior to those of pure Rh ( $E_{10} = 53 \text{ mV}$  and  $E_{50} = 90 \text{ mV}$ ), Co<sub>3</sub>O<sub>4</sub> BNSs ( $E_{10} = 244 \text{ mV}$  and  $E_{50} = 491 \text{ mV}$ ), and are even comparable to those of commercial Pt/C ( $E_{10} = 38 \text{ mV}$  and  $E_{50} = 76 \text{ mV}$ ). The reaction kinetics of the HER process on all catalysts was revealed by the Tafel slope (Fig. S16†). As depicted in Fig. 4b, the Rh-Co<sub>3</sub>O<sub>4</sub> BNSs exhibit a sharply decreased Tafel slope (27.0 mV dec<sup>−1</sup>) relative to those of Pt/C (48.6 mV dec<sup>−1</sup>),



**Fig. 3** (a) Rh 3d XPS spectra of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs and pure Rh; (b) Co 2p XPS spectra of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs and Co<sub>3</sub>O<sub>4</sub> BNSs; (c) the normalized Co K-edge XANES spectra; (d) Fourier-transforms of  $K^3$ -weight Co K-edge EXAFS spectra; (e) the normalized Rh K-edge XANES spectra; (f) Fourier-transforms of the  $K^3$ -weight Rh K-edge EXAFS spectra; (g) wavelet transforms for the  $K^3$ -weight Co K-edge EXAFS signals; (h) wavelet transforms for the  $K^3$ -weight Rh K-edge EXAFS signals.

pure Rh (42.3 mV dec<sup>-1</sup>) and Co<sub>3</sub>O<sub>4</sub> BNSs (285 mV dec<sup>-1</sup>), implying the fastest HER kinetics at the Rh-Co<sub>3</sub>O<sub>4</sub> BNS surface. The Tafel slope of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs is close to 29.9 mV dec<sup>-1</sup>, illustrating that the Rh-Co<sub>3</sub>O<sub>4</sub> BNSs catalyze the HER by a Volmer-Tafel mechanism.<sup>44</sup> The low overpotentials and small Tafel slope of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs are also significantly lower than those of the Rh<sub>7.9</sub> wt%-Co<sub>3</sub>O<sub>4</sub> BNSs and Rh<sub>31.7</sub> wt%-Co<sub>3</sub>O<sub>4</sub> BNSs (Fig. 4c and S17<sup>†</sup>), as well as most of the previously reported typical catalysts (data confirmed by using the DigCat database: <https://www.digcat.org/>; illustrated in Fig. 4d and Table S1<sup>†</sup>). The above results suggest that the synergistic effect of Rh and Co<sub>3</sub>O<sub>4</sub> components facilitates the HER process. To better understand the synergistic effect of Rh and Co<sub>3</sub>O<sub>4</sub> components, electrochemical impedance spectroscopy (EIS) was carried out and the electrochemical double-layer capacitance ( $C_{dl}$ ) were investigated. As shown in EIS Nyquist plots (Fig. 4e), the Rh-Co<sub>3</sub>O<sub>4</sub> BNSs present the lowest electron transfer resistance ( $R_{ct}$ ) relative to pure Rh and Co<sub>3</sub>O<sub>4</sub> BNSs,

indicating that the interaction between Rh and Co<sub>3</sub>O<sub>4</sub> enhances the charge transfer efficiency of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs. The  $C_{dl}$  was calculated by using cyclic voltammetry (CV) measurements at different scan rates in the non-faradaic region (Fig. S18<sup>†</sup>). The Rh-Co<sub>3</sub>O<sub>4</sub> BNSs exhibit a high  $C_{dl}$  of about 10.32 mF cm<sup>-2</sup> (Fig. 4f), which is higher than those of Pt/C (8.49 mF cm<sup>-2</sup>), pure Rh (5.85 mF cm<sup>-2</sup>), and Co<sub>3</sub>O<sub>4</sub> BNSs (3.24 mF cm<sup>-2</sup>). Given the linear relationship between the  $C_{dl}$  and the electrochemical surface area (ECSA), Rh-Co<sub>3</sub>O<sub>4</sub> BNSs exhibit a larger ECSA and expose more active sites, thus increasing HER activity. To evaluate the stability of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs, the accelerated durability test (ADT) was performed by 2000 CV cycles in the voltage window from -0.08 to -0.02 V (vs. RHE) with a scan rate of 100 mV s<sup>-1</sup>. As shown in Fig. 4g, the overpotential at 10 mA cm<sup>-2</sup> in the HER polarization curve of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs after 2000 cycles only increases by 3 mV compared with the original one, which is smaller than that of Pt/C (13 mV), pure Rh (5 mV), and Co<sub>3</sub>O<sub>4</sub> BNSs (65



