


 Cite this: *RSC Adv.*, 2021, 11, 19630

Heterostructure Ni₃S₄–MoS₂ with interfacial electron redistribution used for enhancing hydrogen evolution†

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Developing highly effective and inexpensive electrocatalysts for hydrogen evolution reaction (HER), particularly in a water-alkaline electrolyzer, are crucial to large-scale industrialization. The earth-abundant molybdenum disulfide (MoS₂) is an ideal electrocatalyst in acidic media but suffers from a high overpotential in alkaline solution. Herein, nanospherical heterostructure Ni₃S₄–MoS₂ was obtained via a one-pot synthesis method, in which Ni₃S₄ was uniformly integrated with MoS₂ ultrathin nanosheets. There were abundant heterojunctions in the as-synthesized catalyst, which were verified by X-ray photoelectron spectroscopy (XPS) and high-resolution transmission electron microscopy (HRTEM). The structure features with interfacial electron redistribution was proved by XPS and density functional theory (DFT) calculations, which offered several advantages to promote the HER activity of MoS₂, including increased specific surface area, exposed abundant active edge sites and improved electron transfer. Ni₃S₄–MoS₂ exhibited a low overpotential of 116 mV at 10 mA cm⁻² in an alkaline solution with a corresponding Tafel slope of 81 mV dec⁻¹ and long-term stability of over 20 h. DFT simulations indicated that the synergistic effects in the system with the chemisorption of H on the (002) plane of MoS₂ and OH on the (311) plane of Ni₃S₄ accelerated the rate-determining water dissociation steps of HER. This study provides a valuable route for the design and synthesis of inexpensive and efficient HER electrocatalyst, heterostructure Ni₃S₄–MoS₂.

Received 12th April 2021

Accepted 17th May 2021

DOI: 10.1039/d1ra02828f

rsc.li/rsc-advances

Introduction

With the increasing environmental protection demands, developing sustainable and fossil-free renewable energy plays a major role.¹ Due to its environmentally friendly, zero-emission, high-energy capacity and sustainable merits, hydrogen (H₂) has received extensive attention.² The most efficient method to generate H₂ (2H₂O → 2H₂ + O₂) is water splitting by electric power generated from renewable energy sources.^{3–5} Currently, some noble metals, such as Pt, Rh and Ir, have been proved to possess excellent catalytic performance as HER electrocatalysts, including low overpotential, low Tafel slope and low impedance.^{6,7} However, the exorbitant cost and limited earth abundance of these noble metal materials have hindered their industrialization and commercialization.⁸ Therefore, developing electrocatalysts that are low cost, highly

active and stable from nonprecious and earth-abundant metal materials is urgent.

In recent years, earth-abundant 2D MoS₂ has been considered as an ideal alternative to the precious Pt-based catalysts as the next-generation electrocatalytic material due to its unique structure and chemical properties.^{9–11} DFT calculations indicated that MoS₂ exhibits excellent HER performance in acidic solutions since its edge sites permit a near-optimal hydrogen adsorption free energy (ΔG_{H*} = 0.08 eV).¹² Moreover, the tremendous amount of S sites in the basal plane of pure MoS₂ are quite inert and not sufficiently utilized.¹³ Unfortunately, MoS₂ has also been found to have poor activity in alkaline media,¹⁴ even though alkaline catalysis is a more widespread application. Numerous strategies have been employed to improve the catalytic activity of 2D MoS₂, such as generating the sulfur vacancies,¹⁵ introducing heteroatoms,¹⁶ changing conductive supports.¹⁷ It has been both experimentally and theoretically identified that the fabrication of heterogeneous nanostructures with abundant and accessible exposed active sites is a very effective way for improving the catalytic activity.¹⁸

MoS₂ decorated with transition metals, such as Fe, Co and Ni, by heterostructure engineering has shown excellent electrocatalytic performance.¹⁹ Because of the versatile electronic structure of these metals and the ability to fill d orbitals with

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† Electronic supplementary information (ESI) available. See DOI: 10.1039/d1ra02828f



electrons from another transition metal, they provide distinctive catalytic properties. For example, nickel-based catalysts have been shown to have impressive potential for HER electrocatalysts due to their conductivity and low cost.^{20,21} Some reports have indicated that constructing heterostructure for MoS₂ *via* introducing nickel sulfides (*e.g.*, Ni₃S₂,²² NiS₂ (ref. 23) and NiS²⁴) could provide superior HER activity. However, the intrinsic motivation of the enhanced catalytic performance is not clear. Moreover, the impact of constructing a heterogeneous structure *via* introducing Ni₃S₄ into MoS₂ on HER performance remains to be studied. Moreover, an in-depth understanding of the interfacial electron redistribution for the improved HER performance is important for its wide application.

In this study, we fabricated the heterostructure Ni₃S₄-MoS₂ with a nanospherical morphology *via* a one-step hydrothermal strategy and applied it as an HER catalyst. To improve the electronic conductivity and expose abundant active edge sites of MoS₂, we constructed the heterostructure *via* introducing Ni₃S₄ into MoS₂ ultra-thin nanosheets, which significantly enhanced the HER activity. The heterostructure of Ni₃S₄-MoS₂ was investigated *via* XPS, SEM and HRTEM techniques. For researching the electron redistribution on the interface of Ni₃S₄-MoS₂ and the mechanism of electro-catalysis during HER, we also applied the DFT simulation. It is indicated that the heterostructure Ni₃S₄-MoS₂ optimized water dissociation energies and H* absorption free energy.

