Supplementary Information for

Rational strain engineering of single-atom ruthenium on nanoporous MoS$_2$ for highly efficient hydrogen evolution

Jiang et al.
Supplementary Figure 1. The calculation of formation energy.

(a) Formation energy of S-vacancy in 1T-MoS$_2$. (b) 1) Formation energy of Ru atom replaces Mo site. 2) Formation energy of S-vacancy in Ru/1T-MoS$_2$.

The formation energy ($E_f$) of Ru atom replaces Mo site was calculated as following equation:

$$E_f = E_{doped} - E_{perfect} + (\mu_{Mo} - \mu_{Ru})$$

Where, $E_{doped}$, $E_{perfect}$, $\mu_{Mo}$, and $\mu_{Ru}$ are the total energy for MoS$_2$ with Ru doped, the total energy for perfect MoS$_2$, the chemical potential for Mo, and the chemical potential for Ru, respectively.

The formation energy ($E_f$) for S-vacancy in 1T-MoS$_2$ was calculated as following equation:

$$E_f = E_{SV} + \mu_S - E_{perfect}$$

Where, $E_{SV}$, $\mu_S$, and $E_{perfect}$ are the total energy for MoS$_2$ with S-vacancy, the chemical potential for S, and the total energy for perfect MoS$_2$, respectively.

The formation energy ($E_f$) for S-vacancy in Ru/1T-MoS$_2$ was calculated as following equation:

$$E_f = E_{Ru/SV} + \mu_S - E_{Ru/perfect}$$

Where, $E_{Ru/SV}$, $\mu_S$, and $E_{Ru/perfect}$ are the total energy for Ru/1T-MoS$_2$ with S-vacancy, the chemical potential for S, and the total energy for perfect Ru/1T-MoS$_2$, respectively.

In the formation energy calculations, we need to calculate the chemical potential of Mo, Ru, and S atoms. In this paper, the calculated chemical potentials are equal to the DFT total energies of their ground states (Ref. 1).
Supplementary Figure 2. The calculations of H₂O adsorption energy.

The calculations of H₂O adsorption energy at different sites on the surface of Ru/MoS₂ before and after the applied strain.
Supplementary Figure 3. DFT calculations.

Calculated free energy profiles of alkaline HER.
Supplementary Figure 4. DFT model.

H adsorption on different atom sites of Ru/MoS$_2$. 
Supplementary Figure 5. DFT model.

H adsorption on different atom sites of strained Ru/MoS$_2$. 

![Strained Ru site](image1)
![Strained Mo site](image2)
![Strained S site](image3)
Supplementary Figure 6. Schematic illustration of the preparation of np-MoS$_2$.

(a) SEM image of nanoporous Au. (b) Corresponding EDS spectrum. Inset: the compositions of nanoporous Au result from EDS analyses. (c) Schematic illustration of the preparation of np-MoS$_2$. Scale bar: 200 nm.

NPG were prepared by chemically dealloying (Supplementary Fig. 6a) (Ref. 2). Specifically, the Au$_{35}$Ag$_{65}$ alloy were etched by HNO$_3$ (69 vol.%) at room temperature for 10 h, in which the Ag component were selectively leach while Au were remained to form the nanoporous structure (Supplementary Fig. 6b). The as-prepared NPG were washed three times with water to remove the residual acid in the nanopore channels. Afterwards, we use the NPG as a support on which Mo(CO)$_6$ vapor decomposes to form the Mo/Au surface alloy (Supplementary Fig. 6c) (Ref. 3). Under atmospheric pressure, the sulfidation of Mo/Au surface alloy were occurred by using S powder as a sulfur source. After sulfidation, a few layers of MoS$_2$ were group up on the surface of NPG to form the MoS$_2$-NPG hybrid materials. Finally, the np-MoS$_2$ were obtained by etching the Au component with I$_2$-KI solution.
Supplementary Figure 7. SEM characterizations of np-MoS$_2$ and Ru/np-MoS$_2$.