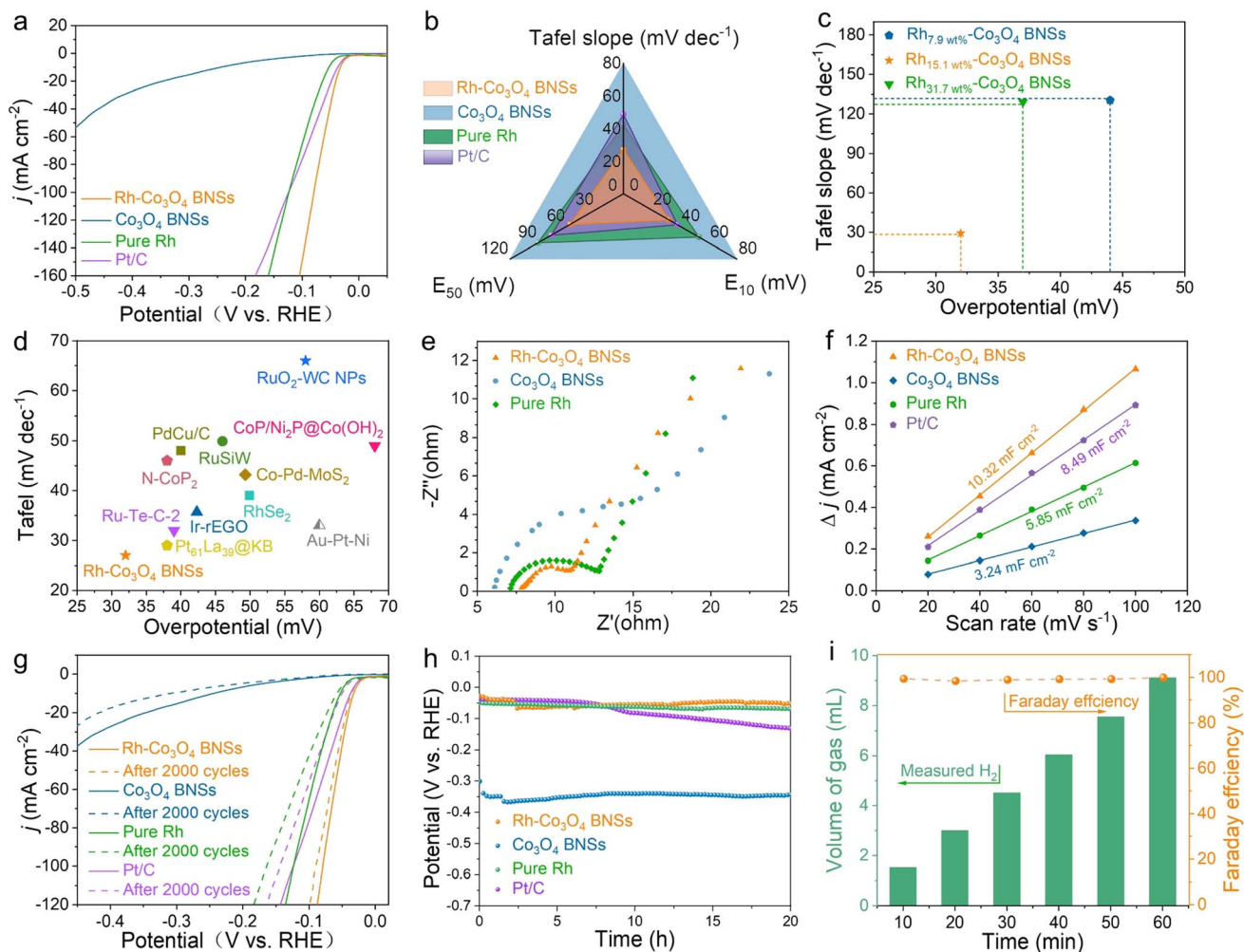


Fig. 4 (a) HER polarization curves of the catalysts in 0.5 M H<sub>2</sub>SO<sub>4</sub> at a scan rate of 5 mV s<sup>-1</sup>; (b) Tafel slope and overpotential at 10 mA cm<sup>-2</sup> and 50 mA cm<sup>-2</sup> of the catalysts; (c) comparison of the Tafel slope and overpotential for Rh-Co<sub>3</sub>O<sub>4</sub> BNSs at different Rh loadings; (d) comparison of the Tafel slope and overpotential of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs and the reported catalysts; (e) EIS Nyquist plots of the catalysts; (f)  $\Delta j$  values of the catalysts; (g) HER polarization curves of the catalysts before and after 2000 CV cycles; (h) chronopotentiometric curves of the catalysts at 10 mA cm<sup>-2</sup>; (i) Faraday efficiency of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs.

mV). The chronopotentiometry measurement was further applied to evaluate the long-term durability of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs at a current density of at 10 mA cm<sup>-2</sup> (Fig. 4h). In comparison to the other three catalysts, the superior alkaline HER activity is well retained on Rh-Co<sub>3</sub>O<sub>4</sub> BNSs after continuous hydrogen production for more than 20 h. After chronopotentiometry, the Rh-Co<sub>3</sub>O<sub>4</sub> BNSs still retain the branched nanosheet structure and uniform height distribution of Rh particles on the Co<sub>3</sub>O<sub>4</sub> surface (Fig. S19†). The XPS spectra of recovered Rh-Co<sub>3</sub>O<sub>4</sub> BNSs show a slight decrease in the proportion of Rh in the oxidized state with no significant change for Co species (Fig. S20†). In addition, the Rh-Co<sub>3</sub>O<sub>4</sub> BNSs exhibit a high faradaic efficiency (FE) of about 100% during the HER, indicating the high HER selectivity of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs (Fig. 4i and S21†).

### Electrocatalytic performance towards the HzOR

The electrochemical performance of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs for the HzOR was then evaluated in H<sub>2</sub>SO<sub>4</sub>/N<sub>2</sub>H<sub>4</sub> electrolyte. We first

determined that the HzOR activity of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs is optimal in 0.5 M H<sub>2</sub>SO<sub>4</sub> + 0.05 M N<sub>2</sub>H<sub>4</sub> electrolyte (Fig. S22†). When the concentration of N<sub>2</sub>H<sub>4</sub> exceeds 0.05 M in H<sub>2</sub>SO<sub>4</sub> solution, hydrazine sulfate precipitation is easily observed.<sup>45</sup> Fig. 5a shows the HzOR and OER polarization curves of the Rh-Co<sub>3</sub>O<sub>4</sub> BNS electrode in 0.5 M H<sub>2</sub>SO<sub>4</sub> with and without 0.05 M N<sub>2</sub>H<sub>4</sub>. It can be seen that the Rh-Co<sub>3</sub>O<sub>4</sub> BNSs require a low working potential of 0.26 V vs. RHE to reach a current density of 10 mA cm<sup>-2</sup> for the HzOR, which is 1.39 V less than that of the OER and other reported small-molecule oxidative reactions (Table S2†), indicating that the Rh-Co<sub>3</sub>O<sub>4</sub> BNSs possess excellent HzOR activity and can be utilized as an alternative OER catalyst to reduce the electrical energy consumption. The HzOR activity of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs was then compared with that of Co<sub>3</sub>O<sub>4</sub> BNSs, pure Rh and Pt/C control samples (Fig. 5b). As observed in Fig. 5c, the working potentials at a current density of 10 and 50 mA cm<sup>-2</sup> for Rh-Co<sub>3</sub>O<sub>4</sub> BNSs are merely 0.26 V and 0.44 V, which are much lower than that of Co<sub>3</sub>O<sub>4</sub> BNSs and pure Rh, and even exceeds that of commercial Pt/C, suggesting the significantly

