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Controllable synthesis of self-templated hierarchical Ni₃S₂@N-doped carbon for enhanced oxygen evolution reaction†

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Rational construction of self-supporting electrodes has been extensively investigated in energy conversion and storage. In this work, hierarchical N-doped carbon-encapsulated Ni₃S₂ grown on a 3D porous Ni foam (H-Ni₃S₂@NC/NF) was controllably synthesized by a one-pot self-templated solvothermal method. Herein, we highlight the self-templated growth of multilayered Ni₃S₂ with N-doped carbon intercalation at a certain temperature. The unique H-Ni₃S₂@NC/NF shows enhanced active sites and a modulated electronic structure, which facilitates mass/electron transport. Thereby, the H-Ni₃S₂@NC outperforms a lower overpotential of 238 mV at 10 mA cm⁻² and a low Tafel slope of 62 mV dec⁻¹ than that of binary and ternary metal sulfides, suggesting an excellent mono-metal sulfide as a self-supporting electrode for oxygen evolution reaction.

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1 Introduction

The rapid development of human productivity greatly accelerates the unbalance of traditional fossil fuels and ecosystems. The demand for energy conversion technology accompanied by sustainable energy resources is extremely urgent.¹ Electrocatalytic water splitting has been considered as a potential energy technology for the high acceptance of diverse energy units such as solar, wind, nuclear and tidal-based energy systems, converting intermittent energy resources to storable H₂ energy, and applied to pollution-free energy devices.^{2,3} However, the efficiency of H₂ production is largely restricted by its anodic oxygen evolution reaction (OER, 4OH⁻ → O₂ + 2H₂O + 4e⁻), which has also been extensively investigated in numerous energy fields such as metal-air cells and fuel cells.⁴ The key issue in the OER process is the sluggish kinetics of uphill energy barrier for the O=O bond formation, leading to excessive cost for large-scale production.⁵ To date, IrO₂ and RuO₂ are proverbially acknowledged as benchmark electrocatalysts for water oxidation, while their high cost and rare reservation limit industrial water splitting.⁶ Hence, it is urgent to develop efficient OER electrocatalysts with low cost and high abundance.

Recently, self-supporting Ni₃S₂ materials have aroused widespread attention in energy fields due to their intrinsic conductivity, electrocatalytic activity and fabricability.⁷ Ni foams are the most widely used substrate for in-situ growth of Ni₃S₂ due to its porous 3D framework, binder-free nature and nickel supplementary.⁸ As far as we know, metal atom introduction, anion doping and carbon compounds are effective strategies to improve the electrocatalytic activity of Ni₃S₂ due to the morphology modification electronic redistribution and synergistic effect of metal atoms. On the one hand, different metal modifications lead to tremendous diversity in morphology by a hydrothermal/solvothermal method, for instance, nanoneedle-like Fe-doped Ni₃S₂/NF,⁹ nanosheet-like Co/Ce-Ni₃S₂/NF,¹⁰ diamond-like Mo-Ni₃S₂/NF and particle-like Mo/Mn-Ni_xS_y/NF.¹¹ However, the construction of well-designed morphology is exactly decided by complicated synthesis parameters such as reaction temperature, time, sulfur source and heteroatom.^{12,13} In addition, the catalytic active central of the resulting binary and ternary metal sulfides is difficult to be distinguished. On the other hand, the anion doping and carbon compounds, for instance, N-, F-doping, and introduction of CNTs or graphenes, mainly work on the regulation of electronic redistribution, adsorption/desorption energy, and enhanced conductivity due to larger electronegativity than that of transition metals.¹⁴⁻¹⁶ Generally, the preparation of anion doping and carbon composites is carried out by a multi-step process or high-temperature calcination with additional nitrogen-containing precursors, leading to high cost and safety concerns.^{17,18} Therefore, facile preparation and systematic

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exploration of Ni₃S₂ compounded with N-doped carbon are significant to the deep understanding of the growth mechanism and improved electrocatalytic activity.

In this work, hierarchical Ni₃S₂ with N-doped carbon intercalation grown on the NF was systematically prepared by a self-templated solvothermal method at a certain temperature and time. Specifically, Ni₃S₂ exhibits a nanosheet-like morphology at first, and with the increase in reaction temperature and time, it forms multilayer structured Ni₃S₂ compounded with N-doped carbon, resulting in high conductivity and enlarged active sites. The unique morphology and modified electronic structure are highly expected to witness a favorable electrocatalytic performance of H-Ni₃S₂@NC/NF for alkaline water splitting.

2 Experimental section

2.1 Chemical reagents

KOH, HCl, Na₂S, NiCl₂ · 6H₂O, Ni(NO₃)₂ · 6H₂O, NiSO₄ · 6H₂O, Ni(CH₃COO)₂ · 4H₂O, thiourea (TU), ethylene glycol (EG), ethanol and acetone were of analytical grade and purchased from Chengdu Kelong Chemical Reagent Factory (Chengdu, China). Ruthenium oxide (RuO₂) was purchased from Shanghai Macklin Biochemical Co., Ltd (Shanghai, China). Nafion solution (5 wt%) was purchased from Shanghai Aladdin Biochemical Technology Co., Ltd (Shanghai, China). NF was purchased from Jinan Henghua Chemical Reagent Factory (Jinan, China).

2.2 Synthesis of hierarchical H-Ni₃S₂@NC/NF

Briefly, 1.0 mmol of TU and 0.3 mmol of NiCl₂ · 6H₂O were dispersed in 50 mL EG and then transferred into a 100 mL Teflon-lined stainless autoclave. Subsequently, a piece of pretreated NF substrate (1 cm × 2 cm) was vertically put into the above solution and maintained at 160 °C for 8 h. Finally, after cooling to room temperature, the modified NF was alternately rinsed several times with deionized water and ethanol, and then dried in a vacuum oven at 60 °C for 8 h, which was named H-Ni₃S₂@NC-3/NF. As comparison, NiCl₂ · 6H₂O with different contents of 0, 0.1, and 0.5 mmol was employed to prepare Ni₃S₂/NF and H-Ni₃S₂@NC-*X*/NF (*X* = 1 and 5), respectively. The obtained samples were used as the working electrode, and the average areal mass loading of active materials was weighed as 3.1 mg cm⁻².