Experimental section

Materials

Sodium molybdate (vi) dihydrate (Na₂MoO₄·2H₂O), nickel(ii) chloride hexahydrate (NiCl₂·6H₂O), urea, sodium sulfide nonahydrate (Na₂S·9H₂O) and thiourea (CH₄N₂S) were obtained from Beijing Chemical Works. A 5 wt% Nafion solution was obtained from Du Pont China Holding Co., Ltd. A nickel foam (NF) having a thickness of 0.5 mm was bought from Changsha Lyrun New Materials Co., Ltd., and it (cut as 1.0 cm × 1.0 cm in size) was washed with hydrochloric acid, ethanol and deionized water. All other chemicals were of analytical grade and were purchased from Sinopharm Chemical Reagents Co. All chemicals were used without further purification.

Synthesis of MoS₂, Ni₃S₄-MoS₂ and Ni₄S₃ nanosheets

3.5 mmol (0.847 g) of Na₂MoO₄·2H₂O and 15 mmol (1.14 g) of thiourea were dissolved in 30 mL of deionized water and dispersed by ultrasonication for 10 min to form a uniform solution. The mixture was transferred into a 50 mL Teflon-lined stainless-steel autoclave and maintained at 180 °C for 24 h. The as-prepared MoS₂ was washed with deionized water and ethanol several times and then dried in a vacuum at 60 °C. Ni₃S₄-MoS₂ was synthesized by a simple one-pot step method that was the same as the above process for MoS₂. However, in the Na₂MoO₄·2H₂O and thiourea mixed solution, different amounts of NiCl₂·6H₂O were added. Then, the Ni₃S₄-MoS₂ nanosheets were obtained after the same hydrothermal treatment, washing and drying.

Ni₃S₄ was prepared according to the method in the reported literature.²⁵ Briefly, 1.5 mmol (0.357 g) of NiCl₂·6H₂O and 10 mmol (0.60 g) of urea were dissolved in 30 mL deionized water, and the mixture was dispersed by ultrasonication for 10 min to form a uniform solution. The solution was then transferred into a 50 mL Teflon-lined stainless-steel autoclave and maintained at 130 °C for 2 h. The as-prepared Ni(OH)₂ was washed with deionized water and ethanol several times and then dried in a vacuum at 60 °C. Then, the as-prepared Ni(OH)₂ precursor together with 30 mL of 15 mmol (3.6 g) sodium sulfide (Na₂S·9H₂O) aqueous solution was placed in the Teflon-lined stainless-steel autoclave and maintained at 90 °C for 9 h. The as-prepared Ni₃S₄ was washed with deionized water and ethanol several times and then dried in a vacuum at 60 °C for 12 h.

Characterization

X-ray diffraction (XRD) patterns were collected on a Rigaku XRD-6000 diffractometer using Cu K α radiation from 3° to 80° at the scan rate of 10° min⁻¹. The morphologies were investigated *via* SEM (Zeiss SUPRA 55) at an accelerating voltage of 20 kV. A Brunauer-Emmett-Teller (BET, ASAP 2460) apparatus was used to measure the surface area. HRTEM images were recorded using a JEOL JEM-2010 field-emission transmission electron microscope at an accelerating voltage of 200 kV, combined with energy-dispersive X-ray spectroscopy (EDS). XPS measurements were performed on a Thermo VG ESCALAB 250 X-ray photoelectron spectrometer with Al K α radiation at a pressure of about 2 × 10⁻⁹ Pa. Inductively coupled plasma-optical emission spectrometry (ICP-OES) was adopted to analyze the chemical components of the catalysts.

Electrochemical measurements

Electrochemical measurements were performed on an electrochemical workstation (CHI 660E, CH Instruments Inc., Chenhua, Shanghai) using a three-electrode mode in an Ar-saturated 1 mol L⁻¹ KOH aqueous solution. A platinum electrode was used as the counter electrode, a silver/silver chloride (Ag/AgCl) electrode was used as the reference electrode, and the as-fabricated materials were used as the working electrodes. The potentials were converted to the RHE scale using the following Nernst equation: $E(\text{RHE}) = E(\text{Ag/AgCl}) + 0.059 \text{ pH} + 0.197$. To accelerate the electrochemical performance tests, 5 mg of the as-prepared catalysts, 2 mg conductive carbon, 35 μL of the 5 wt% Nafion solution and 1 mL anhydrous ethanol were mixed and ultrasonicated for 10 min to form homogeneous catalyst inks. The catalyst inks were dripped respectively onto the as-prepared NF to obtain the working electrodes with a loading of $\sim 5 \text{ mg cm}^{-2}$, which were dried at 60 °C for 1 h. The electrochemical impedance spectroscopy (EIS) tests were performed in the frequency range from 100 kHz to 0.1 Hz at an overpotential of 180 mV. The cyclic voltammograms (CV) were obtained between 0.1 and -0.3 V vs. RHE at 100 mV s⁻¹ to investigate the cycling stability. The long-term stability tests were recorded by taking a chronoamperometric curve current density that reached 10 mA cm⁻². All data were presented



without IR compensation, and all the electrochemical tests were tested at room temperature.