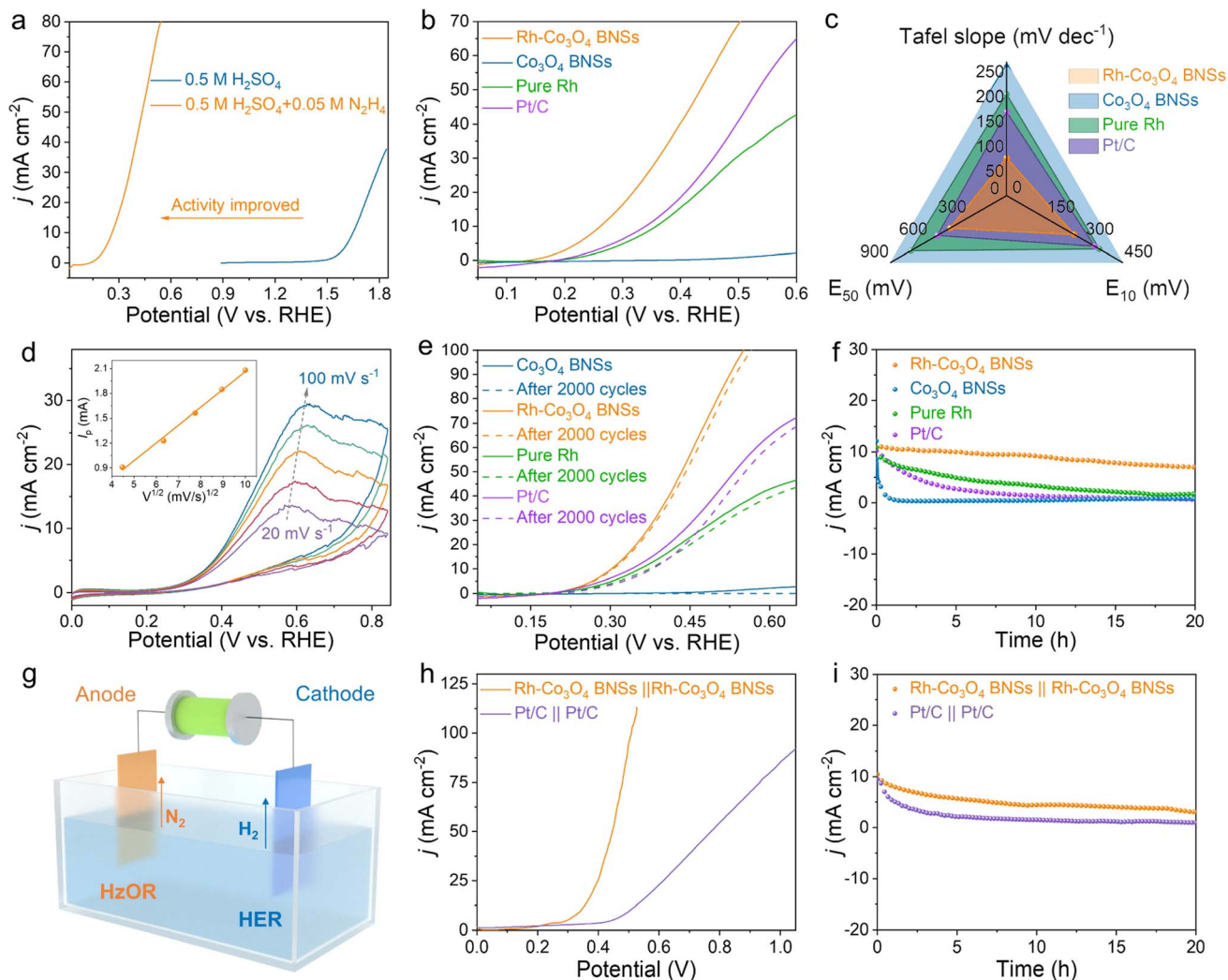


Fig. 5 (a) The polarization curves of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs in 0.5 M H<sub>2</sub>SO<sub>4</sub> with and without 0.05 M N<sub>2</sub>H<sub>4</sub> at a scan rate of 5 mV s<sup>-1</sup>; (b) H<sub>2</sub>OR polarization curves of the catalysts in 0.5 M H<sub>2</sub>SO<sub>4</sub> + 0.05 M N<sub>2</sub>H<sub>4</sub> electrolyte; (c) comparison of the Tafel slope and working potential at 10 mA cm<sup>-2</sup> and 50 mA cm<sup>-2</sup> recorded from panel (c); (d) CV curves of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs in 0.5 M H<sub>2</sub>SO<sub>4</sub> + 0.05 M N<sub>2</sub>H<sub>4</sub> electrolyte at different scanning rates from 20 to 100 mV s<sup>-1</sup>, the inset shows the  $i_p$  vs.  $\nu^{1/2}$  plot; (e) H<sub>2</sub>OR polarization curves of the catalysts before and after 2000 CV cycles; (f) chronopotentiometry curves of the catalysts for the H<sub>2</sub>OR recorded at 10 mA cm<sup>-2</sup> in 0.5 M H<sub>2</sub>SO<sub>4</sub> + 0.05 M N<sub>2</sub>H<sub>4</sub> electrolyte; (g) schematic illustration of a homemade OhzS electrolyzer; (h) OH<sub>2</sub>R polarization curves of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs || Rh-Co<sub>3</sub>O<sub>4</sub> BNSs and Pt/C || Pt/C; (i) chrono-potentiometry curves for OH<sub>2</sub>R recorded at 10 mA cm<sup>-2</sup>.

improved H<sub>2</sub>OR activity by the synergistic effect of Rh and Co<sub>3</sub>O<sub>4</sub> components. The corresponding Tafel slope value of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs is about 76.0 mV dec<sup>-1</sup> (Fig. 5c and S23†), which is considerably smaller than that of Pt/C (168.9 mV dec<sup>-1</sup>), pure Rh (204.5 mV dec<sup>-1</sup>), and Co<sub>3</sub>O<sub>4</sub> BNSs (264.5 mV dec<sup>-1</sup>), proving the faster H<sub>2</sub>OR kinetics of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs. The interfacial electron transfer kinetics of catalysts during the H<sub>2</sub>OR was investigated by EIS, where the Rh-Co<sub>3</sub>O<sub>4</sub> BNSs exhibit a smaller charge-transfer resistance than that of pure Rh and Co<sub>3</sub>O<sub>4</sub> BNSs (Fig. S24†). Based on the CV measurement at varying scan rates ( $\nu$ ) shown in Fig. 5d, the peak oxidation current density ( $i_p$ ) of the H<sub>2</sub>OR increases in proportion to the square root of  $\nu$  ( $\nu^{1/2}$ ); while the  $E_p$  value increases linearly with  $\log(\nu)$  from 20 to 100 mV s<sup>-1</sup> (Fig. S25†), indicating that the H<sub>2</sub>OR of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs is a diffusion-controlled irreversible process.<sup>45</sup> The Rh-Co<sub>3</sub>O<sub>4</sub>

BNSs also present excellent electrocatalytic stability for the H<sub>2</sub>OR, as verified by ADT and chronopotentiometry measurements. The ADT measurement shows that the working potential of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs at 10 mA cm<sup>-2</sup> only increases by 3 mV after 2000 CV cycles (Fig. 5e), which is significantly lower than that of other comparative samples. Meanwhile, the chronoamperometric curve at 10 mA cm<sup>-2</sup> remains relatively stable over 20 h (Fig. 5f). In addition, the Rh-Co<sub>3</sub>O<sub>4</sub> BNSs show superior stability in the H<sub>2</sub>OR in comparison to their performance in the OER (Fig. S26†). After the prolonged H<sub>2</sub>OR process, the Rh clusters on Co<sub>3</sub>O<sub>4</sub> BNSs exhibit a slight tendency to aggregate, while the dispersion remains relatively homogeneous (Fig. S27†). The XPS full spectra of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs after the H<sub>2</sub>OR show that the Co and Rh species still exist after the long oxidation process (Fig. S28a†). The main peaks of Co 3d and the ratio of Co<sup>3+</sup>/Co<sup>2+</sup> for

recovered Rh-Co<sub>3</sub>O<sub>4</sub> BNSs did not change significantly (Fig. S28b†). For the Rh3d XPS spectrum, the peaks of recovered Rh-Co<sub>3</sub>O<sub>4</sub> BNSs shift to higher binding energies compared with those of the original one, accompanied by an increase in the oxidized state (Fig. S28c†). The preferential oxidation of Rh clusters facilitates the HzOR process by avoiding excessive oxidation of Co<sup>3+</sup> in Co<sub>3</sub>O<sub>4</sub> to acidic soluble Co<sup>4+</sup>.<sup>46</sup>