2.3 Synthesis of A-Ni₃S₂/C

The optimal H-Ni₃S₂@NC-3/NF was selected to explore the self-templated growth by the annealing process. One piece of H-Ni₃S₂@NC-3/NF was heated to 500, 600 and 700 °C at a rate of 10 °C min⁻¹ in argon atmosphere and maintained at this temperature for 2 h, which was named A-Ni₃S₂/C-500, A-Ni₃S₂/C-600, and A-Ni₃S₂/C-700, respectively.

2.4 Synthesis of RuO₂/NF

First, 10 mg of RuO₂ was dispersed in 750 μL of ethanol and 250 μL of deionized water under ultrasonication for 20 min. Subsequently, 50 μL of Nafion solution (5 wt%) was added into

the above suspension for continuous ultrasonication. After that, 326 μL of uniform mixture was loaded on the pretreated NF and dried in a vacuum oven at 60 °C for 8 h.

2.5 Material characterization

X-Ray diffraction (XRD) was conducted using an X'Pert PRO diffractometer with Cu Kα radiation ($\lambda = 1.54056 \text{ \AA}$). Field emission scanning electron microscopy (FESEM) was carried out using a Carl Zeiss AG instrument. Transmission electron microscopy (TEM), high-resolution transmission electron microscopy (HRTEM), selected area electron diffraction (SAED), high-angle annular dark field scanning transmission electron microscopy (HAADF-STEM) and the corresponding energy-dispersive spectroscopic (EDS) mapping analysis were performed using a FEITecni G2 F30. X-Ray photoelectron spectroscopy (XPS) was conducted using a Thermo Scientific instrument with Al K_α radiation. Raman spectrum of H-Ni₃S₂@NC-3/NF was recorded using a Renishaw spectrometer with a 532 nm laser as an excitation source. Fourier transform infrared (FTIR) spectra of H-Ni₃S₂@NC-3/NF were recorded using a Nicolet 5700 in the wavenumber range of 4000–400 cm⁻¹.

2.6 Electrocatalytic performance measurement

All electrochemical tests were conducted using a classic three-electrode system (CHI 660D, Chenhua), with a graphite rod and a Hg/HgO electrode as the counter and reference electrodes, respectively. The as-prepared H-Ni₃S₂@NC/NF, A-Ni₃S₂/C and RuO₂/NF were used as the working electrode. The OER polarization curves were evaluated by linear sweep voltammetry (LSV) at a scan rate of 1 mV s⁻¹ in 1.0 M KOH solution. A Tafel slope was derived from the linear part of polarization curve based on the Tafel equation: $\eta = b \log j + a$, where η is the overpotential, j is the current density, and b is the Tafel slope. Cyclic voltammetry (CV) was employed to evaluate double-layer capacitance (C_{dl}) in the potential region of 1.22–1.32 V at different scan rates of 5–120 mV s⁻¹. Electrochemical impedance spectroscopy (EIS) was measured from 10⁵ to 10⁻¹ Hz with an amplitude potential of 5 mV. Long-term stability was evaluated by the *i*-*t* test at a constant potential of 1.47 V for 20 h. All potentials were *iR* corrected and converted into the RHE potential by the following equation: $E_{RHE} = E_{Hg/HgO} + 0.059 \times \text{pH} + 0.098 \text{ V}$, pH = 14.

3 Results and discussion

3.1 Morphology and chemical structure

As shown in Fig. 1a, hierarchical H-Ni₃S₂@NC-3/NF can be facilely obtained by a self-templated solvothermal method. The unique H-Ni₃S₂@NC-3/NF is composed of broccoli-like microspheres and multilayered polyhedrons with a size of 1–2 μm and 10–30 μm, respectively (Fig. 1b). As shown in Fig. 1c and d, the microspheres are assembled with nanosheets while polyhedrons are constructed layer by layer with nanosheets homogeneously presented on their surface. It is generally acknowledged



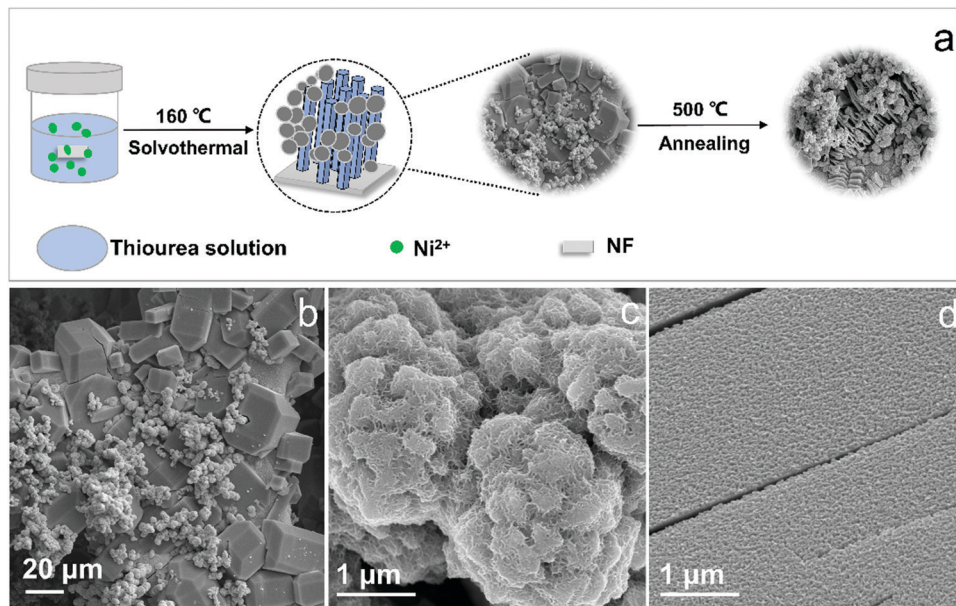


Fig. 1 Schematic of the preparation (a) and SEM images (b–d) of H-Ni₃S₂@NC-3/NF at different magnifications.

that nanomaterials possess special photoelectric/physical/chemical properties, which are beneficial for the electrocatalytic process.