Computational methods

All first principles calculations were performed *via* DFT in the Cambridge Sequential Total Energy Package (CASTEP) module in the Materials Studio. The MoS₂ (002) plane consisting of six layers of Mo and S, and the Ni₃S₄ (311) slab composed of six layers of atoms were constructed as our models, because the (002) plane of MoS₂ and the (311) plane of Ni₃S₄ were dominant crystal faces from the HRTEM images. The exchange–correlation interactions were treated within the generalized gradient approximation of the Perdew–Burke–Ernzerhof (PBE) type. The plane-wave cutoff energy was 400 eV, and a k-mesh of 3 × 3 × 1 was adopted to sample the Brillouin zone. The convergence

threshold for energy and Hellmann–Feynman forces on each atom were set to 10^{−5} eV and 0.01 eV Å^{−1}. Vacuum layers of 15 Å were introduced to minimize interactions between adjacent layers in all supercells.¹⁵ All the atom positions in the model were optimized by the conjugate-gradient optimization procedure.

Gibbs free-energy of the adsorption atomic hydrogen was calculated as the following formula:

$$\Delta G = \Delta E + \Delta ZPE - T\Delta S \quad (1)$$

where ΔE is the adsorption energy of adsorbed species on the given unit cell. ΔZPE and $T\Delta S$ are the zero-point energy and entropy difference of hydrogen in the adsorbed state and the gas phase, respectively. The value of ZPE and TS for the

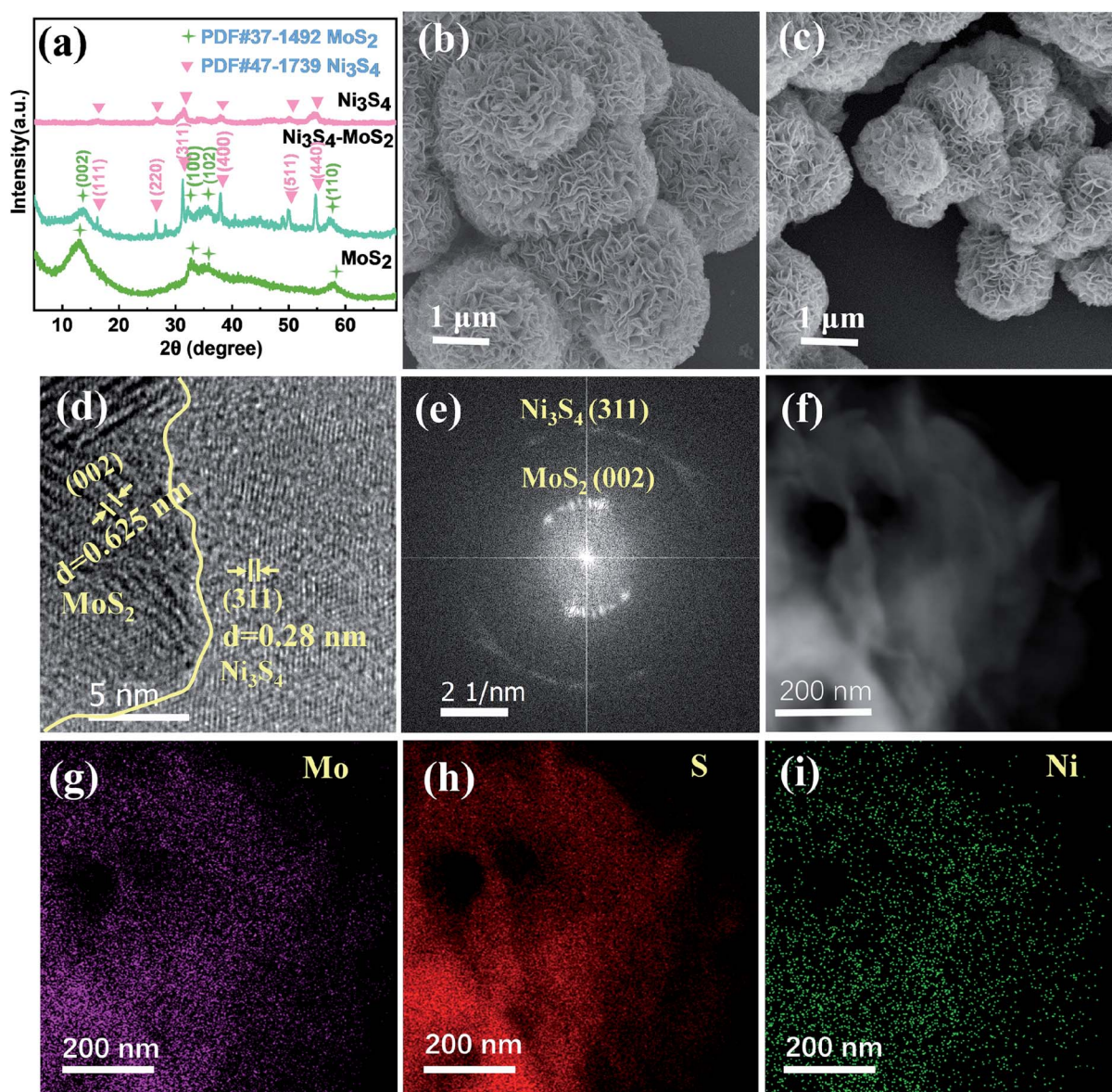


Fig. 1 (a) XRD patterns of Ni₃S₄–MoS₂, Ni₃S₄ and MoS₂. (b) SEM image of the Ni₃S₄–MoS₂. (c) SEM image of the MoS₂. (d) TEM image and (e) corresponding SAED pattern of Ni₃S₄–MoS₂. (f) TEM image of Ni₃S₄–MoS₂ and corresponding elemental mappings: Mo (g), S (h) and Ni (i).