Considering the excellent bifunctional performance of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs for both the HER and HzOR, an overall hydrazine splitting (OH<sub>2</sub>S) electrolyzer was constructed to explore the possibility of hydrazine-assisted hydrogen production, as schematically illustrated in Fig. 5g. The HER polarization curves of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs remain unchanged before and after the introduction of 0.05 M N<sub>2</sub>H<sub>4</sub> (Fig. S29†), indicating a high HER selectivity of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs.<sup>1</sup> The OH<sub>2</sub>S electrolyzer achieves a current density of 10 mA cm<sup>-2</sup> at a lower cell voltage of 0.34 V (Fig. S30†), which is 1.38 V lower than that of overall water splitting (OWS), demonstrating the great potential of the Rh-

Co<sub>3</sub>O<sub>4</sub> BNS-based OH<sub>2</sub>S electrolyzer to reduce the energy consumption. In addition, the Rh-Co<sub>3</sub>O<sub>4</sub> BNSs||Rh-Co<sub>3</sub>O<sub>4</sub> BNS-based OH<sub>2</sub>S outperforms the Pt/C||Pt/C-based OH<sub>2</sub>S (Fig. 5h), and many reported OWS systems (Table S3†). During the chronopotentiometry measurement, the driving current of the OH<sub>2</sub>R electrolyzer on Rh-Co<sub>3</sub>O<sub>4</sub> BNSs||Rh-Co<sub>3</sub>O<sub>4</sub> BNSs decays at a slower rate than that of the Pt/C||Pt/C-based OH<sub>2</sub>R electrolyzer, further implying the superior stability of Rh-Co<sub>3</sub>O<sub>4</sub> BNSs (Fig. 5i).

### Insights into the catalytic mechanism

DFT calculations were conducted to investigate the HER and HzOR mechanisms on Rh-Co<sub>3</sub>O<sub>4</sub> BNSs. As shown in Fig. 6a, the projected density of states (PDOS) of Rh-Co<sub>3</sub>O<sub>4</sub> reveals that the Rh 4d states are closer to the Fermi level ( $E_F$ ), than the Co 3d states below the  $E_F$ , indicating the main contribution of Rh 4d states for catalytic performance. Furthermore, the d-band center of Co in Rh-Co<sub>3</sub>O<sub>4</sub> BNSs exhibits an increasing trend

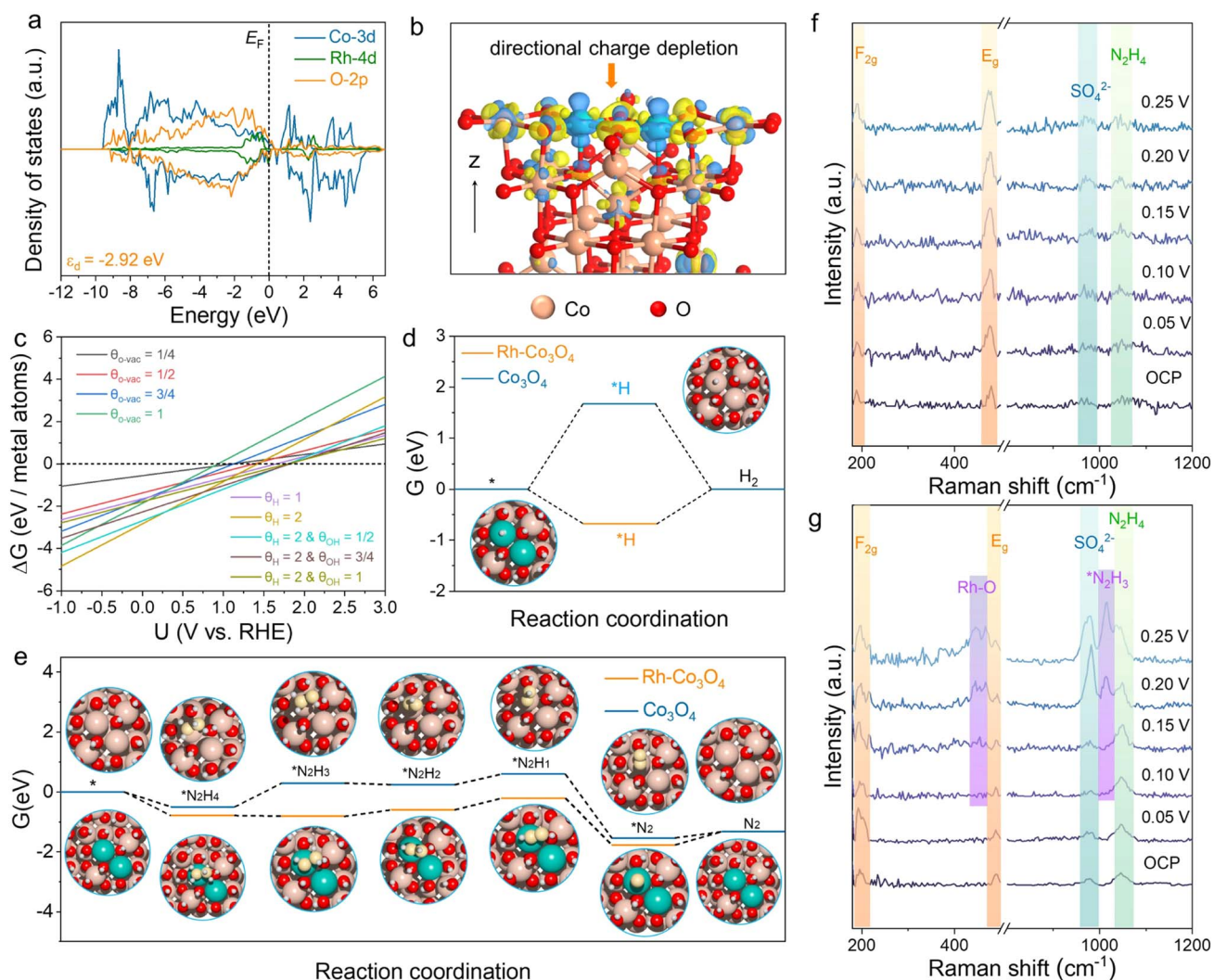


Fig. 6 (a) PDOS of Rh-Co<sub>3</sub>O<sub>4</sub> (100); (b) charge density difference of Rh-Co<sub>3</sub>O<sub>4</sub> (100) upon the combination of two counterparts (yellow color represents charge accumulation, and blue color represents charge depletion in the space); (c) surface Pourbaix diagram at 25 °C; (d) Gibbs free energy diagrams of Co<sub>3</sub>O<sub>4</sub> and Rh-Co<sub>3</sub>O<sub>4</sub> (100) for the HER; (e) Gibbs free energy diagrams of Co<sub>3</sub>O<sub>4</sub> and Rh-Co<sub>3</sub>O<sub>4</sub> (100) for the HzOR; *in situ* Raman spectrum of (f) Co<sub>3</sub>O<sub>4</sub> BNSs and (g) Rh-Co<sub>3</sub>O<sub>4</sub> BNSs.



