Green synthesis of NiFe LDH/Ni foam at room temperature for highly efficient electrocatalytic oxygen evolution reaction

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ABSTRACT Clean energy technologies such as water splitting and fuel cells have been intensively pursued in the last decade for their free pollution. However, there is plenty of fossil energy consumed in the preparation of the catalysts, which results in a heavy pollution. Therefore, it is much desired but challenging to fabricate high-efficiency catalysts without extra energy input. Herein, we used a facile one-pot room-temperature method to synthesize a highly efficient electrocatalyst of nickel iron layered double hydroxide grown on Ni foam (NiFe LDH/NF) for oxygen evolution reaction (OER). The formation of the NiFe LDH follows a dissolution-precipitation process, in which the acid conditions by hydrolysis of Fe^{3+} combined with NO_3^- could etch the NF to form Ni^{2+} . Then, the obtained Ni^{2+} was co-precipitated with the hydrolysed Fe^{3+} to *in situ* generate NiFe LDH on the NF. The NiFe LDH/NF exhibits excellent OER performance with a low potential of about 1.411 V vs. reversible hydrogen electrode (RHE) at a current density of 10 mA cm^{-2} , a small Tafel slope of 42.3 mV dec^{-1} and a significantly low potential of $\sim 1.452 \text{ V}$ vs. RHE at 100 mA cm^{-2} in 1 mol L^{-1} KOH. Moreover, the material also keeps its original morphology and structure over 20 h. This energy-efficient strategy to synthesize NiFe LDH is highly promising for widespread application in OER catalyst industry.

Keywords: green synthesis, nickel iron layered double hydroxide, room temperature, electrocatalyst, oxygen evolution reaction (OER)

INTRODUCTION

The massive fossil consumption has caused increasing environmental pollution and global warming, which has

stimulated extensive research on many alternative sustainable and green energy carriers, for instance, water splitting and fuel cells [1,2]. In order to achieve high energy conversion and storage efficiency, substantial efforts have been made for rational design of electrocatalysts to reduce the overpotential of electrode reactions [3–5]. An appropriate electrocatalyst should possess outstanding catalytic activity and environmental friendliness [6–10]. Besides, the cost of catalyst also has to be considered, including material and the manufacturing cost. The noble-metal based materials are unfit for practical applications due to their high price and low reservation, although they present the state-of-the-art electrocatalytic performance [11–13]. Up to now, many noble-metal-free materials were designed to give excellent catalytic activities for these electrochemical processes to improve their energy conversion efficiency [14–16]. Nevertheless, their preparation procedure needs to input high cost and leads to a vicious cycle, which hinders their applications in reality. Therefore, it is urgent to develop a green synthetic strategy for non-noble-metal electrocatalysts with high efficiency without extra energy input.

Various non-precious metal materials, such as first-row transition metal oxide, hydroxide and their derivatives, have been extensively studied as electrocatalytic catalysts/precatalysts for oxygen evolution reaction (OER) due to their excellent performance and high reserves [17–24]. Among them, nickel iron-based materials (e.g., NiFe layered double hydroxide (NiFe LDH), NiFe hydroxide, NiFe oxide) have been regarded as one of the most efficient noble-metal-free alternatives towards OER in alkaline media [25–32]. To synthesize these catalysts, the

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conventional methods mainly include hydrothermal/solvothermal, co-precipitation and electrolytic deposition. For instance, Liu *et al.* [33] used hydrothermal method to synthesize single-crystalline Fe-Ni(OH)₂ nanoflake arrays on Ni foam (NF), showing self-activated electrocatalysis for OER. Gong and co-workers [34] reported a NiFe LDH nanoplate/CNT complex for advanced OER electrocatalysis by solvothermal method. Qi *et al.* [35] synthesized porous nickel-iron oxide *via* co-precipitation reaction at 60°C, which exhibited highly efficient OER performance. Lu *et al.* [36] prepared amorphous NiFe hydroxide nanosheets on Ni foam *via* electrodeposition as efficient OER electrode. However, all these approaches require extra energy replenishment, which costs a lot and runs counter to green energy. Consequently, it is necessary to exploit new cost-effective strategies to synthesize high-efficiency NiFe based materials without extra energy supply. Furthermore, the transitional-metal-based electrocatalysts usually combine with polymer binders like Nafion as electrodes, which results in poor conductivity and inferior mechanical stability [35,37]. A feasible solution is to directly grow active electrocatalysts on conductive substrate such as Ni foam (NF) as electrode.