adsorbed species were calculated from the vibration frequencies, as shown in the previous literature.¹⁵

Results and discussion

Morphology and structure of Ni₃S₄-MoS₂

A series of Ni₃S₄-MoS₂ with different Ni contents were synthesized *via* a one-pot hydrothermal method. The ICP-OES measurements provided the contents of Ni in Ni₃S₄-MoS₂, as shown in Table S1.† The XRD patterns of the Ni₃S₄-MoS₂ composite, pure Ni₃S₄ and MoS₂ are shown in Fig. 1a. For the Ni₃S₄ and MoS₂ samples, all of their peaks were well matching with the Ni₃S₄ (JCPDS no. 47-1739) and MoS₂ phases (JCPDS no. 37-1492), respectively. For the XRD pattern of Ni₃S₄-MoS₂, the diffraction peaks at 14.5°, 32.7° and 58.3° corresponded to the (002), (100) and (110) lattice planes of the MoS₂ phase (JCPDS Card no. 37-1492).²⁶ There are six sharp peaks at 16.2°, 26.6°, 31.3°, 37.9°, 50.0° and 54.7°, which can be indexed to the (111), (220), (311), (400), (511) and (440) planes of Ni₃S₄ (JCPDS no. 47-1739).²⁷ The XRD diagram implied the hybrid of these two metal sulfides in Ni₃S₄-MoS₂.

The SEM image of Ni₃S₄-MoS₂ identifies that the morphology of the sample is a hierarchical nanosphere composed of nanosheets with a size of about 1 μm and a thickness of about 30 nm (Fig. 1b). By comparison Fig. 1b with c, it is found that the nanosheets of Ni₃S₄-MoS₂ are bigger and thinner than that of MoS₂ (average size is about 0.6 μm and thickness is 40 nm, as shown in Fig. S1†). Besides, the heterostructure Ni₃S₄-MoS₂ has a larger specific surface area (2.7 m² g⁻¹) than that of the pure MoS₂ (0.6 m² g⁻¹). The information illustrates that the construction of the heterojunction increased the surface area of samples. The HRTEM images provide further details of the microstructure for the heterostructure Ni₃S₄-MoS₂. The lattice spacing of 0.625 nm corresponds to the (002) plane of MoS₂,^{28,29} and 0.28 nm corresponds to the (311) plane of Ni₃S₄,³⁰ indicating that the sample consisted of Ni₃S₄ and MoS₂. The HRTEM image suggests that the (002) plane of MoS₂ and (311) plane of Ni₃S₄ constitute important heterointerfaces in the composite (Fig. 1d). The crystal structure of the Ni₃S₄-MoS₂ composite was further verified by the select area electron diffraction (SAED) (Fig. 1e). It showed that the inner ring was strong and the outer ring pattern correspond to the (002) plane of the MoS₂ crystal and the (311)