towards the Fermi energy level, from  $-2.92$  to  $-2.81$  eV, in comparison to that of the PDOS of  $\text{Co}_3\text{O}_4$  (Fig. S31<sup>†</sup>), confirming the effective electronic interaction within the  $[\text{Rh}-\text{O}-\text{Co}]$  site. This upshift is considered to favor the adsorption of intermediates during the HER and HzOR process, thereby improving the kinetic performance.<sup>20,47</sup> The charge density difference plot of  $\text{Rh}-\text{Co}_3\text{O}_4$  was further obtained to understand the electronic redistribution (Fig. 6b). It can be observed that Rh atoms show directional charge depletion, while the O atoms and partially Co atoms exhibit charge accumulation, which is consistent with the XANES analysis. The surface Pourbaix diagrams were obtained to confirm the surface state for initiating the reaction process, including oxygen vacancies,  $^*\text{H}$ , and hydroxyls coverages (Fig. 6c and S32<sup>†</sup>). Although the formation of oxygen vacancies is facilitated at low bias potential, the coverage of 2 monolayer (ML)  $^*\text{H}$  shares the lowest energy below the bias potential of  $0 \text{ V}_{\text{RHE}}$ , where the exposed surface unsaturated lattice oxygen atoms can be covered by  $^*\text{H}$ . Based on such a surface state, the HER process of  $\text{Rh}-\text{Co}_3\text{O}_4$  BNSs was further discussed. Generally, the free energy of hydrogen adsorption ( $\Delta G_{\text{H}^*}$ ) is regarded as a descriptor to characterize the HER activity. As shown in Fig. 6d,  $\text{Co}_3\text{O}_4$  exhibits a high  $\Delta G_{\text{H}^*}$  of  $1.67$  eV, implying that adsorption of hydrogen atoms is challenging. Conversely,  $\text{Rh}-\text{Co}_3\text{O}_4$  exhibits a low  $\Delta G_{\text{H}^*}$  of  $-0.68$  eV, which is closer to  $0$  eV, implying the low reaction energy barrier of the HER on the  $\text{Rh}-\text{Co}_3\text{O}_4$  surface. Fig. 6e describes the stepwise dehydrogenation process of  $\text{N}_2\text{H}_4$  with various intermediates on  $\text{Rh}-\text{Co}_3\text{O}_4$  and the  $\text{Co}_3\text{O}_4$  surface. It is revealed that when the HzOR takes place on the  $\text{Co}_3\text{O}_4$  surface, the first dehydrogenation step ( $\text{N}_2\text{H}_4^* \rightarrow \text{N}_2\text{H}_3^*$ ) serves as the potential-determining step (PDS) with a change in Gibbs free energy ( $\Delta G$ ) of  $0.79$  eV. After the introduction of Rh, the PDS on the  $\text{Rh}-\text{Co}_3\text{O}_4$  surface turns into the third dehydrogenation step ( $\text{N}_2\text{H}_2 \rightarrow \text{N}_2\text{H}_1^*$ ), whose  $\Delta G$  significantly decreased to  $0.38$  eV. Therefore, the reaction pathway of  $\text{Rh}-\text{Co}_3\text{O}_4$  is more favorable than that of  $\text{Co}_3\text{O}_4$  in the HzOR process.

To gain insights into the role of the  $\text{Rh}-\text{O}-\text{Co}$  unit in the HzOR mechanism, electrochemical *in situ* Raman spectroscopy was employed to monitor surface transformations and reaction intermediates of  $\text{Rh}-\text{Co}_3\text{O}_4$  and  $\text{Co}_3\text{O}_4$  BNSs at different potentials in a  $0.5 \text{ M H}_2\text{SO}_4 + 0.05 \text{ M N}_2\text{H}_4$  solution (Fig. 6f and g). The peaks at  $\sim 191 \text{ cm}^{-2}$  and  $\sim 475 \text{ cm}^{-2}$  in *in situ* Raman spectra correspond to the  $\text{F}_{2g}$  and  $\text{E}_g$  modes of spinel  $\text{Co}_3\text{O}_4$ , respectively.<sup>48</sup> An intense peak at  $\sim 976 \text{ cm}^{-1}$  corresponds to the symmetric stretching vibrational mode of  $\text{SO}_4^{2-}$ , indicating that the  $\text{Rh}-\text{Co}_3\text{O}_4$  BNSs and  $\text{Co}_3\text{O}_4$  BNSs possess excellent wettability. Compared with  $\text{Co}_3\text{O}_4$  BNSs, the  $\text{Rh}-\text{Co}_3\text{O}_4$  BNSs exhibit increased peak intensities associated with  $\text{N}_2\text{H}_4$  ( $\sim 1050 \text{ cm}^{-1}$ ) bond absorption, which suggests that the introduction of Rh into  $\text{Co}_3\text{O}_4$  enhances the adsorption of  $\text{N}_2\text{H}_4$ .<sup>49–51</sup> When the working potential of  $\text{Rh}-\text{Co}_3\text{O}_4$  BNSs increases to  $0.20 \text{ V}$  vs. RHE, the Co–N bond exhibits a slight weakening, and a scattering peak representing the vibrational mode of Rh–O stretching appeared at  $460 \text{ cm}^{-2}$ .<sup>52</sup> Note that the Raman spectra of  $\text{Rh}-\text{Co}_3\text{O}_4$  BNSs display a new peak ( $\sim 1013 \text{ cm}^{-2}$ ) between the  $\text{N}_2\text{H}_4$  and  $\text{SO}_4^{2-}$  peaks corresponding to the  $^*\text{N}_2\text{H}_3$  intermediate produced after the first dehydrogenation step. However, this

peak is unobservable in Raman spectra of  $\text{Co}_3\text{O}_4$  BNSs. The *in situ* Raman results indicate that Rh clusters anchored on  $\text{Co}_3\text{O}_4$  BNSs are susceptible to exhibit a high oxidation state during the HzOR, which can serve as an important active site to lower the continuous dehydrogenation energy barrier of  $\text{Co}_3\text{O}_4$  BNSs.

## Conclusion

In summary, we have developed a highly effective bifunctional catalyst by anchoring Rh on  $\text{Co}_3\text{O}_4$  branched nanosheets ( $\text{Rh}-\text{Co}_3\text{O}_4$  BNSs) synthesized through an innovative arginine-induced strategy. The prepared  $\text{Rh}-\text{Co}_3\text{O}_4$  BNSs require ultra-low working potentials of only  $32 \text{ mV}$  for the acidic HER and  $0.26 \text{ V}$  for the acidic HzOR to achieve current densities of  $10 \text{ mA cm}^{-2}$ , and significantly outperform commercial Pt/C and other reported catalysts. When used in two-electrode hydrazine-assisted water electrolysis, it delivers a current density of  $10 \text{ mA cm}^{-2}$  at a low voltage of  $0.34 \text{ V}$ , which is  $1.38 \text{ V}$  lower than that of traditional overall water splitting, and provides excellent stability over  $20 \text{ h}$ . XAS and XPS analyses demonstrated that charge redistribution between Rh clusters and  $\text{Co}_3\text{O}_4$  substrates occurs *via* distinctive Rh–O–Co sites. This optimizes their valence electronic structures, which has the potential to enhance their catalytic activity and stability. Theoretical calculations further confirmed that the optimized valence electronic structure within the Rh–O–Co sites not only reduced the adsorption energy barrier of  $\text{Co}_3\text{O}_4$  for  $\text{H}^*$  in the HER, but also enhanced hydrazine adsorption in the HzOR with an accelerated dehydrogenation process, as indicated by *in situ* Raman spectroscopy. This work provides new ideas for the construction of bifunctional catalysts with excellent performance and stability for efficient hydrogen production under acidic conditions.