Herein, we used a facile one-pot room-temperature method without any extra energy input to synthesize nickel iron layered double hydroxide grown on NF (NiFe LDH/NF). And the as-prepared NiFe LDH/NF was directly used as working electrode and exhibited excellent OER performance with a potential of about 1.411 V *vs.* reversible hydrogen electrode (RHE) at a current density of 10 mA cm⁻², a small Tafel slope of 42.3 mV dec⁻¹ and a significantly low potential of ~1.452 V *vs.* RHE at 100 mA cm⁻² in 1 mol L⁻¹ KOH and remained its original morphology and structure over 20 h.

EXPERIMENTAL SECTION

Chemicals

All chemicals were used as received without further purification. Iron (III) nitrate nonahydrate (AR ≥99.0%), iron (III) chloride hexahydrate (AR ≥99.0%), nickel nitrate hexahydrate (AR ≥98.0%), hydrochloric acid (36 wt.% in H₂O) and ethanol (AR, anhydrous, ≥99.7%) were of analytical grade and obtained from Sinopharm Chemical Reagent Co., Ltd. KOH solution (HPLC, 45 wt.% in H₂O) was purchased from Sigma-Aldrich. Ruthenium (IV) dioxide (metal basis, 99.9%) was purchased from Alfa Aesar. The deionized water for the experiments was purified through a Millipore system.

Synthesis of NiFe LDH/NF

Typically, a piece of NF (2 cm×3 cm) was precleaned in 5 mol L⁻¹ HCl under sonication, and then washed with water and ethanol. Then, 60 mg Fe(NO₃)₃·9H₂O was dissolved in a mixture of 15 mL deionized water and 5 mL ethanol under continuous stirring for 5 min. Subsequently, the prepared NF was immersed in the above solution and left undisturbed at room temperature for 24 h. Then, the products were obtained and washed with deionized water for several times. Loading amount of the NiFe LDH in NiFe LDH/NF is about 0.51 mg cm⁻² according to the inductively coupled plasma mass spectrometry (ICP-MS) technology.

Synthesis of Ni(OH)₂/NF

To prepare Ni(OH)₂/NF, 87 mg Ni(NO₃)₂·6H₂O was dissolved in a mixture of 30 mL deionized water and 10 mL ethanol under continuous stirring for 5 min. Subsequently, the solution was transferred into a 50 mL Teflon-lined stainless steel autoclave and the prepared NF was immersed in it to react at 180°C for 6 h. The Ni(OH)₂ loading amount of Ni(OH)₂/NF is about 2.13 mg cm⁻².

Characterization

The morphologies of the products were characterized through a Tecnai G2 F20 S-Twin transmission electron microscope (TEM) at an acceleration voltage of 200 kV, and a Quanta 400 FEG scanning electron microscope (SEM) at 20 kV, respectively. Energy-dispersive spectroscopy (EDS) and high resolution TEM (HR-TEM) were also recorded on Tecnai G2 F20 S-TEM. Atomic force microscopy (AFM) images were obtained on an ICON Bruker instrument operating in ScanAsyst mode at room temperature. Powder X-ray diffraction (XRD) patterns were recorded on a Bruker D8 Advance powder X-ray diffractometer at a scanning rate of 4° min⁻¹, using Cu-Kα radiation (λ=1.54056 Å). X-ray photoelectron spectroscopy (XPS) data were performed by a PHI 5000 Versaprobe X-ray photoelectron spectrometer, using nonmonochromatized Al-Kα X-ray as the excitation source. ICP-MS technology was recorded on Thermo Fisher Scientific ICAP Qc.

Electrochemical measurement

Synthesis of RuO₂/NF electrode: 5 mg RuO₂ powder and 32 μL of 5 wt.% Nafion solution were dispersed in 0.968 mL of 4:1 (V/V) water/ethanol by sonication for at least 30 min to form a homogeneous ink. Then 50 μL of the catalyst ink (containing 0.25 mg of RuO₂ catalyst) was loaded onto a 1 cm×1 cm NF.