SEM images of np-MoS$_2$ (a) and Ru/np-MoS$_2$ (b). (c) The compositions of np-MoS$_2$ and Ru/np-MoS$_2$ result from EDS analyses. (d) The average diameters of ligament for np-MoS$_2$ and Ru/np-MoS$_2$. Error bars represent the standard deviation from multiple measurements. Scale bars: (a, b) 500 nm.
Supplementary Figure 8. TEM characterizations of Ru/np-MoS$_2$.

TEM image of Ru/np-MoS$_2$, showing the nanotube-shaped ligaments. Scale bar: 100 nm.
Supplementary Figure 9. XAS characterizations of np-MoS$_2$ and Ru(np-MoS$_2$).

Mo L$_{3}$-edge XANES spectra of np-MoS$_2$ and Ru(np-MoS$_2$).

The Mo L$_{3}$- and S K-edges (Fig. 2e) XANES spectra were measured by using the Lytle detector under TFY mode.
Supplementary Figure 10. HAADF-STEM characterizations of Ru/P-MoS₂.

HAADF-STEM image of Ru/P-MoS₂, showing a few layers of MoS₂. Scale bar: 50 nm.
Supplementary Figure 11. HAADF-STEM characterizations of strain.

Representative HAADF-STEM images at unstrained region (Ru/P-MoS$_2$) and strained region (Ru/np-MoS$_2$). Their intensity profile analyses were shown below the images.
Supplementary Figure 12. STEM-EDX element mapping.

STEM image and corresponding STEM-EDX element mapping of Ru/np-MoS$_2$. Scale bar: 100 nm.
Supplementary Figure 13. HAADF-STEM characterizations of Ru_{np}/np-MoS₂.

HAADF-STEM image of Ru_{np}/np-MoS₂ (a), showing that Ru nanoparticles are uniformly distributed on the ligament of np-MoS₂ with an average diameter of ~6.25 nm (b). Magnified HAADF-STEM image of Ru_{np}/np-MoS₂ (c), showing many Ru nanoparticles and clusters on the surface of MoS₂. Scale bars: (a) 20 nm, (b) 10 nm.
Supplementary Figure 14. FT-EXAFS fitting curves of Ru/np-MoS$_2$.

The local atomic structure of Ru in Ru/np-MoS$_2$ derived by EXAFS fitting matches well with the Ru-S4 model, suggesting the loss of two S atoms around Ru atom thus forming the SVs. The emerge of Ru-Mo bond with a bond length of 2.85 Å in Ru/np-MoS$_2$ indicates the substitutional doping of Ru atom in 1T-MoS$_2$ (Ref. 4).

Note: R represents the interatomic distance; CN represents the coordination number; $\sigma^2$ represents the Debye-Waller factor; $\Delta E_0$ represents the edge-energy shift.
Supplementary Figure 15. Spectral features of Mo K-edge XANES spectra.

Spectral features of Mo K-edge XANES spectra of np-MoS$_2$ and Ru/np-MoS$_2$. 
Supplementary Figure 16. XPS characterizations of np-MoS$_2$ and Ru/np-MoS$_2$.

High-resolution Au 4f (a), Mo 3d (b), and S 2p (c) XPS data of Ru/np-MoS$_2$. The XPS data of np-MoS$_2$ are also shown as a reference. (d) The compositions of np-MoS$_2$ and Ru/np-MoS$_2$ result from XPS analyses.

As shown in Supplementary Figure 16b, the Mo 3d peaks of np-MoS$_2$ shows the negative energy shifts as comparison with that of 2H-MoS$_2$ (Ref. 5), indicating the co-existence of 2H-MoS$_2$ and 1T-MoS$_2$ in np-MoS$_2$. After the introduction of Ru atoms, the Mo 3d peaks of Ru/np-MoS$_2$ displays the further negative energy shifts as comparison with that of np-MoS$_2$, suggesting the increase of 1T-MoS$_2$ in Ru/np-MoS$_2$. 
Supplementary Figure 17. SEM characterizations of Ru/Lnp-MoS$_2$.