## Data availability

The authors confirm that the data supporting the findings of this study are available within the article and its ESI.<sup>†</sup>

## Author contributions

Jinrui Hu and Xuan Wang did the majority of experimental work, including synthesis, characterization and analysis. Yi Zhou, Meihan Liu and Caikang Wang participated in the electrochemistry test and analysis. Meng Li also participated in the data analysis and contributed to the preparation of the manuscript. Heng Liu and Hao Li were responsible for the DFT calculation analysis. Yawen Tang and Gengtao Fu conceived the idea, supervised the experimental work, and analyzed the data. The initial draft of the manuscript was written by Jinrui Hu and later refined by Gengtao Fu and Hao Li. All authors have reviewed and approved the final manuscript.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (22279062 and 22232004), JSPS KAKENHI (JP24K23069) and Ensemble Grants for Early Career Researchers 2024. The authors are grateful for the support from the National and Local Joint Engineering Research Center of Biomedical Functional Materials and a project sponsored by the Priority Academic Program Development of Jiangsu Higher Education Institutions. H. Li acknowledges the Center for Computational Materials Science, Institute for Materials Research, Tohoku University for the use of MASAMUNE-IMR (202312-SCKXX-0203) and the Institute for Solid State Physics (ISSP) at the University of Tokyo for the use of their supercomputers.

## References

- 1 Y. Zhu, J. Zhang, Q. Qian, Y. Li, Z. Li, Y. Liu, C. Xiao, G. Zhang and Y. Xie, Dual Nanoislands on Ni/C Hybrid Nanosheet Activate Superior Hydrazine Oxidation-Assisted High-Efficiency  $H_2$  Production, *Angew. Chem., Int. Ed.*, 2021, **61**, e202113082.
- 2 Y. Xue, J. Zhao, L. Huang, Y. R. Lu, A. Malek, G. Gao, Z. Zhuang, D. Wang, C. T. Yavuz and X. Lu, Stabilizing ruthenium dioxide with cation-anchored sulfate for durable oxygen evolution in proton-exchange membrane water electrolyzers, *Nat. Commun.*, 2023, **14**, 8093.
- 3 Y. Zhang, W. Zhu, J. Fang, Z. Xu, Y. Xue, J. Pei, R. Sui, X. Wang, X. Zhang and Z. Zhuang, Electrochemical converting ethanol to hydrogen and acetic acid for large scale green hydrogen production, *Nano Res.*, 2023, **17**, 1542–1551.
- 4 Y. Wang, F. Ma, G. Zhang, J. Zhang, H. Zhao, Y. Dong and D. Wang, Precise synthesis of dual atom sites for electrocatalysis, *Nano Res.*, 2024, **17**, 9397–9427.
- 5 J. Zhang, L. Xu, X. Yang, S. Guo, Y. Zhang, Y. Zhao, G. Wu and G. Li, Amorphous  $MnRuO_x$  Containing Microcrystalline for Enhanced Acidic Oxygen-Evolution Activity and Stability, *Angew. Chem., Int. Ed.*, 2024, **63**, e202405641.
- 6 Y. Liu, J. Zhang, Y. Li, Q. Qian, Z. Li and G. Zhang, Realizing the Synergy of Interface Engineering and Chemical Substitution for  $Ni_3N$  Enables its Bifunctionality Toward Hydrazine Oxidation Assisted Energy-Saving Hydrogen Production, *Adv. Funct. Mater.*, 2021, **31**, 2103673.
- 7 Y. Zhu, X. Wu, Z. Wu, X. Wang, X. Wang, C. Wang, X. Zhu, M. Li, D. Sun, H. Li, Y. Tang and G. Fu, Europium Oxide Evoked Multisite Synergism to Facilitate Water Dissociation for Alkaline Hydrogen Evolution, *Adv. Funct. Mater.*, 2024, 2409324.
- 8 C. Rong, S. Wang, X. Shen, C. Jia, Q. Sun, Q. Zhang and C. Zhao, Defect-balanced active and stable  $Co_3O_{4-x}$  for proton exchange membrane water electrolysis at ampere-level current density, *Energy Environ. Sci.*, 2024, **17**, 4196–4204.
- 9 Z. Li, X. Wu, X. Jiang, B. Shen, Z. Teng, D. Sun, G. Fu and Y. Tang, Surface carbon layer controllable  $Ni_3Fe$  particles confined in hierarchical N-doped carbon framework boosting oxygen evolution reaction, *Adv. Powder Mater.*, 2022, **1**, 100020.
- 10 C. Huang, Y. Huang, C. Liu, Y. Yu and B. Zhang, Integrating Hydrogen Production with Aqueous Selective Semi-Dehydrogenation of Tetrahydroisoquinolines over a  $Ni_2P$  Bifunctional Electrode, *Angew. Chem., Int. Ed.*, 2019, **58**, 12014–12017.
- 11 Z. Zhou, X. Pan, L. Sun, Y. Xie, J. Zheng, L. Li and G. Zhao, Boosting Hydrogen Production *via* Selective Two-electron Mild Electrochemical Oxidation of Tetrahydroisoquinolines Completely to Dihydroisoquinolines, *Angew. Chem., Int. Ed.*, 2023, **62**, e202216347.
- 12 M. Zhong, M. Xu, S. Ren, W. Li, C. Wang, M. Gao and X. Lu, Modulating the electronic structure of  $Ni(OH)_2$  by coupling with low-content Pt for boosting the urea oxidation reaction enables significantly promoted energy-saving hydrogen production, *Energy Environ. Sci.*, 2024, **17**, 1984–1996.
- 13 X. Xu, H. Ullah, M. Humayun, L. Li, X. Zhang, M. Bououdina, D. P. Debecker, K. Huo, D. Wang and C. Wang, Fluorinated Ni-O-C Heterogeneous Catalyst for Efficient Urea-Assisted Hydrogen Production, *Adv. Funct. Mater.*, 2023, **33**, 2303986.
- 14 Q. Qian, J. Zhang, J. Li, Y. Li, X. Jin, Y. Zhu, Y. Liu, Z. Li, A. El-Harairy, C. Xiao, G. Zhang and Y. Xie, Artificial Heterointerfaces Achieve Delicate Reaction Kinetics towards Hydrogen Evolution and Hydrazine Oxidation Catalysis, *Angew. Chem., Int. Ed.*, 2021, **60**, 5984–5993.
- 15 R. A. Senthil, S. Jung, A. Min, A. Kumar, C. J. Moon, M. Singh and M. Y. Choi, Revealing the Impact of Pulsed Laser-Produced Single-Pd Nanoparticles on a Bimetallic  $NiCo_2O_4$  Electrocatalyst for Energy-Saving Hydrogen Production *via* Hybrid Water Electrolysis, *ACS Catal.*, 2024, **14**, 3320–3335.
- 16 T. Y. Burshtein, Y. Yasman, L. Muñoz-Moene, J. H. Zagal and D. Eisenberg, Hydrazine Oxidation Electrocatalysis, *ACS Catal.*, 2024, **14**, 2264–2283.
- 17 T. Wang, X. Cao and L. Jiao, Progress in Hydrogen Production Coupled with Electrochemical Oxidation of Small Molecules, *Angew. Chem., Int. Ed.*, 2022, **61**, e202213328.
- 18 Y. Li, S. Niu, P. Liu, R. Pan, H. Zhang, N. Ahmad, Y. Shi, X. Liang, M. Cheng, S. Chen, J. Du, M. Hu, D. Wang, W. Chen and Y. Li, Ruthenium Nanoclusters and Single Atoms on  $\alpha$ -MoC/N-Doped Carbon Achieves Low-Input/ Input-Free Hydrogen Evolution *via* Decoupled/Coupled Hydrazine Oxidation, *Angew. Chem., Int. Ed.*, 2024, **63**, e202316755.
- 19 Y. Zhu, Y. Chen, Y. Feng, X. Meng, J. Xia and G. Zhang, Constructing Ru-O-TM Bridge in  $NiFe$ -LDH Enables High Current Hydrazine-assisted  $H_2$  Production, *Adv. Mater.*, 2024, **36**, 2401694.
- 20 Y. Liu, J. Zhang, Y. Li, Q. Qian, Z. Li, Y. Zhu and G. Zhang, Manipulating dehydrogenation kinetics through dual-doping  $Co_3N$  electrode enables highly efficient hydrazine oxidation assisting self-powered  $H_2$  production, *Nat. Commun.*, 2020, **11**, 1853.