Here, the H-Ni₃S₂@NC-3/NF material with a micro-nano structure benefits the OER process thanks to the following reasons: (i) the hierarchically assembled surface structure leads to more exposed active sites; (ii) the layered polyhedrons offer multi-pathways for fast charge transfer; and (iii) N-doped carbon gives rise to a modified electronic structure.¹⁹ The EDS spectra of H-Ni₃S₂@NC-3/NF in Fig. S1 (ESI[†]) illustrate the presence of Ni and S elements on the microsphere and Ni, S, N, C, and O elements on the polyhedron, indicating the self-templated synthesis of a nickel–thiourea coordination complex that induces carbon intercalation.

Comparatively, Ni₃S₂/NF obtained without the addition of the Ni²⁺ precursor shows a nanocoral-like morphology (Fig. S2a and b, ESI[†]). The EDS spectrum and elemental mapping images shown in Fig. S2c–f (ESI[†]) display only Ni and S elements on its surface, revealing the significance of the Ni²⁺ precursor for the formation of N-doped carbon. The crystalline structures of Ni₃S₂/NF and H-Ni₃S₂@NC-3/NF are demonstrated in Fig. 2a. The peaks at 21.87°, 31.33°, 38.06°, 50.15° and 55.52° are indexed to the (101), (110), (003), (113) and (122) planes of hexagonal Ni₃S₂ (JCPDS No. 44-1418), respectively.^{20,21} The peaks at 44.87°, 52.19° and 76.63° are ascribed to the (111), (200) and (220) planes of NF (JCPDS No. 04-0850).²² The broad peak at 23.65° is assigned to carbon (JCPDS No. 46-0945).²³

The phase structure was further characterized by Raman spectrum. As illustrated in Fig. S5a (ESI[†]), the bands at 220, 300, and 350 cm⁻¹ represent the excitation bands of Ni₃S₂ whereas peaks located at around 1374 and 1598 cm⁻¹ correspond to D and G bands of carbon, respectively.^{24,25} The low I_D/I_G value of 0.56 indicates the introduction of graphitic carbon into Ni₃S₂ materials, which suggests smoother electron communication between multilayered polyhedron. Fig. S5b (ESI[†])

delivers the FTIR spectrum of H-Ni₃S₂/NF-0.3, where the absorption bands at 1052 and 1390 cm⁻¹ are assigned to conjugated C–C and C–O stretching vibration.²⁶ The characteristic bands at 2172 and 1625 cm⁻¹ indicate the presence of C≡N and C=N, whereas the bands at 3433 and 875 cm⁻¹ are related to the stretching vibrations of C–OH and C–S, suggesting the successful intercalation of N-doped carbon.²⁷

To have a deeper understanding of composition and phase structure of H-Ni₃S₂@NC-3/NF, active materials scraped from the NF substrate are obtained for TEM, HRTEM, SAED and EDS analysis. Fig. 2c and d show the TEM images for broccoli-like microspheres and multilayered polyhedrons, respectively. The broccoli-like microspheres exhibit an obvious nanosheet morphology with diffraction spots shown in the SAED pattern (inset of Fig. 2c), which corresponds to the (202), (122), (113) and (042) planes of Ni₃S₂, as evidenced by the XRD pattern above. In addition, the HRTEM image (Fig. 2e) indicates the characteristic lattice fringes of crystal Ni₃S₂ and parts of amorphous states. As for polyhedrons, amorphous states are observed in the SAED pattern (inset of Fig. 2d) and HRTEM image (Fig. 2f) due to the N-doped carbon intercalation, which is consistent with the EDS spectrum (Fig. 2b), HAADF-STEM image and elemental mapping analysis (Fig. S3, ESI[†]).

The composition and chemical valences of Ni₃S₂/NF and H-Ni₃S₂@NC-3/NF are characterized by XPS measurement. The survey spectrum of Ni₃S₂/NF (Fig. S4a, ESI[†]) suggests the presence of Ni, S, C and O. In the high-resolution Ni 2p spectrum (Fig. S4b, ESI[†]), the peaks at 855.74 and 873.38 eV are assigned to Ni 2p_{3/2} and Ni 2p_{1/2}, whereas 861.06 and 879.41 eV are attributed to their shakeup satellites (identified as “Sat.”).²⁸ The peaks at 852.43 and 869.65 eV are attributed to metal Ni that originated from the NF substrate.²⁹ In the high-resolution S 2p spectrum (Fig. S4c, ESI[†]), the peaks at 162.11 and 163.36 eV are assigned to S 2p_{3/2} and S–metal bond, respectively.³⁰