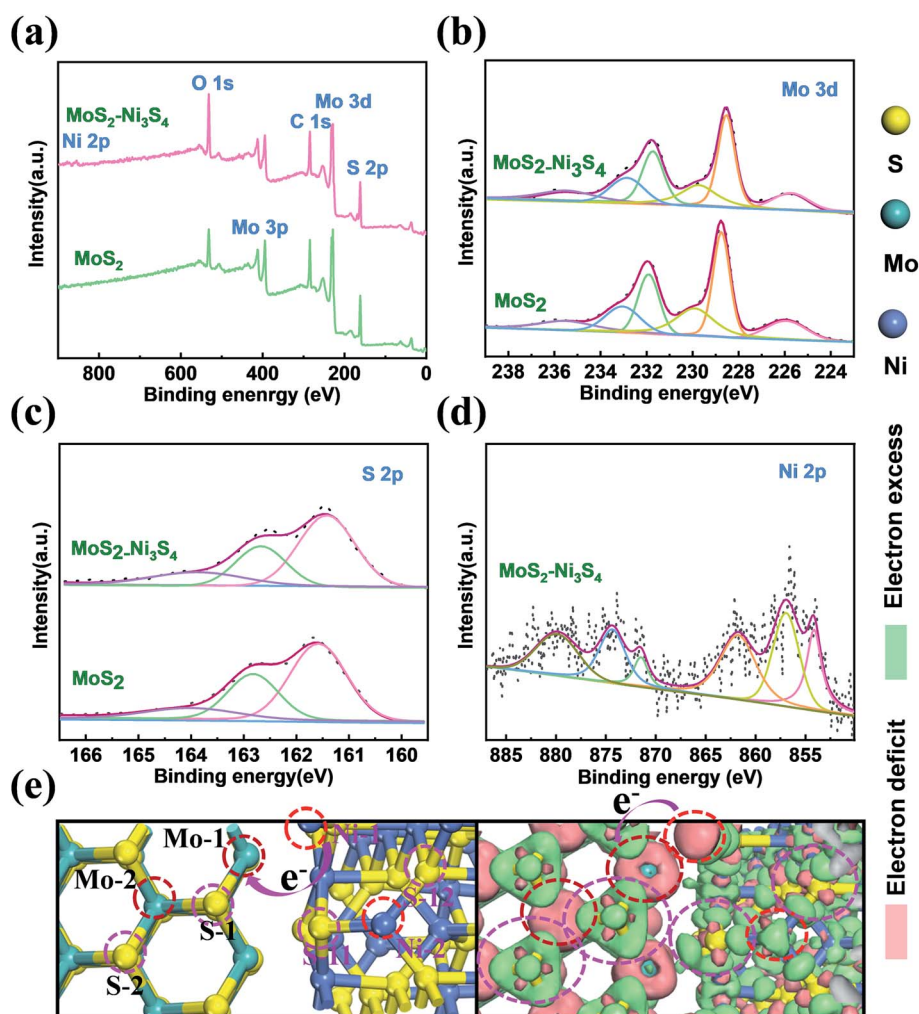


Fig. 2 XPS spectra of Ni₃S₄-MoS₂ and MoS₂: (a) Survey spectra, (b) Mo 3d, (c) S 2p and (d) Ni 2p. (e) Top views of the most stable structure and charge density difference for the Ni₃S₄-MoS₂.



plane of Ni₃S₄, respectively, matching well with the XRD spectra (Fig. 1a). The EDS elemental mapping of Ni₃S₄-MoS₂ indicates that the Mo, S and Ni elements distributed uniformly in the entire nanosheets (Fig. 1f-i), and the contents of Mo, S and Ni of Ni₃S₄-MoS₂ are consistent with the results of ICP-OES tests (Fig. S2 and Table S2†).

XPS spectra were obtained to confirm the chemical composition and valence state of atoms in Ni₃S₄-MoS₂ and pure MoS₂, as shown in Fig. 2. It shows the existence of C, Mo, S, Ni and O elements in Ni₃S₄-MoS₂ and the presence of all the elements but no Ni signal in MoS₂ (Fig. 2a). The O 1s signal was assigned to the absorbed O-containing species, such as O₂, CO₂ and H₂O. The high-resolution Mo 3d spectra of Ni₃S₄-MoS₂ directly evidence the concurrent presence of Mo³⁺ and Mo⁴⁺ (Fig. 2b) with four definite fitting peaks assigned to Mo³⁺ (3d_{3/2} at 231.8 eV and 3d_{5/2} at 228.6 eV) and Mo⁴⁺ (3d_{3/2} at 232.8 eV and 3d_{5/2} at 229.7 eV), respectively.¹⁷ The binding energies of Mo 3d_{5/2} and Mo 3d_{3/2} in Ni₃S₄-MoS₂ are negative shifts (0.2 eV) compared with the corresponding peaks of pristine MoS₂,^{31,32} indicating the lower valence state of Mo in Ni₃S₄-MoS₂. Thus, the charge transfer behavior from Ni₃S₄ to MoS₂ is determined. The change of Mo valence was ascribed to the electronegativity difference between Mo and Ni, where the introduced Ni₃S₄ led to the rearrangement of the electron cloud between Mo and S, thus, forming a new hybridized electronic state. The S 2p spectrum of Ni₃S₄-MoS₂ (Fig. 2c) was deconvoluted into three peaks at 161.4 (S 2p_{3/2}), 162.6 (S 2p_{1/2}) and 164.8 eV (S²⁻),

respectively, and the S 2p shifts to the lower binding energy (about 0.2 eV, S 2p_{3/2} and S 2p_{1/2}) compared with the pristine MoS₂ (Fig. 2c), indicating the lower valence state of S in Ni₃S₄-MoS₂. The result was consistent with the previous reports for other transition metals decorated with MoS₂.^{33,34} The lower valence state of S in Ni₃S₄-MoS₂ than that in MoS₂ indicated that S in Ni₃S₄-MoS₂ had a higher electric charge density that was contributed to H adsorption, which helped to improve the HER properties. The Ni 2p spectrum of Ni₃S₄-MoS₂, as shown in Fig. 2d, exhibits the apparent Ni 2p_{3/2} and 2p_{1/2} peaks at 854.8 and 872.1 eV, respectively, that are attributed to Ni²⁺, and the other peaks at 856.9 and 874.3 eV, attributed to Ni³⁺.²¹ Two satellite peaks at 862.1 and 879.6 eV attributed to Ni 2p_{3/2} and 2p_{1/2}, respectively, were observed.³⁵ It was further confirmed that the material contained compound Ni₃S₄,³⁶ which is in agreement with the XRD and HRTEM measurements.

To investigate the electron redistribution on the heterostructure of Ni₃S₄-MoS₂, the electron density different diagram and the Bader charge analysis was performed by DFT calculations (Fig. 2e and Table S3†). The different electron density diagrams demonstrated that the electric charge densities of Mo and S increased on the interfaces Mo-1, S-1 and S-11 in Ni₃S₄-MoS₂, compared with that on the base Mo-2, S-2 and S-12 in Ni₃S₄-MoS₂, indicating that the binding energies of Mo and S in the heterojunction of Ni₃S₄-MoS₂ reduced, which is in accordance with the XPS spectra and Bader charge analysis. The electric charge density of Ni on the interface Ni-1, compared