- 21 H. Y. Wang, L. Wang, J. T. Ren, W. W. Tian, M. L. Sun and Z. Y. Yuan, Heteroatom-Induced Accelerated Kinetics on Nickel Selenide for Highly Efficient Hydrazine-Assisted Water Splitting and Zn-Hydrazine Battery, *Nano-Micro Lett.*, 2023, **15**, 155.
- 22 G. Feng, L. An, B. Li, Y. Zuo, J. Song, F. Ning, N. Jiang, X. Cheng, Y. Zhang and D. Xia, Atomically ordered non-precious  $\text{Co}_3\text{Ta}$  intermetallic nanoparticles as high-performance catalysts for hydrazine electrooxidation, *Nat. Commun.*, 2019, **10**, 4514.
- 23 Y. Hu, T. Chao, Y. Li, P. Liu, T. Zhao, G. Yu, C. Chen, X. Liang, H. Jin, S. Niu, W. Chen, D. Wang and Y. Li, Cooperative Ni(Co)-Ru-P Sites Activate Dehydrogenation for Hydrazine Oxidation Assisting Self-powered  $\text{H}_2$  Production, *Angew. Chem., Int. Ed.*, 2023, **62**, e202308800.
- 24 G. Liu, T. Nie, H. Wang, T. Shen, X. Sun, S. Bai, L. Zheng and Y.-F. Song, Size Sensitivity of Supported Palladium Species on Layered Double Hydroxides for the Electro-oxidation Dehydrogenation of Hydrazine: From Nanoparticles to Nanoclusters and Single Atoms, *ACS Catal.*, 2022, **12**, 10711–10717.
- 25 G. Feng, Y. Pan, D. Su and D. Xia, Constructing Fully-Active and Ultra-Active Sites in High-Entropy Alloy Nanoclusters for Hydrazine Oxidation-Assisted Electrolytic Hydrogen Production, *Adv. Mater.*, 2024, **36**, e2309715.
- 26 Z. Fan, F. Liao, Y. Ji, Y. Liu, H. Huang, D. Wang, K. Yin, H. Yang, M. Ma, W. Zhu, M. Wang, Z. Kang, Y. Li, M. Shao, Z. Hu and Q. Shao, Coupling of nanocrystal hexagonal array and two-dimensional metastable substrate boosts  $\text{H}_2$ -production, *Nat. Commun.*, 2022, **13**, 5828.
- 27 H. Cao, Q. Wang, Z. Zhang, H. M. Yan, H. Zhao, H. B. Yang, B. Liu, J. Li and Y. G. Wang, Engineering Single-Atom Electrocatalysts for Enhancing Kinetics of Acidic Volmer Reaction, *J. Am. Chem. Soc.*, 2023, **145**, 13038–13047.
- 28 G. Fu, H. Liu, N. You, J. Wu, D. Sun, L. Xu, Y. Tang and Y. Chen, The dendritic platinum-copper bimetallic nanoassemblies with tunable composition and structure: arginine driven self-assembly and their enhanced electrocatalytic activity, *Nano Res.*, 2016, **9**, 755–765.
- 29 C. Lin, J.-L. Li, X. Li, S. Yang, W. Luo, Y. Zhang, S.-H. Kim, D.-H. Kim, S. S. Shinde, Y.-F. Li, Z.-P. Liu, Z. Jiang and J.-H. Lee, *In situ* reconstructed Ru atom array on  $\alpha\text{-MnO}_2$  with enhanced performance for acidic water oxidation, *Nat. Catal.*, 2021, **4**, 1012–1023.
- 30 X. Wang, J. Wang, P. Wang, L. Li, X. Zhang, D. Sun, Y. Li, Y. Tang, Y. Wang and G. Fu, Engineering 3d-2p-4f Gradient Orbital Coupling to Enhance Electrocatalytic Oxygen Reduction, *Adv. Mater.*, 2022, **34**, e2206540.
- 31 S. Ning, M. Li, X. Wang, D. Zhang, B. Zhang, C. Wang, D. Sun, Y. Tang, H. Li, K. Sun and G. Fu, Importing Antibonding-Orbital Occupancy through Pd-O-Gd Bridge Promotes Electrocatalytic Oxygen Reduction, *Angew. Chem., Int. Ed.*, 2023, **62**, e202314565.
- 32 L. Zhou, Y. Shao, F. Yin, J. Li, F. Kang and R. Lv, Stabilizing non-iridium active sites by non-stoichiometric oxide for acidic water oxidation at high current density, *Nat. Commun.*, 2023, **14**, 7644.
- 33 Y. Guo, X. Yang, X. Liu, X. Tong and N. Yang, Coupling Methanol Oxidation with Hydrogen Evolution on Bifunctional Co-Doped Rh Electrocatalyst for Efficient Hydrogen Generation, *Adv. Funct. Mater.*, 2022, **33**, 2209134.
- 34 J. Hu, Z. Li, D. Zhao, Z. Han, X. Wu, J. Zhai, Z. Liu, Y. Tang and G. Fu, L-Lysine-induced green synthesis of  $\text{CoS}/\text{Co}_3\text{O}_4$  nanoframes for efficient electrocatalytic oxygen evolution, *Green Chem.*, 2023, **25**, 7309–7317.
- 35 M. Li, X. Wang, K. Liu, H. Sun, D. Sun, K. Huang, Y. Tang, W. Xing, H. Li and G. Fu, Reinforcing Co–O Covalency via Ce(4f)–O(2p)–Co(3d) Gradient Orbital Coupling for High-Efficiency Oxygen Evolution, *Adv. Mater.*, 2023, **35**, 2302462.
- 36 M. Li, X. Wang, D. Zhang, Y. Huang, Y. Shen, F. Pan, J. Lin, W. Yan, D. Sun, K. Huang, Y. Tang, J.-M. Lee, H. Li and G. Fu, Atomic rare earths activate direct O–O coupling in manganese oxide towards electrocatalytic oxygen evolution, *Nano Energy*, 2024, **128**, 109868.
- 37 Y. Huang, M. Li, F. Pan, Z. Zhu, H. Sun, Y. Tang and G. Fu, Plasma-induced Mo-doped  $\text{Co}_3\text{O}_4$  with enriched oxygen vacancies for electrocatalytic oxygen evolution in water splitting, *Carbon Energy*, 2023, **5**, e279.
- 38 Y. Zhu, J. Wang, T. Koketsu, M. Kroschel, J.-M. Chen, S.-Y. Hsu, G. Henkelman, Z. Hu, P. Strasser and J. Ma, Iridium single atoms incorporated in  $\text{Co}_3\text{O}_4$  efficiently catalyze the oxygen evolution in acidic conditions, *Nat. Commun.*, 2022, **13**, 7754.
- 39 Y. Lu, T. Liu, C. L. Dong, Y. C. Huang, Y. Li, J. Chen, Y. Zou and S. Wang, Tuning the Selective Adsorption Site of Biomass on  $\text{Co}_3\text{O}_4$  by Ir Single Atoms for Electrosynthesis, *Adv. Mater.*, 2021, **33**, e2007056.
- 40 X. Huang, C. Lee, Y. Li, J. Xu and D. Liu, Acid-Treated  $\text{RuO}_2/\text{Co}_3\text{O}_4$  Nanostructures for Acidic Oxygen Evolution Reaction Electrocatalysis, *ACS Appl. Nano Mater.*, 2024, **7**, 9244–9251.
- 41 Y. Chen, Y. Liu, W. Zhai, H. Liu, T. Sakthivel, S. Guo and Z. Dai, Metastabilizing the Ruthenium Clusters by Interfacial Oxygen Vacancies for Boosted Water Splitting Electrocatalysis, *Adv. Energy Mater.*, 2024, **14**, 2400059.
- 42 J. Wu, J. Fan, X. Zhao, Y. Wang, D. Wang, H. Liu, L. Gu, Q. Zhang, L. Zheng, D. J. Singh, X. Cui and W. Zheng, Atomically Dispersed  $\text{MoO}_x$  on Rhodium Metallene Boosts Electrocatalyzed Alkaline Hydrogen Evolution, *Angew. Chem., Int. Ed.*, 2022, **61**, 5389.
- 43 B. Zhang, C. Zhu, Z. Wu, E. Stavitski, Y. H. Lui, T.-H. Kim, H. Liu, L. Huang, X. Luan, L. Zhou, K. Jiang, W. Huang, S. Hu, H. Wang and J. S. Francisco, Integrating Rh Species with NiFe-Layered Double Hydroxide for Overall Water Splitting, *Nano Lett.*, 2019, **20**, 136–144.
- 44 J. Gu, L. Li, Y. Xie, B. Chen, F. Tian, Y. Wang, J. Zhong, J. Shen and J. Lu, Turing structuring with multiple nanotwins to engineer efficient and stable catalysts for hydrogen evolution reaction, *Nat. Commun.*, 2023, **14**, 5389.
- 45 Y. Zhao, N. Jia, X.-R. Wu, F.-M. Li, P. Chen, P.-J. Jin, S. Yin and Y. Chen, Rhodium phosphide ultrathin nanosheets for hydrazine oxidation boosted electrochemical water splitting, *Appl. Catal., B*, 2020, **270**, 118880.
- 46 W. Zhu, F. Yao, K. Cheng, M. Zhao, C.-J. Yang, C.-L. Dong, Q. Hong, Q. Jiang, Z. Wang and H. Liang, Direct Dioxygen