(a) SEM image of Ru/Lnp-MoS$_2$. (b) The average diameters of ligament for Ru/Lnp-MoS$_2$. Error bars represent the standard deviation from multiple measurements. Scale bar: 500 nm.
Supplementary Figure 18. Characterizations of Ru content.

The Ru contents of Ru/np-MoS\textsubscript{2}, Ru/P-MoS\textsubscript{2}, and Ru/Lnp-MoS\textsubscript{2} result from EDS analyses.

The Ru content in this work is relatively high compared with the works reported so far (Supplementary Table 2). For the common synthesis strategy of single-atom catalysts, the numbers of defect or anchoring ligand always limit the metal load. However, the isolated metal atoms are substitutional doped into the MoS\textsubscript{2} in the spontaneous reduction strategy, thus avoiding the limitation of the number of defect or anchoring ligand. This is main responsible for the high metal content in the catalysts prepared by spontaneous reduction strategy.
Supplementary Figure 19. Characterizations for Ru/P-MoS$_2$ and Ru/Lnp-MoS$_2$.

CVs of Ru/P-MoS$_2$ (a), Ru/Lnp-MoS$_2$ (d), and Ru/np-MoS$_2$ (g) measured in non-Faradaic region. (b, e, h) The corresponding plots of current densities against scan rates. $\Delta j$ is the difference between anodic and cathodic current densities at a same potential. The half of the value of the slope is used as the double-layer capacitance of electrodes. (c, f, i) The compositions of Ru/P-MoS$_2$, Ru/Lnp-MoS$_2$, and Ru/np-MoS$_2$ resulting from EDS analyses.
Supplementary Figure 20. Electrochemical impedance spectroscopy analyses.

Nyquist plots of np-MoS$_2$ and Ru/np-MoS$_2$ at the overpotential of 30 mV.
Supplementary Figure 21. Double-layer capacitance measurements.

CVs of np-MoS$_2$ (a) and Lnp-MoS$_2$ (c) measured in non-Faradaic region. (b, d) The corresponding plots of current densities against scan rates. $\Delta j$ is the difference between anodic and cathodic current densities at a same potential. The half of the value of the slope is used as the double-layer capacitance of electrodes.
Supplementary Figure 22. Catalytic HER performances.

Polarization curves of Ru/Lnp-MoS$_2$ and Ru/np-MoS$_2$ as compared with that of Lnp-MoS$_2$ and np-MoS$_2$ in alkaline (a) and acidic (d) solutions. (b, e) Corresponding ECSA-normalized polarization curves. The increment of ECSA-normalized current density (at -0.10 V vs. RHE) after the formation of local Ru/1T-MoS$_2$ active structure for Ru/Lnp-MoS$_2$ and Ru/np-MoS$_2$ in alkaline (c) and acidic (f) solutions. $j$ represents the current density.
Supplementary Figure 23. XPS characterizations.

High-resolution Ru 3p (a), Mo 3d (b), and S 2p (c) XPS data of Ru/np-MoS$_2$ and Ru/Lnp-MoS$_2$. 
Supplementary Figure 24. Faradaic efficiency measurements for H₂ production.

Faradaic efficiencies of Ru/np-MoS₂ for H₂ production at different applied potentials.

Inset shows the device for Faradaic efficiency measurements. Error bars represent the standard deviation from multiple measurements.
Supplementary Figure 25. XAS characterizations after long-time operation.

(a, c) XANES spectra at Ru K- and Mo K-edges. (b, d) Corresponding FT-EXAFS spectra at Ru K- and Mo K-edges.