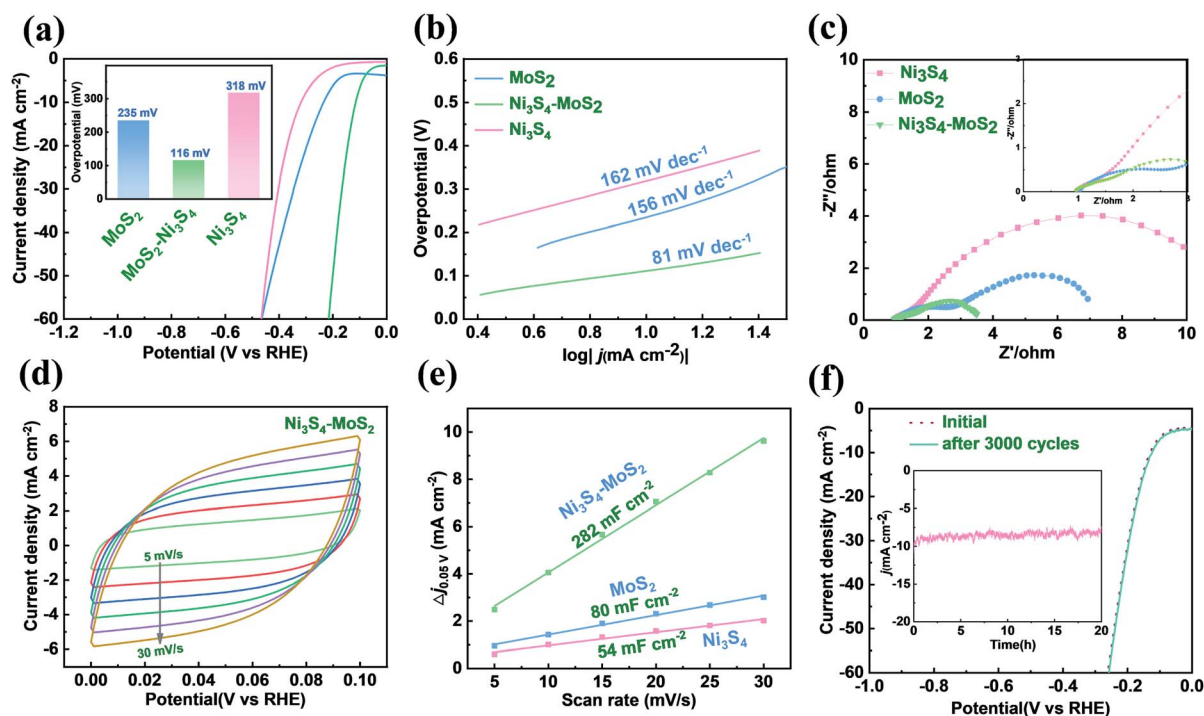


Fig. 3 The HER behavior of Ni₃S₄-MoS₂, Ni₃S₄ and MoS₂ in 1 M KOH. (a) The LSV curves and overpotential (η_{10}) without IR correction. (b) The Tafel slopes. (c) Nyquist plots collected at the overpotential of 180 mV. (d) CV curves of Ni₃S₄-MoS₂ at the scan rates of 5, 10, 15, 20, 25 and 30 mV s⁻¹, respectively. (e) Differences in current density variation ($\Delta J = J_a - J_c$) at 0.05 V vs. RHE plotted against scan rate fitted to linear regression for estimation of C_{dl} values of Ni₃S₄-MoS₂, Ni₃S₄ and MoS₂. (f) The initial and 3000th polarization curves of Ni₃S₄-MoS₂. The inset is the chronoamperometric curve recorded at 10 mA for a continuous 20 h.



with that on the base Ni-2 in Ni₃S₄-MoS₂, was decreased, indicating that the electrons were transferred from Ni to Mo or S on the interfaces. These data confirmed the electron redistribution in the heterostructure Ni₃S₄-MoS₂.

HER catalytic behavior

The HER activities of MoS₂, Ni₃S₄-MoS₂ and Ni₃S₄ on NF were measured in a 1 M KOH solution. There was a significant enhancement of the HER activity for Ni₃S₄-MoS₂, as shown in Fig. 3a. The pure MoS₂ exhibited an overpotential of 10 mA cm⁻² (η_{10}) at 235 mV, which is in agreement with the reported literature.³⁷ The η_{10} of Ni₃S₄-MoS₂ is 116 mV, which is much lower than that of the pure MoS₂ (235 mV) and pristine Ni₃S₄ (318 mV). The heterostructure Ni₃S₄-MoS₂ showed superior η_{10} in an alkaline solution and is comparable with the electrocatalysts reported in literature (see Table S4† for more details).³⁸⁻⁴⁰ The HER catalytic performance of the electrocatalysts with different Ni contents in Ni₃S₄-MoS₂ was investigated, as shown in Fig. S3,† indicating that Ni₃S₄-MoS₂ with 7.7 wt% Ni has the lowest overpotential (116 mV) at 10 mA cm⁻² in the alkaline solution.

The Tafel curves of MoS₂, Ni₃S₄-MoS₂ and Ni₃S₄ on NF are shown in Fig. 3b. The Tafel slope of Ni₃S₄-MoS₂ (81 mV dec⁻¹) was much lower than that of MoS₂ (156 mV dec⁻¹), indicating that Ni₃S₄ played a key role in promoting the kinetics of HER. The EIS diagrams exhibited similar impedance characteristics, which implied similar electrochemical processes of these samples (Fig. 3c). Ni₃S₄-MoS₂ showed a much lower charge-transfer-resistance (R_{ct}) value when compared with the other catalysts, suggesting that Ni₃S₄-MoS₂ had better charge-transfer property and HER kinetics. In addition, not only the electric conductivity but also the wettability of MoS₂ was influenced by Ni₃S₄. The contact angle tests of the materials in 1 mol L⁻¹ KOH electrolyte were carried out to explain such influence. The contact angle decreased from 21.36° for MoS₂ to 15° for Ni₃S₄-MoS₂ (Fig. S3†). It is shown that Ni₃S₄-MoS₂ had better wettability in the KOH electrolyte than that of initial MoS₂.