The OER tests were carried out in a three electrode electrochemical cell by using CHI660E with an Ag/AgCl (3 mol L⁻¹ KCl) electrode as the reference electrode and a Pt foil electrode as the counter electrode in 1 mol L⁻¹ KOH. 1 cm×1 cm NiFe LDH/NF, Ni(OH)₂/NF, RuO₂/NF and bare NF were investigated as the working electrode. Linear scanning voltammetry (LSV) was carried out at a scan rate of 2 mV s⁻¹. Electrochemical impedance spectroscopy (EIS) was recorded in the frequency range of 0.1 Hz to 100 kHz with an amplitude of 5 mV. All the potentials reported in this work are with 95% *iR* correction, which are given *versus* RHE according to $E_{\text{vs. RHE}} = E_{\text{vs. Ag/AgCl}} + E_{\text{Ag/AgCl}}^{\theta} + 0.059 \text{ pH}$.

Faradaic efficiency: Assuming that four electrons are needed to produce one O₂ molecule, the Faradaic efficiency (η) can be calculated as follows:

$$\eta = 4 \times F \times n_{\text{O}_2} / Q, \quad (1)$$

where F is the Faraday constant. n_{O_2} is the number of moles of total produced O₂, which was measured using drainage gas gathering method. Q is the total charge passed through the cell: $Q = I \cdot t$ (C), where I and t are the constant oxidation current (A) and time (s).

RESULTS AND DISCUSSION

The NiFe LDH/NF was synthesized *via* a simple one-pot room-temperature method shown in Fig. 1a. Typically, a piece of NF after acid treatment was immersed in a H₂O/ethanol solution containing Fe(NO₃)₃, and left undisturbed at room temperature for 24 h, then the NiFe LDH/NF was obtained. The morphology of the NiFe LDH/NF was carefully characterized. As shown in Fig. 1b and Fig. S1, the SEM images reveal that the well-aligned NiFe LDH arrays are laid on the NF. And the TEM image in Fig. 1c details the NiFe LDH with ultrathin film structure, presented by the AFM image in Fig. S2. An HRTEM image in Fig. 1d features that the NiFe LDH has an interplane distance of the lattice fringe of 0.25 nm, which corresponds to that of the (012) facet of NiFe LDH. Then, the powder XRD pattern of the NiFe LDH/NF was characterized. As displayed in Fig. S3, only Ni foam peaks could be found and the signal of NiFe LDH was undetectable which was ascribed to the very thin NiFe LDH film on NF substrate. Then, the NiFe LDH was scraped off the substrate and collected to measure its crystal phase. In Fig. 1e, the XRD pattern presents the major diffraction peaks at 11.4°, 23.6°, 34.5°, 60.3°, which can be indexed to the (003), (006), (012), and (110) facets of the hydrotalcite-like NiFe LDH [38]. The EDS (Fig. S4) was further executed to demonstrate the presence of Ni, Fe

Figure 1 (a) The synthetic process of NiFe LDH/NF at room temperature. Characterization of the NiFe LDH, (b) SEM image, (c) TEM image, (d) HRTEM image, (e) XRD pattern, (f–i) HAADF STEM image and EDS element mappings. Scale bar: 50 nm. The NiFe LDH sample for XRD pattern, TEM, and EDS element mappings was scraped off the substrate and dispersed in ethanol ultrasonically.

and O. And the high-resolution high-angle annular dark-field (HAADF) STEM image and the corresponding EDS element mapping of the sample in Fig. 1f–i illustrate that the Ni, Fe and O were homogeneously distributed in the NiFe LDH. In order to evaluate the electrocatalytic activity of NiFe LDH/NF, a control sample of Ni(OH)₂ nanosheet on NF (Ni(OH)₂/NF) was prepared as characterized in Figs S5–S7. The SEM images of the Ni(OH)₂/NF demonstrate the well-defined Ni(OH)₂ nanosheet vertically grown on the NF. The HRTEM image and XRD pattern indicate that the sample is β -phase Ni(OH)₂.

Further, the surface chemical states of the NiFe LDH/NF were investigated by XPS. As depicted in Fig. 2a, the survey spectra confirm that the NiFe LDH/NF are composed of Fe, Ni, O and no Fe signal presents in Ni(OH)₂/NF, which highly agree with the EDS results. The high resolution Fe 2p region in Fig. 2b exhibits three binding

Figure 2 (a) XPS survey spectra of the NiFe LDH/NF and Ni(OH)₂/NF. (b) Deconvoluted high resolution Fe 2p region of the NiFe LDH/NF. (c) High resolution Ni 2p region of the NiFe LDH/NF and Ni(OH)₂/NF. (d) High resolution O 1s region of the NiFe LDH/NF and Ni(OH)₂/NF.