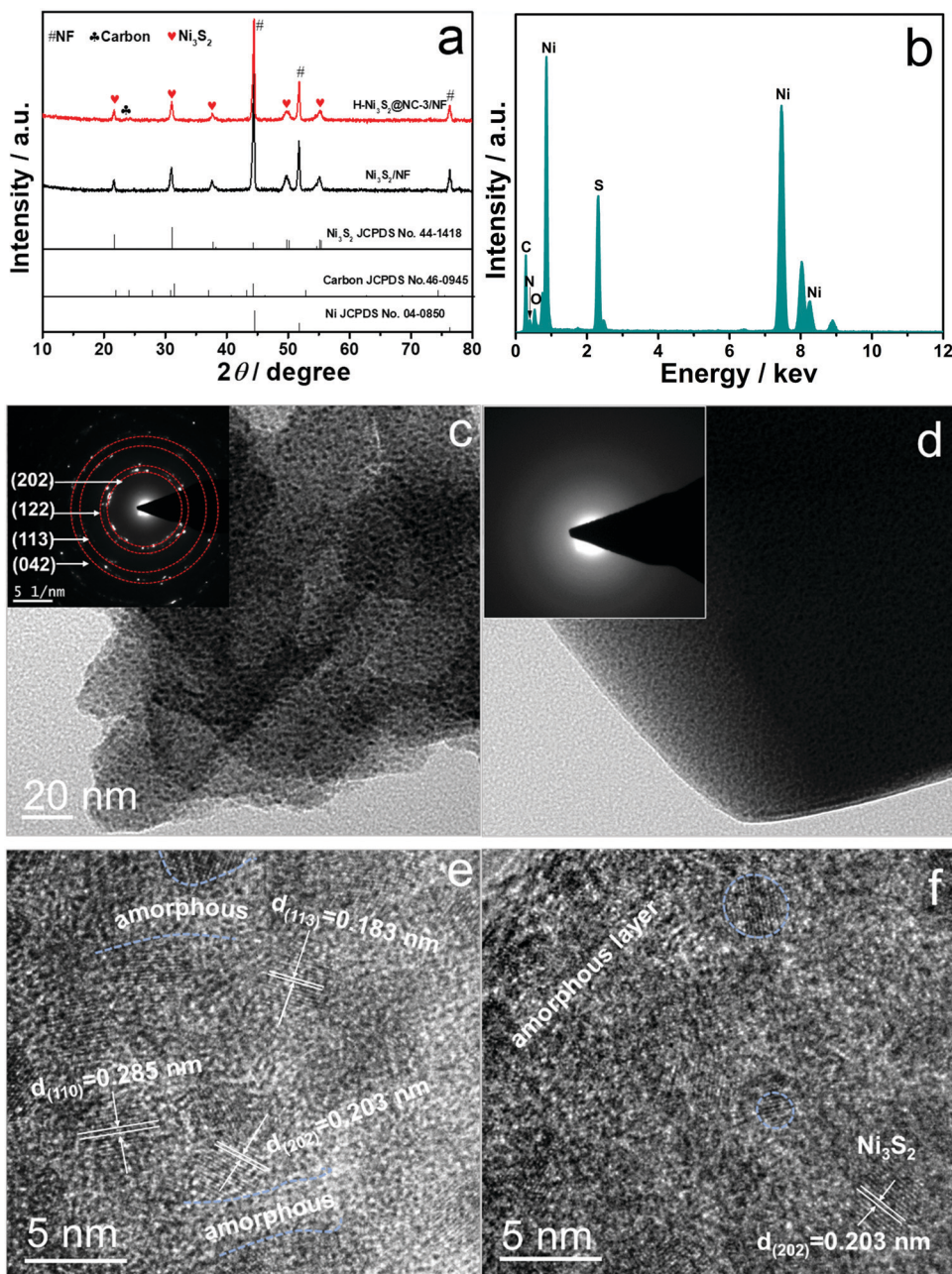


Fig. 2 XRD patterns (a) of $\text{Ni}_3\text{S}_2/\text{NF}$ and $\text{H-Ni}_3\text{S}_2@\text{NC-3/NF}$; EDS spectrum (b) of $\text{H-Ni}_3\text{S}_2@\text{NC-3/NF}$; TEM with SAED patterns (inset of c and d), and HRTEM images for broccoli-like Ni_3S_2 (c and e) and multilayered polyhedrons (d and f), respectively.

As for $\text{H-Ni}_3\text{S}_2@\text{NC-3/NF}$, the XPS survey spectrum shown in Fig. 3a exhibits Ni, S, C, N and O elements. The presence of N elements suggests successful N-doping and, more importantly, the controllable structure formation induced by the nickel-TU coordination complex.³¹ In high-resolution Ni 2p spectrum (Fig. 3b), the peaks at 855.84 and 873.54 eV are ascribed to Ni 2p_{3/2} and Ni 2p_{1/2}, respectively.³² The other peaks at 852.48 and 869.76 eV are indexed to metal Ni. The peaks located at 861.22 and 879.57 eV are assigned to Ni 2p (Sat.). The XPS spectrum of S 2p shown in Fig. 3c displays three peaks at 161.80, 162.95 and 165.60 eV, attributing to S 2p_{3/2}, S-metal bond and surface oxidation.³³ The XPS spectrum of N 1s (Fig. 3d) displays a

characteristic peak of C–N=C at 398.26 eV, suggesting the existence of N elements in $\text{H-Ni}_3\text{S}_2@\text{NC-3/NF}$.³⁴ The XPS spectrum of C 1s (Fig. 3e) reveals the presence of C=C/C–C (284.40 eV), C–N/C–S (285.43 eV) and O=C–O (288.31 eV).^{35,36} Similarly, XPS spectrum of O 1s (Fig. 3f) shows the characteristic O=C at 532.03 eV, and the peak at 530.57 eV is assigned to metal–oxygen.³⁷ Here, TU served as N and C precursor bridges with nickel salts in the presence of porous NF, leading to reconstructed microspheres and multilayered polyhedrons on NF spontaneously. This unprecedented morphology and electronic structure are convenient for ion diffusion and charge transfer.³⁸