Electrochemical active surface area (ECSA) is a standard parameter applied in the evaluation of electrochemical catalysts. To investigate the exposed active sites, the ECSA of Ni₃S₄-MoS₂, MoS₂ and Ni₃S₄ were calculated by the double-layer capacitance (C_{dl}) through plotting CV curves. The CV curves of the samples were tested in the potential range of 0.0–0.1 V at the

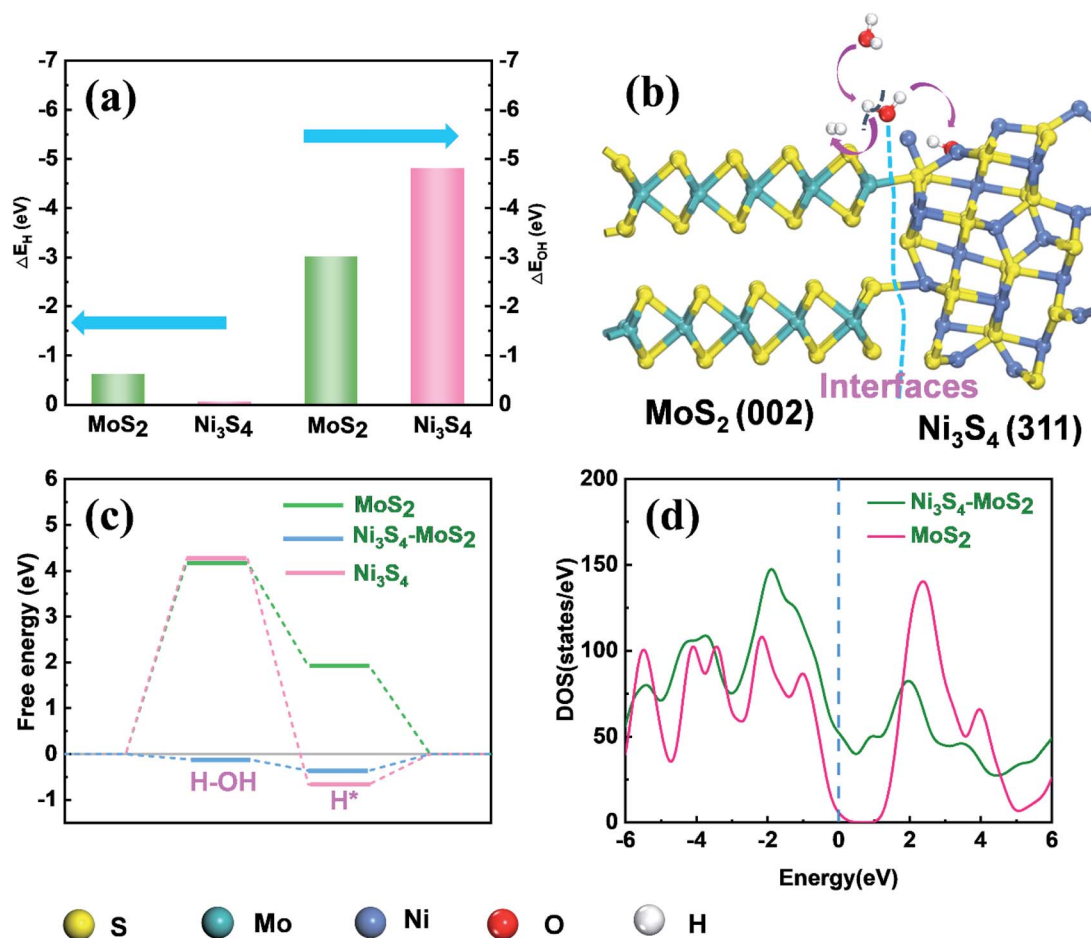


Fig. 4 (a) DFT-calculated adsorption energies of H and OH at different sites on the surfaces of Ni₃S₄-MoS₂, respectively. (b) The illustration of a mechanism for the electrocatalytic HER under alkaline conditions. (c) Free energy diagrams on the surface of MoS₂, Ni₃S₄ and Ni₃S₄-MoS₂ in alkaline solution. (d) DOSs of pristine MoS₂ and Ni₃S₄-MoS₂.



scan rates of 5, 10, 15, 20, 25 and 30 mV s⁻¹ in 1.0 M KOH, respectively (Fig. 3d and S5[†]). The C_{dl} value of Ni₃S₄-MoS₂ was 282 mF cm⁻², which is much higher than that of MoS₂ (80 mF cm⁻²) and Ni₃S₄ (54 mF cm⁻²) (Fig. 3e), indicating that the additional electrochemical active sites were generated after Ni₃S₄ was introduced. The C_{dl} value of Ni₃S₄-MoS₂ was much more than that of MoS₂ and Ni₃S₄, indicating there are more active sites exposed for HER.