The FT-EXAFS spectra at Ru K-edges show the negative-shift of Ru-Mo peak after long-time operation, indicating the shrinkage of interatomic distance between Ru atoms and Mo atoms. This irreversible shrinkage structure may be able to stabilize the isolated Ru atoms. The operation for a long-time also lead to the slight changes in oxidation state and structure of np-MoS$_2$, manifesting as the positive-shift of rising edge in XANES spectra at Mo-K edge and the low-R shift of Mo-S peak in corresponding FT-EXAFS spectra.
Supplementary Figure 26. The fitted average oxidation states.

The fitted average oxidation states of Ru from XANES spectra.

In the determining of oxidation state of Ru, we analyzed the absorption energy, which was obtained from the first maximum in the first-order derivative as the electron vacancy. The RuCl$_3$ (+3) and RuO$_2$ (+4) were used as the comparison standards.
Supplementary Figure 2.7. Operando Ru K-edge FT-EXAFS spectra.

The FT-EXAFS spectra of Ru/np-MoS$_2$ recorded at different applied voltages.
Supplementary Figure 28. Magnified rising edge XANES regions.

Magnified rising edge XANES regions recorded at the Mo K-edge of np-MoS\textsubscript{2} and Ru/np-MoS\textsubscript{2}.
Supplementary Figure 29. The device for AP-XPS measurements.

AP-XPS measurements were performed at on the 24A1 beamline of NSRRC. In order to ensure the accuracy of the experiment, we prepared an np-MoS$_2$ material and cut it into two identical np-MoS$_2$ films (inset of Supplementary Fig. 29). One of them was used as an undoped sample (np-MoS$_2$) while another one was used as support for Ru doping (Ru/np-MoS$_2$). The Ru/np-MoS$_2$ film, np-MoS$_2$ film, and Au foil were directly covered on the carbon conductive adhesive, thus avoiding the influence of carbon conductive adhesive signal. Then, the sample holder loaded with Ru/np-MoS$_2$ film, np-MoS$_2$ film, and Au foil was exposed in the analysis chamber. The AP-XPS analyses were conducted under UHV, a water pressure of 0.01 torr, and a water pressure of 0.1 torr, respectively. The obtained XPS data were corrected by using the Au 4f XPS spectrum of Au foil.
Supplementary Figure 30. AP-XPS measurements.

In order to acquire accurate results, we performed two AP-XPS measurements. Similar results were obtained in the two tests, which further proved the accuracy of the results. It is distinct that the O 1s XPS spectra of Ru/np-MoS\textsubscript{2} display obvious high-energy shifts with the increase of water pressure, resulting from the increase contribution of adsorbed water (Ads. H\textsubscript{2}O) (Fig. 5g). Therefore, it is deduced that Ru/np-MoS\textsubscript{2} own stronger water affinity than np-MoS\textsubscript{2} due to the formation of strained SVs, which expose strained Mo sites as optimal water adsorption sites in Ru/np-MoS\textsubscript{2}. Even though there are hydrophilic Ru atoms in Ru/np-MoS\textsubscript{2}, Mo atoms contribute more water adsorption sites due to the low content of Ru atoms (Note that the H\textsubscript{2}O adsorption energy of strained Mo sites is close to that of strained Ru sites, as shown in Supplementary Fig. 2).
Supplementary Note 1: DFT calculations.

DFT calculations were performed by using the Vienna Ab Initio Simulation Package (VASP). The projector augmented wave (PAW) method was conducted to describe/treat interactions between the valence electrons and the ion cores. The exchange correlation energy was modelled using Perdew-Burke-Ernzerhof (PBE) functional within the generalized gradient approximation (GGA). The cut-off energy was set to 450 eV and employed for the expansion of the wave functions. During structural optimization and the self-consistent calculations, the Brillouin zone (BZ) was sampled by a Monkhorst-Pack k-mesh of 5×5×1. A vacuum layer of 20 Å was added perpendicular to the slab surface. The van der Waals interactions are taking account by employing DFT-D3 (BJ) method developed by S. Grimme et al. (Ref. 6, 7).