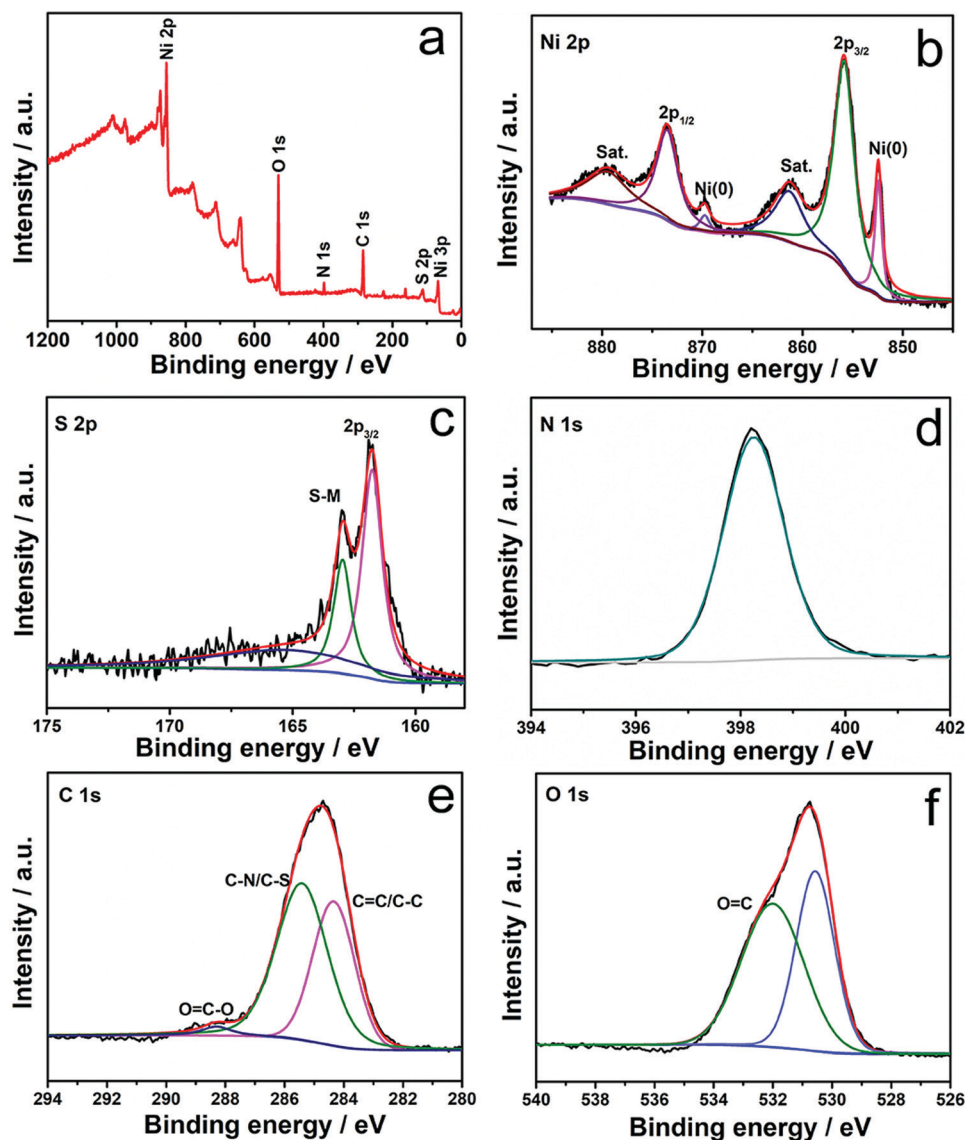


Fig. 3 XPS survey spectra (a) and high-resolution XPS spectra of Ni 2p (b), S 2p (c), N 1s (d), C 1s (e), and O 1s (f) for H-Ni₃S₂@NC-3/NF.

3.2 Growth mechanism

Surprisingly, the addition of Ni²⁺ precursor leads to extensive difference in composition and morphology. The unique formation of polyhedrons on NF by a self-templated solvothermal method has been rarely reported. We speculate that the addition of Ni²⁺ acts as a structure-directing agent, resulting in the coexistence of microspheres and polyhedrons. To further investigate the growth mechanism of H-Ni₃S₂@NC-3/NF, contrast experiments are systematically carried out based on the reaction temperature, time, metal substrate, as well as Ni²⁺ and S sources. Ultimately, the formation mechanism is proposed that the Ni²⁺ precursor coordinates with TU to form multilayered polyhedrons with simultaneous growth of nanosheet-reconstructed microspheres on the NF driven by different diffusion rates of nickel in reaction systems.

The formation of H-Ni₃S₂@NC-3/NF presents high reliance on temperature (Fig. 4). The SEM images in Fig. S6 (ESI[†]) verify the successful synthesis of H-Ni₃S₂@NC-3/NF at 150, 160, 170,

and 180 °C although in a relatively irregular shape, while some polyhedrons on the NF prepared at 180 °C show the tendency of

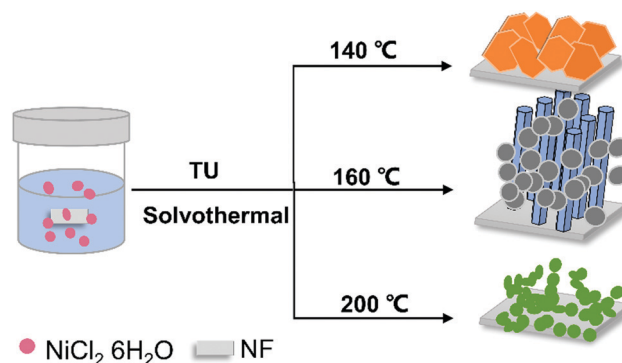


Fig. 4 Schematic of the preparation of H-Ni₃S₂@NC-3/NF at 140, 160 and 200 °C for 8 h.



structural collapse. In addition, only nanosheets and microspheres presented at 140 and 200 °C, respectively. This phenomenon indicates a temperature-dependent synthesis of H-Ni₃S₂@NC-3/NF, which means that thiourea releases H₂S etching NF to form nanosheet-like Ni₃S₂ at 140 °C. In the region of 150–180 °C, H₂S etching NF accompanied by the isomerization of thiourea and nickel ion coordination complexes leads to hierarchical N-doped carbon-encapsulated Ni₃S₂. When the temperature reaches 200 °C, only microsphere-like Ni₃S₂ presented on NF, which may be due to the melting of thiourea. The crystalline structure of samples obtained at 140, 160 and 200 °C is assigned to hexagonal Ni₃S₂ (JCPDS No. 44-1418), suggesting the facile construction of Ni₃S₂ at different temperatures (Fig. S7a, ESI†). It is noted that the optimal temperature is decided by OER performance, as shown in Fig. S7b (ESI†). H-Ni₃S₂@NC-3/NF prepared at 160 °C shows great electroactivity with a lower overpotential and a higher current density, which may be due to the synergistic effect of the internal highly active nanoparticles with the exposed (110) plane of Ni₃S₂ and the outer N-doped carbon in the sample, resulting in enhanced active sites on the catalyst surface.³⁹