peaks at 711.9, 724.9 and 717.5 eV belong to Fe 2p_{3/2}, Fe 2p_{1/2} and satellite peaks, suggesting the +3 oxidation state of the Fe species in NiFe LDH/NF [35]. In Ni 2p spectrum of NiFe LDH/NF (Fig. 2c), the peaks at 855.8 and 873.5 eV correspond to the Ni²⁺, accompanied by two prominent shakeup satellite peaks (861.6 and 879.5 eV). The peaks at 852.5 and 869.5 eV belong to Ni⁰, emanating from the underlying NF substrate. Moreover, compared with Ni(OH)₂/NF, the Ni 2p_{3/2} and Ni 2p_{1/2} peaks in NiFe LDH/NF shift to higher binding energy by about 0.4 eV, which is attributed to the electron transfer from the Ni d band to the Fe d band, indicating strong interaction between the Fe³⁺ and Ni²⁺ species in NiFe LDH/NF [35,37]. In high-resolution O 1s spectrum of NiFe LDH/NF (Fig. 2d), the peaks at 529.4, 531.4 and 533.2 eV are assigned to metal-O (Fe-O and Ni-O), metal-OH and adsorbed H₂O species, respectively [37]. Compared with Ni(OH)₂/NF, the metal-OH peak in NiFe LDH/NF also exhibits a positive shift of about 0.4 eV, further suggesting the strong electron interaction between the Fe³⁺ and Ni²⁺ species in NiFe LDH/NF, which transforms the chemical state of oxygen and affects the binding energy of O 1s. This is conducive to improving the OER activity of the

NiFe LDH/NF. Additionally, in Ni 2p region of the Ni(OH)₂/NF, the peaks of Ni⁰ disappeared because of the thick layer of covered Ni(OH)₂ nanosheet on NF.

The growth mechanism of the NiFe LDH/NF follows a dissolution-precipitation process. It is known that Fe(NO₃)₃ are readily to hydrolyze in water, which makes the solution acidic (pH = 2.3 in our system) (Equation 2) and etches the NF surface to form Ni²⁺ ions (Equation 3) based on the standard electrode potentials of $E^\theta(\text{NO}_3^-/\text{NO}) = 0.96 \text{ V}$, $E^\theta(\text{Ni}^{2+}/\text{Ni}) = -0.257 \text{ V}$ [39]. The generated Ni²⁺ ions are then co-precipitated with Fe³⁺ ions to *in situ* form NiFe LDH on the NF (Equation 4). This synergy effect between Fe³⁺ and Ni²⁺ ions gives rise to the formation of NiFe LDH.

It was noteworthy that the NO₃⁻ plays a crucial role in the formation of NiFe LDH. When the Fe(NO₃)₃ change

Figure 3 OER performance of the NiFe LDH/NF, Ni(OH)₂/NF, RuO₂/NF and bare NF. (a) The polarization curves at a scan rate of 2 mV s⁻¹ in 1 mol L⁻¹ KOH. (b) The corresponding Tafel plots. (c) Nyquist plots at potential of 1.48 V vs. RHE, inset: large-magnification Nyquist plots. (d) Chronoamperometric curve of NiFe LDH/NF at ~1.48 V vs. RHE without *iR* correction.

to FeCl₃, the NF remains its innate surface and no NiFe LDH forms under the same reaction conditions (Fig. S8). We deem that, although, the $E^0(\text{Fe}^{3+}/\text{Fe}^{2+})$ of 0.771 V is larger than $E^0(\text{Ni}^{2+}/\text{Ni})$ of -0.257 V, the strong coordination between Cl⁻ and Fe³⁺ could suppress the growth of NiFe LDH on the NF with FeCl₃ as Fe source. Moreover, the NO₃⁻ can also stabilize the NiFe LDH. In this NiFe LDH system, Fe³⁺ replaces partial Ni²⁺ sites in the Ni(OH)₂ lattice, which results in the LDH lattice with positive charges, and consequently the anion NO₃⁻ must incorporate into the interlayers of the LDH to keep electric neutrality overall the LDH. The XPS spectrum of N 1s in Fig. S9 also confirms the presence of NO₃⁻.