A unit cell (4×4×1) of 1T-MoS$_2$ was select to establish the model. For the Ru/1T-MoS$_2$ model, the Ru atom was exposed on the surface of 1T-MoS$_2$ by replacing a Mo atom and losing two S atoms. Usually, the adatom or dopant cannot change the lattice structure of the MoS$_2$, but causing local distortions. Thus, while we optimize the structures, we keep the lattice structure stable and optimize the positions of atoms. The unit cell was optimized until the force and total energy were set to be 0.01 eV/Å and $10^{-5}$ eV, respectively. For the application of strain, our preliminary work before this work suggests that the np-MoS$_2$ experience tensile strain (about 10%) originated from the nanotube-shaped ligament (Ref. 8, 9). Ideally, the uniaxial tensile strain (10%) was applied on the above model. The subsequent HAADF-STEM
characterizations show that the value of tensile strain is about 12% (Fig. 2g).

The generally accepted alkaline HER mechanism consists of two steps, with the Volmer step followed by the Tafel step or Heyrovsky step:

**Volmer step:** cat + H₂O + e⁻ → H⁺@cat + OH⁻ (Equation 1)

**Tafel step:** 2H⁺@cat → H₂ (Equation 2)

**Heyrovsky step:** H⁺@cat + H₂O + e⁻ → cat + OH⁻ + H₂ (Equation 3)

The free energies of step (1) and step (3) should be the same at equilibrium potential.

Computations on the exact free energy of OH⁻ in solutions could be avoided by using computational hydrogen electrode based on the above assumption (Ref. 10).

The free energies (ΔG) of steps 1-3 are calculated using the following equation adopted from Ref. 11:

\[ ΔG = ΔE + ΔZPE + ΔU(0 → T) − TΔS \] (Equation 4)

Where, ΔE, ΔZPE, ΔU(0→T), and TΔS are the adsorption energy of adsorbed species on the given unit cell, the differences corresponding to the zero-point energy, the difference of the correction to the thermal energy, and the differences corresponding to the entropy (at 298.15 K), respectively. ΔZPE could be derived after frequency calculation by the following equation: (Ref. 12):

\[ ZPE = \frac{1}{2} ∑ hν_i \] (Equation 5)

Where h is the Planck constant, ν_i are the computed vibrational frequencies.

The thermal energy correction is calculated by the following equation:

\[ U(0 → T) = ∑ \frac{hν_i}{\exp(βhν_i) − 1} \] (Equation 6)

The TS values of adsorbed species are calculated in the following equation (Ref. 11,
Where $\beta = 1/\kappa T$, $\{v_i\}$ are vibrational modes, $\kappa$ is the Boltzmann constant, $T$ is the temperature (which is set to 298 K in the present work), respectively. In the present study, the Gibbs free energy is calculated using VASPKIT, and the frequencies below 50 cm$^{-1}$ are approximately equal to 50 cm$^{-1}$ during the calculations of the vibration contributions to the adsorbed molecular free energy correction (Ref. 15).
Supplementary Note 2: The syntheses of Ru/P-MoS$_2$ and Ru/Lnp-MoS$_2$

The P-MoS$_2$ was synthesized by using Au foil as substrates for the chemical vapor deposition of monolayer MoS$_2$. Then, the monolayer MoS$_2$@Au composites were etched by I$_2$-KI solution for 24 h to obtain the P-MoS$_2$. The Lnp-MoS$_2$ was synthesized by using the same method as np-MoS$_2$, excepting for increasing the heat preservation of NPG before the sulfidation. This leads to the coarsening of NPG ligament, thus providing the templates with large ligament for the growth of the monolayer MoS$_2$. Finally, Ru/P-MoS$_2$ and Ru/Lnp-MoS$_2$ with the same Ru load to Ru/np-MoS$_2$ were prepared by using the spontaneous reduction technique.
Supplementary Note 3: Calculation of ECSA.