With the increase in reaction time, nanosheets accumulate to micron-sized polyhedrons. In detail, the Ni²⁺ precursor coordinated with TU leads to multilayer stacked nanosheets on NF in the first 2 h (Fig. S8a, ESI†) due to the abundant dangling bond on the surface of the 2D interlayer. Subsequently, smaller-sized nanosheets reconstruct to larger-sized polyhedrons with increasing layer thickness as time goes on (Fig. S8b–d, ESI†). Simultaneously, microsphere-like Ni₃S₂ grows on the NF by the diffusion rate difference based on adding Ni²⁺ and NF substrates. Here, TU as a complexing agent offers C, N and S elements, achieving an obvious polyhedral structure with N-doped carbon intercalation. In order to investigate the effect of the NF substrate and TU on hybrid formation, a Ni plate (NP), carbon cloth (CC) and Na₂S were used as alternatives in the process of H-Ni₃S₂@NC-3/NF, and named H-Ni₃S₂/NP, Ni₃S₂/CC and Ni₃S₂/NF nanoparticles, respectively. Evidently, the NF substrate is the key to anchor the position of polyhedrons. As shown in Fig. S9 (ESI†), H-Ni₃S₂/NP presents little amounts of polyhedrons on dense NP, revealing propense anchoring on porous substrates. However, Ni₃S₂/CC shows the absence of polyhedrons due to the inert substrate of CC, indicating the importance of the 3D porous Ni substrate. Ni₃S₂/NF nanoparticles prepared by Na₂S confirm the significant coordination of nickel–TU, resulting in innovative polyhedrons. By the light of Ni²⁺ precursors for the formation of polyhedrons, other nickel salts are studied to verify the consistent synthesis route. As displayed in Fig. S10 (ESI†), three kinds of nickel salts as Ni²⁺ precursors all successfully induced the formation of polyhedrons, except for differences in shape and surface in details. The above-mentioned results prove the nickel–TU-induced controllable synthesis of polyhedrons under certain reaction conditions.

The annealing process is carried out to manifest the bridge-interlayer structure of polyhedrons. The H-Ni₃S₂@NC-3/NF are heated at 500, 600 and 700 °C in argon atmosphere and named

A-Ni₃S₂/C-500, A-Ni₃S₂/C-600, A-Ni₃S₂/C-700, respectively. The porous NF skeleton of A-Ni₃S₂/C-700 completely collapsed at high temperatures. Interestingly, polyhedrons exfoliate to accordion-like morphology with the decrescent volume, which is attributed to the broken C–N/C–S bridge bonds under the annealing process, resulting in a weak interface of layers (Fig. S11a–c, ESI†). Moreover, A-Ni₃S₂/C-500 and A-Ni₃S₂/C-600 consist of Ni, S and C elements with obvious loss of N elements, which further proves the significance of nickel–TU template-induced growth (Fig. S11d, ESI†). The lower electrocatalytic activity of A-Ni₃S₂/C-500 and A-Ni₃S₂/C-600 than that of H-Ni₃S₂@NC-3/NF may be due to the dilapidation of the hierarchical structure with N loss and amorphous states (Fig. S12, ESI†). Comparison of the above-mentioned studies confirms the accordance between growth mechanism and reaction parameters, where Ni²⁺ acts as a structure-directing agent, TU the self-templated bridging materials, and NF the anchor substrate within the temperature range of 150–180 °C. Hence, this new synthesis route is expected to manufacture well-designed nanostructures with great electrocatalytic performance for oxygen evolution reaction.

3.3 Electrocatalytic performance

As illustrated above, H-Ni₃S₂@NC/NF can be controllably fabricated by a solvothermal method under certain conditions. Therefore, H-Ni₃S₂@NC/NF with different amounts of Ni²⁺ precursors were prepared, and the corresponding SEM images are shown in Fig. S13 (ESI†). With the increase in the amount of Ni²⁺ precursors, more polyhedrons are observed grown on the NF and the corresponding OER properties are obtained by polarization curves at 1 mV s^{−1} in 1.0 M KOH solution. As shown in Fig. S14 (ESI†), the peak at approximately 1.4 V belongs to the oxidation of Ni.⁴⁰ Clearly, H-Ni₃S₂@NC-3/NF exhibits better OER performance with a lower overpotential and a higher current density. To achieve the current density of 10 mA cm^{−2}, H-Ni₃S₂@NC-3/NF shows a lower overpotential of 238 mV than H-Ni₃S₂@NC-1/NF (270 mV) and H-Ni₃S₂@NC-5/NF (260 mV), suggesting the synergetic effect of the microsphere and polyhedron structure on OER electroactivity. Herein, the optimal H-Ni₃S₂@NC-3/NF was adopted to have a deep OER mechanism over Ni₃S₂/NF, bare NF and RuO₂/NF by LSV, Tafel slope, CV, EIS and *i*–*t* measurements in the following process.