- Radical Coupling Driven by Octahedral Ruthenium–Oxygen–Cobalt Collaborative Coordination for Acidic Oxygen Evolution Reaction, *J. Am. Chem. Soc.*, 2023, **145**, 17995–18006.
- 47 Y. Zhai, C. Jin, Q. Xia, W. Han, J. Wu, X. Zhao and X. Zhang, Atomically Confined Ru Sites in Octahedral  $\text{Co}_3\text{O}_4$  for High-Efficiency Hydrazine Oxidation, *Adv. Funct. Mater.*, 2023, **34**, 2311063.
- 48 L. Qiao, D. Liu, A. Zhu, J. Feng, P. Zhou, C. Liu, K. W. Ng and H. Pan, Nickel-facilitated *in situ* surface reconstruction on spinel  $\text{Co}_3\text{O}_4$  for enhanced electrochemical nitrate reduction to ammonia, *Appl. Catal., B*, 2024, **340**, 123219.
- 49 Q. Meng, Y. Hou, F. Yang, C. Cao, Z. Zou, J. Luo, W. Zhou, Z. Tong, S. Chen, S. Zhou, J. Wang and S. Deng, Modulation of surface properties on cobalt phosphide for high-performance ambient ammonia electrosynthesis, *Appl. Catal., B*, 2022, **303**, 120874.
- 50 W. Zheng, M. Liu and L. Y. S. Lee, Electrochemical Instability of Metal–Organic Frameworks: *In Situ* Spectroelectrochemical Investigation of the Real Active Sites, *ACS Catal.*, 2019, **10**, 81–92.
- 51 G. Meng, Z. Chang, L. Zhu, C. Chen, Y. Chen, H. Tian, W. Luo, W. Sun, X. Cui and J. Shi, Adsorption Site Regulations of [W–O]-Doped CoP Boosting the Hydrazine Oxidation-Coupled Hydrogen Evolution at Elevated Current Density, *Nano-Micro Lett.*, 2023, **15**, 212.
- 52 Y. Li, X. Wang, Y. Wang, Z. Shi, Y. Yang, T. Zhao, Z. Jiang, C. Liu, W. Xing and J. Ge, The decisive role of adsorbed  $\text{OH}^*$  in low-potential CO electro-oxidation on single-atom catalytic sites, *Carbon Energy*, 2023, **5**, e310.