The real surface area of catalysts for HER was calculated from the ECSA, which can be converted from the specific capacitance. The specific capacitance for a flat surface is generally found to be in the range of 20-60 μF cm$^2_{geo}$.

$$A_{ECSA} = \frac{\text{specific capacitance}}{60 \ \mu\text{F cm}^2_{geometric \ per \ cm}^2_{ECSA}}$$

The ECSA of Ru/np-MoS$_2$, Ru/P-MoS$_2$, and Ru/Lnp-MoS$_2$ were calculated as follow:

$$A_{ECSA}^{Ru/np-MoS_2} = \frac{15.35 \text{ mF cm}^{-2}}{60 \ \mu\text{F cm}^2_{geometric \ per \ cm}^2_{ECSA}} = 255.83 \ \text{cm}^2_{ECSA}$$

$$A_{ECSA}^{Ru/P-MoS_2} = \frac{7.95 \text{ mF cm}^{-2}}{60 \ \mu\text{F cm}^2_{geometric \ per \ cm}^2_{ECSA}} = 132.50 \ \text{cm}^2_{ECSA}$$

$$A_{ECSA}^{Ru/Lnp-MoS_2} = \frac{10.30 \text{ mF cm}^{-2}}{60 \ \mu\text{F cm}^2_{geometric \ per \ cm}^2_{ECSA}} = 171.67 \ \text{cm}^2_{ECSA}$$

The ECSA of np-MoS$_2$ and Lnp-MoS$_2$ were calculated as follow:

$$A_{ECSA}^{np-MoS_2} = \frac{7.35 \text{ mF cm}^{-2}}{60 \ \mu\text{F cm}^2_{geometric \ per \ cm}^2_{ECSA}} = 122.50 \ \text{cm}^2_{ECSA}$$

$$A_{ECSA}^{Lnp-MoS_2} = \frac{4.05 \text{ mF cm}^{-2}}{60 \ \mu\text{F cm}^2_{geometric \ per \ cm}^2_{ECSA}} = 67.5 \ \text{cm}^2_{ECSA}$$
**Supplementary Table 1.** Key values for water dissociation and hydrogen generation on the surface of different models.

| Models         | $\Delta E(H_2O)/eV$ | $\Delta ZPE(H_2O)+U_{(0\rightarrow T_f)}(H_2O)/eV$ | $\Delta S(H_2O)/eV$ | $\Delta G(H_2O)/eV$ |
|----------------|----------------------|---------------------------------------------------|---------------------|---------------------|
| Ru/MoS$_2$     | 0.295                | 0.590+0.102                                       | 0.236               | 0.751               |
| Strained Ru/MoS$_2$ | -0.154            | 0.602+0.064                                       | 0.128               | 0.384               |
| Models         | $\Delta E(H^*)/eV$  | $\Delta ZPE(H^*)+U_{(0\rightarrow T_f)}(H^*)/eV$ | $\Delta S(H^*)/eV$ | $\Delta G(H^*)/eV$ |
| Ru sites       | 0.557                | 0.224+0.010                                       | 0.013               | 0.778               |
| Mo sites       | 0.596                | 0.267+0.005                                       | 0.006               | 0.862               |
| S sites        | 0.945                | 0.208+0.013                                       | 0.018               | 1.148               |
| Strained Ru sites | -0.035            | 0.227+0.008                                       | 0.011               | 0.189               |
| Strained Mo sites | 0.651              | 0.175+0.008                                       | 0.012               | 0.822               |
| Strained S sites | 0.459              | 0.211+0.012                                       | 0.017               | 0.665               |
**Supplementary Table 2.** Structural parameters extracted from the Mo K-edge EXAFS fitting.