Polarization curves of H-Ni₃S₂@NC-3/NF, Ni₃S₂/NF, bare NF and RuO₂/NF are obtained at a scan rate of 1 mV s^{−1} in 1.0 M KOH solution (Fig. 5a). Ni₃S₂/NF displays enhanced OER performance with a lower potential and a higher current density than those of bare NF, suggesting the intrinsic activity of Ni₃S₂ materials. However, Ni₃S₂/NF exhibits an unsatisfactory potential of 1.75 V inferior to RuO₂/NF. When adding Ni²⁺, the obtained H-Ni₃S₂@NC-3/NF shows better electroactivity of 1.59 V at a current density of 50 mA cm^{−2} than Ni₃S₂/NF and RuO₂/NF. Compared with Ni₃S₂/NF, a positive shift of Ni 2p and a negative shift of S 2p are observed in Fig. S15 (ESI†) for H-Ni₃S₂@NC-3/NF due to the strong electronegativity of N, indicating the successful N-doping-modified electronic structure.¹⁶



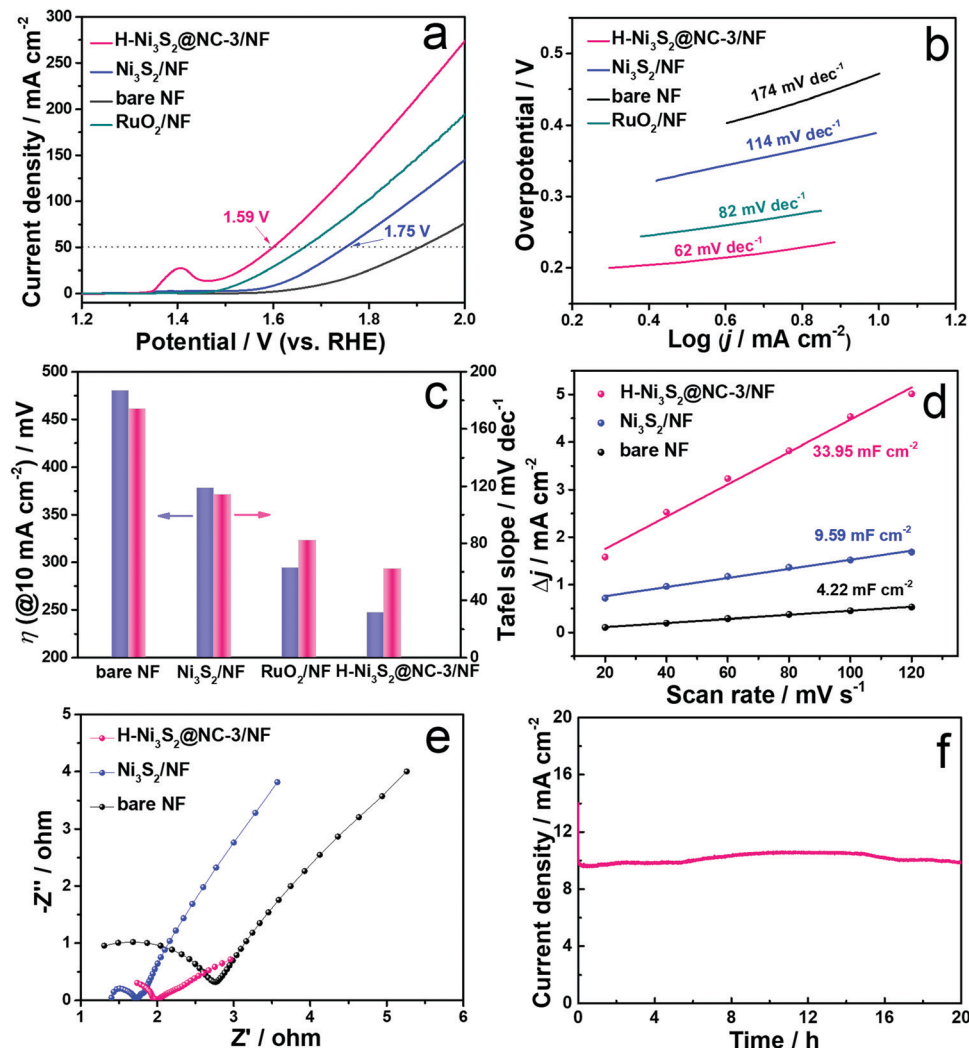


Fig. 5 Polarization curves (a), Tafel slope (b), comparison of η_{10} and Tafel value (c), C_{dl} plots (d), Nyquist plots (e) of H-Ni₃S₂@NC-3/NF, Ni₃S₂/NF and bare NF, long-term stability (f) of H-Ni₃S₂@NC-3/NF for 20 h.

The intensity of Ni(0) for H-Ni₃S₂@NC-3/NF is lower than Ni₃S₂/NF, suggesting the structure agent of Ni²⁺ leads to more high valence of Ni on the surface of H-Ni₃S₂@NC-3/NF. As well known, the high valence of transition metal promotes the charge transfer of intermediates on the catalyst surface. In addition, the superior performance of the catalyst is highly relevant to the morphology structure, crystal phase and electronic structure, thereby resulting in effective active sites and suitable adsorption/desorption energy.⁴¹ The excellent OER performance of H-Ni₃S₂@NC-3/NF is attributed to the following reason: (i) nanosized surface engineering of microspheres and multilayer polyhedrons; (ii) amorphous states observed in HRTEM images and (iii) N atom-modified electronic structure.

To elucidate the kinetics of the as-prepared materials, Tafel slopes were acquired deriving from polarization curves. As presented in Fig. 5b, H-Ni₃S₂@NC-3/NF shows a Tafel slope of 62 mV dec⁻¹, while RuO₂/NF, Ni₃S₂/NF and bare NF display a Tafel slope of 82, 114 and 174 mV dec⁻¹, respectively. The lower value of Tafel slope indicates fast charge transfer between the

intermediates and the catalyst surface. The comparison of overpotential at 10 mA cm⁻² and the corresponding Tafel slope for the as-prepared materials are described in Fig. 5c, suggesting considerable electroactivity of H-Ni₃S₂@NC-3/NF among RuO₂/NF, Ni₃S₂/NF and bare NF.