The OER electrocatalytic performance of the NiFe LDH/NF was then carefully investigated in 1 mol L⁻¹ KOH solution using a standard three-electrode system. And the OER activities of Ni(OH)₂/NF, RuO₂/NF and NF alone were compared under similar measurements. As depicted in Fig. 3a, the polarization curves show that the NiFe LDH/NF exhibits the superior OER catalysis to the Ni(OH)₂/NF and RuO₂/NF. Then, the chronoamperometry was measured to derive the potentials for OER in Fig. S10, revealing the NiFe LDH/NF with an

extremely low potential of ~1.411 V vs. RHE to achieve the current density of 10 mA cm⁻² and a significantly low potential of ~1.452 V vs. RHE at a current density of 100 mA cm⁻². In sharp contrast, the Ni(OH)₂/NF, RuO₂/NF and NF alone exhibit rather poor OER properties (Fig. S11). It is worth noting that the outperformance of Ni(OH)₂/NF over RuO₂/NF in OER electrocatalysis is attributed to the larger mass loading of Ni(OH)₂/NF (2.13 mg cm⁻²) than that of RuO₂/NF (0.25 mg cm⁻²). Considering the surface area normalized polarization curves only reflect the overall activities, we further used mass activities to accurately elucidate the intrinsic activities of the catalysts. As shown in Fig. S12, the results suggest the outstanding OER performance of the NiFe LDH/NF. The superior OER activity of NiFe LDH/NF to Ni(OH)₂/NF is owing to the Fe species in NiFe which plays an important role in enhancing OER catalytic properties under alkaline conditions [25–32].

To further understand the OER activity of these catalysts, the electrochemical double layer capacitance (C_{dl}) measurement was conducted to calculate the electrochemical active surface area (ECSA) according to the equation of $\text{ECSA} = C_{dl}/C_s$ (C_s denotes specific capaci-

Figure 4 (a) The amount of generated O₂ with NiFe LDH/NF electrode at different times with constant current densities of 50 mA cm⁻² in 1 mol L⁻¹ KOH. (b) The corresponding chronoamperometric curve and Faradaic efficiency.

tance and is 0.040 mF cm⁻² in 1 mol L⁻¹ KOH [40,41]. As shown in Fig. S13, the C_{dl} of NiFe LDH/NF, Ni(OH)₂/NF and RuO₂/NF are 6.1, 13.3 and 5.4 mF cm⁻², respectively. And the calculated ECSA of NiFe LDH/NF, Ni(OH)₂/NF and RuO₂/NF are 152.5, 333.7 and 135.0 cm², respectively. It is noted that the ECSA of NiFe LDH/NF is smaller than that of Ni(OH)₂/NF, which is ascribed to the mass loading of NiFe LDH much less than Ni(OH)₂ to cause a lower roughness factor [40,41]. Then, the polarization curves are normalized by the ECSA in Fig. S14, also showing the superior OER activity of the NiFe LDH/NF to the Ni(OH)₂/NF and RuO₂/NF. In the cyclic voltammogram of NiFe LDH/NF (Fig. S15), an intense redox peak is observed, demonstrating that nickel oxyhydroxide (NiOOH) were *in situ* generated on the surface of NiFe LDH/NF, which united with Fe species could provide prominent catalytic activity towards OER [33].

Furthermore, the corresponding Tafel plots calculated by polarization curves in Fig. 3b illustrate that the NiFe LDH/NF yields a considerably small Tafel slope of 42.3 mV dec⁻¹, which is smaller than those of Ni(OH)₂/NF (63.2 mV dec⁻¹) and RuO₂/NF (70.1 mV dec⁻¹), implying the rapid OER kinetics and efficient electron and mass transfer of the NiFe LDH/NF. EIS measurement was carried out to evaluate the kinetics of interfacial processes for these samples. The Nyquist plots present an obvious change of charge-transfer resistance (R_{ct}) of these samples at a constant potential. As presented in Fig. 3c, the NiFe LDH/NF possesses the lowest R_{ct} (0.66 Ω) among all these samples at potential of 1.48 V, indicating the fastest charge transfer rate for OER of NiFe LDH/NF, which suggests the superior OER activities of the as-prepared NiFe LDH/NF to other samples. Additionally, durability is another significant criterion to evaluate the OER catalyst. In Fig. 3d, the chronoamperometric curve of NiFe LDH/NF tested in 1 mol L⁻¹ KOH at ~1.48 V vs. RHE

without *iR* correction illustrates that the current density had a decrease of about 20% after 20 h continuous measurement, which is attributed to the generated O₂ bubbles covered on the electrode in OER. Moreover, the SEM images, XPS spectra and XRD pattern of the NiFe LDH/NF after stability test in Figs S16–S19, present that the morphology and structure of the LDH are well preserved, further demonstrating the great durability of the NiFe LDH/NF electrode. To present the structural recoverability of NiFe LDH/NF during electrocatalysis, the periodic galvanic pluses were investigated. In Fig. S20, the periodic galvanic pulses between 10 and 40 mA cm⁻² exhibit that the current density was restorable, suggesting the great structural recoverability of NiFe LDH/NF during the catalytic OER process.