| Catalysts | Scattering pair | \( CN \) | \( R (\text{Å}) \) | \( \sigma^2 (10^{-3} \text{ Å}^2) \) | \( \Delta E_0 \) (eV) | R-factor |
|-----------|-----------------|----------|-----------------|-----------------|-----------------|----------|
| P-MoS\(_2\) | Mo-S             | 5.1±0.7  | 2.400±0.01      | 1.55±0.8        | 0.272           | 0.005    |
|           | Mo-Mo            | 3.9±0.5  | 3.149±0.01      | 2.48±0.8        | -2.14           |          |
| Lnp-MoS\(_2\) | Mo-S             | 5.9±0.5  | 2.405±0.01      | 2.63±0.6        | 2.53            | 0.008    |
|           | Mo-Mo            | 4.1±0.4  | 3.161±0.01      | 3.70±0.6        | 2.43            |          |
| np-MoS\(_2\) | Mo-S             | 5.7±0.7  | 2.408±0.01      | 2.66±1.3        | 2.77            | 0.010    |
|           | Mo-Mo            | 4.1±0.5  | 3.169±0.01      | 3.42±1.3        | 2.90            |          |

\( CN \) represents the coordination number; \( R \) represents the interatomic distance; \( \sigma^2 \) represents the Debye-Waller factor; \( \Delta E_0 \) represents the edge-energy shift.
### Supplementary Table 3. Comparison of overpotential at 10 mA cm$^{-2}$ and Tafel slope of Ru/np-MoS$_2$ with recently reported SACs and MoS$_2$-based catalysts.

| Catalysts         | Metal content | Electrolyte   | $\eta$@10 mA cm$^{-2}$ (mV) | Tafel slope (mV dec$^{-1}$) | Ref.   |
|-------------------|---------------|---------------|-----------------------------|-----------------------------|-------|
| Ru/np-MoS$_2$     | Ru: 7.94 at%  | 1.0 M KOH     | 30                          | 31                          | This work |
| Ru/C              | 20 wt%        | 1.0 M KOH     | 100                         | 69                          | This work |
| Pt/C              | 20 wt%        | 1.0 M KOH     | 40                          | 46                          | This work |
| NiO@IT-MoS$_2$    | Ni: 4.99 wt%  | 1.0 M KOH     | 46                          | 52                          | 16     |
| C-MoS$_2$         |               | 1.0 M KOH     | 45                          | 46                          | 17     |
| N, Mn-MoS$_2$     | Mn: 3.49 at%  | 1.0 M KOH     | 66                          | 50                          | 18     |
| Ir-MoS$_2$        | Ir: 11.75 at% | 1.0 M KOH     | 44                          | 32                          | 19     |
| Ni-MoS$_2$        | Ni: 13.3 at%  | 1.0 M KOH     | 98                          | 60                          | 20     |
| Ru-MoS$_2$/CNT    | Ru: ~5 at%    | 1.0 M KOH     | 50                          | 62                          | 21     |
| Ni(OH)$_2$/MoS$_2$|               | 1.0 M KOH     | 80                          | 60                          | 22     |
| Pt@PCM            | Pt: 0.53 wt%  | 1.0 M KOH     | 139                         | 73.6                        | 23     |
| Ni NP|Ni-N-C/EG        | Ni: 11.8 wt%  | 1.0 M KOH     | 147                         | 114                        | 24     |
| SA-Ru-MoS$_2$     | Ru: 2.29 at%  | 1.0 M KOH     | 76                          | 21                          | 25     |
| Mo SAs/ML-MoS$_2$ | Mo: 1.23 at%  | 1.0 M KOH     | 209                         | 35.1                        | 26     |
| Co-MoS$_2$/BCCF-21| Co: 1.62 at%  | 1.0 M KOH     | 48                          | 52                          | 27     |
| Pd, Ru-MoS$_2$$_2$OH$_y$ | Ru: ~2 at% | 1.0 M KOH     | 48                          | 45                          | 28     |
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