To evaluate the long-term stability of the heterostructure Ni₃S₄-MoS₂, it was subjected to 3000 continuous CV cycles in an alkaline environment from 0 to -0.3 V vs. RHE. The LSV curves had no clear changes before and after 3000 CV cycles (Fig. 3f), indicating that Ni₃S₄-MoS₂ has excellent catalytic stability during the electrochemical process. Besides, Ni₃S₄-MoS₂ has a stable HER current at a constant current of 10 mA *versus* time over a 20 h period in 1 M KOH (Fig. 3f). Simultaneously, the morphology of Ni₃S₄-MoS₂ was well preserved (Fig. S6[†]), demonstrating excellent catalytic stability during the alkaline HER process.

Mechanism of Ni₃S₄-MoS₂ for HER

According to literature,^{41,42} DFT calculations were also carried out to gain insight into the underlying mechanism of Ni₃S₄-MoS₂ towards the HER activity. In an alkaline medium, the HER reaction mainly includes three steps: water adsorbed on the catalyst, water dissociation, H* formation and H₂ generation.^{43,44} The water dissociation step is considered as the important step for the HER catalytic property in an alkaline solution. The chemisorption free energies of OH (ΔE_{OH}) and H (ΔE_H) on the different sites of Ni₃S₄-MoS₂ were calculated, respectively. To study the optimal chemisorption free energies (ΔE), several feasible positions were chosen for the adsorption of OH and H (Fig. S7[†]). The chemisorption free energy of H adsorbed on the (002) plane of MoS₂ ($\Delta E_H = -0.81$ eV) was lower than that absorbed on the (311) plane of Ni₃S₄ ($\Delta E_H = -0.027$ eV), indicating that H was inclined to be adsorbed on the (002) plane of MoS₂. Compared with the (002) plane of MoS₂ ($\Delta E_{OH} = -3.0$ eV), the (311) plane of Ni₃S₄ showed a predominant binding energy towards OH ($\Delta E_{OH} = -4.8$ eV), which is attributed to the bonding ability between OH and Ni (Fig. 4a). Therefore, OH is intensely adsorbed on the (311) plane of Ni₃S₄ and H on the (002) plane of MoS₂. The appropriate oxidation of Ni in Ni₃S₄-MoS₂ contributes to the adsorption energy of OH. Simultaneously, the partial reduction of S in Ni₃S₄-MoS₂ is beneficial for the adsorption of H. It demonstrated a synergistic effect of Ni₃S₄-MoS₂ with chemisorption of H (on the (002) plane of MoS₂) and OH (on the (311) plane of Ni₃S₄) accelerated the rate-determining water dissociation steps of HER.

The free energy diagrams on the surfaces of MoS₂, Ni₃S₄ and Ni₃S₄-MoS₂ are shown in Fig. S8.[†] The ΔG_{H^*} of Ni₃S₄-MoS₂ was -0.36 eV, which was much lower than that of pure MoS₂ (1.92 eV), indicating the superior capacity of Ni₃S₄-MoS₂ for H* adsorption (Table S4[†]), which benefited from the electron redistribution between Ni₃S₄ and MoS₂. For pure MoS₂, the free energy barrier of water dissociation ΔG_{H_2O} is as high as 4.2 eV, which distinctly hindered the dissociation of H₂O to H*.

Moreover, the ΔG_{H_2O} of Ni₃S₄-MoS₂ was only -0.10 eV, which was much lower than that of MoS₂ (4.2 eV) and Ni₃S₄ (4.3 eV). It is indicated that the ΔG_{H_2O} of Ni₃S₄-MoS₂ efficiently decreased because of the existence of a heterostructure. Hence, the HER process on Ni₃S₄-MoS₂ is highly accelerated and in accordance with our experimental results.

Moreover, the heterostructure improved the electrical transport efficiency of Ni₃S₄-MoS₂. It is found that the total density of state (DOS) curve of MoS₂ shows a clear band gap at the region around 0 eV, confirming the typical semiconductor characteristic. The peak of the valence band of the heterostructure Ni₃S₄-MoS₂ is close to 0 eV (Fig. 4d), leading to the enhanced excitation of charge carriers to the conduction band and showing better electric conductivity, which is consistent with the EIS tests.

Conclusions

In summary, we fabricated the sphere-shaped heterostructure Ni₃S₄-MoS₂ by a one-pot hydrothermal method. The as-synthesized catalyst with the activated interfaces generated abundant active sites and improved the electrical transport efficiency. Benefiting from engineering the heterostructure, the Ni₃S₄-MoS₂ demonstrated the low overpotential of 116 mV with the corresponding Tafel slope of 81 mV dec⁻¹ and long-term stability of over 20 h. DFT calculations proved that the heterostructure Ni₃S₄-MoS₂ resulted in electron redistribution, which indicated the presence of a synergistic effect with MoS₂ as the hydrogen acceptor and Ni₃S₄ as the hydroxyl acceptor, and effectively reduced the intermediate energy barrier of the water dissociation. Hence showing outstanding HER performance in alkaline solution. This work opens the door to develop low-cost and high-activity HER electrocatalyst Ni₃S₄-MoS₂ *via* heterostructure engineering.

Conflicts of interest

The authors declare no competing financial interest.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (nos 2177060378, 21978023, 21627813 and 21521005), the Program for Changjiang Scholars, Innovative Research Teams in Universities (No. IRT1205), and the Fundamental Research Funds for the Central Universities (No. 12060093063 and XK1803-05).

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