The Faradaic efficiency of the NiFe LDH/NF was measured in a gas-tight electrochemical cell in 1 mol L⁻¹ KOH. The theoretical yield of oxygen evolution was calculated by Faraday's law and assuming that four electrons were needed to produce one O₂ molecule. When current density is fixed at 50 mA cm⁻², comparing the experimental yield of the generated O₂ with the theoretical yield, the amount of oxygen evolved is very close to its theoretical data in Fig. 4a and the corresponding Faradaic efficiency is derived up to 98% (shown in Fig. 4b).

All the above data suggest that the as-prepared NiFe LDH/NF is highly efficient catalyst towards OER in terms of both catalytic activity and stability, which is superior to many other reported NiFe-based materials (shown in Table S1 and Fig. S21). This remarkable OER performance of the NiFe LDH/NF can be attributed to the following factors: 1) NF is highly conductive, which facilitates the electron transfer between the active NiFe LDH and Ni substrate; 2) porous NF offers larger specific surface area and active catalytic sites; 3) NiFe LDH has intrinsically excellent OER property [25–32]; 4) the ul-

trathin NiFe LDH *in situ* grown on NF without surfactant on the surface benefits the electron transfer between the substrate and the active species and exposes more active sites; 5) the integrated NiFe LDH/NF as catalyst is robust and promises durable catalytic performance.

CONCLUSIONS

In summary, we have successfully fabricated NiFe LDH grown on Ni foam *via* a facile, green synthetic strategy at room temperature without extra energy consumption. The formation of the NiFe LDH follows a dissolution-precipitation process, in which the acid conditions by hydrolysis of Fe^{3+} combined with NO_3^- could etch the NF to form Ni^{2+} . And then, the obtained Ni^{2+} were co-precipitated with the hydrolysed Fe^{3+} ions to *in situ* generate NiFe LDH film on the NF. In 1 mol L^{-1} KOH, the NiFe LDH/NF exhibits outstanding OER performance with a low potential of about 1.411 V vs. RHE at current density of 10 mA cm^{-2} , a small Tafel slope of 42.3 mV dec^{-1} and a significantly low potential of $\sim 1.452 \text{ V vs. RHE}$ at 100 mA cm^{-2} and superior catalytic stability. This simple and green synthetic strategy with no energy-input is environment-friendly and greatly reduces the cost of catalyst, and the as-prepared electrocatalyst offers splendid OER performance, making its grand feasibility in industrial applications.

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室温绿色合成镍铁层状双氢氧化物/泡沫镍及其高效的电催化析氧反应性能

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摘要 绿色能源技术如电解水和燃料电池等由于其无污染的特点, 近年来一直受到人们的广泛关注. 然而, 在合成其催化剂的过程中多会消耗化石能源, 从而造成环境污染, 形成恶性循环. 因此, 在无额外能量输入的条件下合成高效的电催化剂是非常必要的, 但同时又充满挑战. 本文通过简单的一步合成法在室温下制备了一种具有高效析氧催化性能的镍铁层状双氢氧化物/泡沫镍(NiFe LDH/NF)催化剂. NiFe LDH的形成遵循溶解-沉淀机理: Fe^{3+} 水解产生的酸性环境联合 NO_3^- , 刻蚀泡沫镍表面, 形成 Ni^{2+} , 随后, Ni^{2+} 与水解的Fe物种原位共沉淀于泡沫镍表面, 生成NiFe LDH. 所得到的NiFe LDH/NF在碱性环境下, 表现出高效的电催化析氧反应性能. 在 1 mol L^{-1} 的氢氧化钾溶液中, 当电流密度为 10 mA cm^{-2} 时, 其电位低至 1.411 V vs. RHE , 相应的塔菲尔斜率仅为 42.3 mV dec^{-1} , 而在电流密度为 100 mA cm^{-2} 时, 所需电位也仅为 1.452 V vs. RHE . 此外, 该材料还表现出卓越的结构稳定性. 这种绿色制备NiFe LDH/NF的合成方法有望在OER催化中得到广泛的应用.