To further explore the intrinsic OER electroactivity, CV curves are performed at a scan rate of 5–120 mV s⁻¹ (Fig. S16, ESI[†]). Double-layer capacitances (C_{dl}) shown in Fig. 5d are plotted by the difference between the current density and the scan rate, which is positively correlated with the electrochemical surface area (ECSA). As expected, H-Ni₃S₂@NC-3/NF (33.95 mF cm⁻²) exhibits 3.5 times higher C_{dl} value than that of Ni₃S₂/NF (9.59 mF cm⁻²) and bare NF (4.22 mF cm⁻²). The high C_{dl} value indicates large ECSA and enriched active sites, which is consistent with the results of polarization curves. EIS was carried out at an AC-amplitude of 5 mV and the corresponding fitted Nyquist plots are displayed in Fig. 5e. The Nyquist plots consist of the high-frequency semicircle and the low-frequency straight line, where the semicircle stands for charge transfer



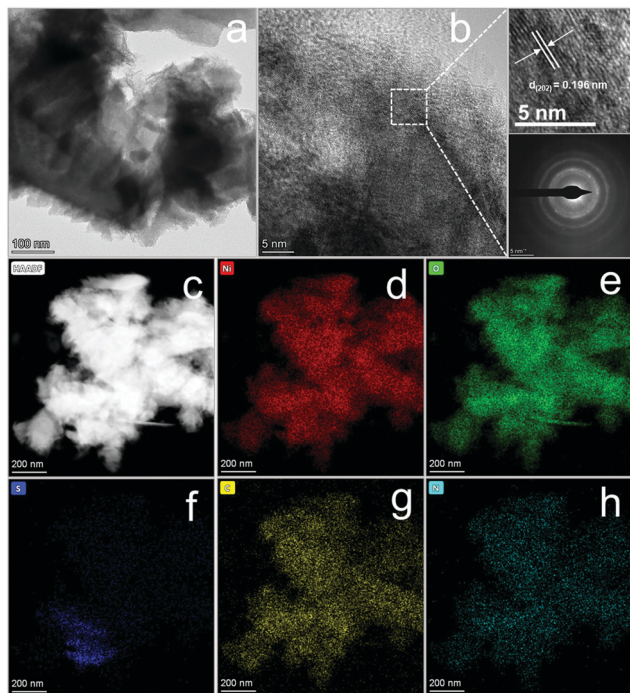


Fig. 6 TEM image (a), HRTEM image (b) and its enlarged lattice fringe image (top) and SAED pattern (down) and elemental mapping images (c–h) of H-Ni₃S₂@NC-3/NF after a long-term *i*-*t* test.

resistance (R_{ct}). The smaller semicircle diameter corresponds to smaller electrochemical impedance of the as-prepared electrode. As shown in Fig. 5e, the lowest R_{ct} of H-Ni₃S₂@NC-3/NF reveals high conductivity of active materials due to the modification of its interlayer carbon.

It is generally acknowledged that a good catalyst shows long-term stability. As depicted in Fig. 5f, H-Ni₃S₂@NC-3/NF exhibits an approximately straight line, indicating the vigorous oxygen evolution process. Furthermore, XRD patterns (Fig. S17a, ESI[†]) suggest the unchanged crystal structure of Ni₃S₂ except for increased intensity after long-term oxygen production. SEM images (Fig. S17b and d, ESI[†]) of H-Ni₃S₂@NC-3/NF for post-OER reveal the formation of nanosheet morphology by an electrocatalytic self-oxidation process. The EDS spectrum (Fig. S17c, ESI[†]) suggests the composition of Ni, S, N, C and O elements, whereas the amount of N elements decreases to an extremely low content. The XPS survey spectrum of H-Ni₃S₂@NC-3/NF for post-OER shows Ni, S, C and O elements (Fig. S18a, ESI[†]). The N element with an extremely low content is not observed, which is in good agreement with the EDS results (Fig. S17c, ESI[†]). The slight decrease in current density after 4 h, as shown in Fig. 5f, may be due to the absence of N-doping, confirming the significance of electronic modification. In addition, the high-resolution XPS spectrum of Ni 2p shows high contents of Ni(III), which is ascribed to the surface oxidation during long-term electrocatalytic process.⁴² The high-resolution XPS spectrum of S 2p reveals the characteristic peak of S-M, indicating the favorable stability of H-Ni₃S₂@NC-3/NF. Although electrocatalytic self-oxidation leads to N loss, it causes

high valence of the Ni center, which is believed to be the effective active site for OERs.⁴³ Moreover, the TEM image, HRTEM image, SAED pattern, and HAADF-element mapping images of the catalyst after long-term stability are shown in Fig. 6. As shown in Fig. 6a, nanosheets formed on the surface of the catalyst after long-term stability test, which is due to the vigorous electrooxidation of oxygen-containing intermediates. Additionally, the resultant nanosheets show a distinct lattice fringe of 0.196 nm, which is assigned to the (202) plane of Ni₃S₂, as shown in Fig. 6b and its enlarged images. The elemental mapping images (Fig. 6c–h) indicate the composition of Ni, S, C, N, and O elements, which are in full agreement with the above-mentioned results of EDS and XPS. Therefore, this unique H-Ni₃S₂@NC-3/NF with continuous electroactivity is considered as a promising alternative to noble-metal-based catalysts for OERs.

4 Conclusions

In summary, TU-templated synthesis of hierarchical H-Ni₃S₂@NC-3/NF and corresponding growth mechanism are proposed. The self-supporting electrocatalyst has been systematically prepared by a solvothermal method with different reaction factors including temperature, time, content, S source, Ni source and substrate. The growth mechanism demonstrates that nickel-thiourea coordination converts N-doped intercalation into multilayered polyhedron-like Ni₃S₂ with nanosheet-reconstructed broccoli-like Ni₃S₂ grown on the NF substrate spontaneously driven by the addition of nickel that induced diffusion rate differences. Compared with Ni₃S₂/NF, the as-prepared H-Ni₃S₂@NC-3/NF exhibits enhanced OER electrocatalytic performance with an overpotential of 238 mV at a current density of 10 mA cm⁻² and long-term stability. Our work proposes a new route to fabricate N-doped carbon-intercalated hierarchical metal sulfides as self-supporting electrodes for water splitting.

Conflicts of interest

The authors declare no conflict of interest.

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