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One-step spontaneous growth of NiFe layered double hydroxide at room temperature for seawater oxygen evolution



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ABSTRACT

Electrochemical seawater splitting is a promising technique because it addresses two major challenges, clean energy production and seawater desalination, at the same time. Therefore, seeking out a facile and cost-effective way to synthesize highly active and stable seawater-splitting catalysts is of great interest to both the research community and industry. Here we developed an Fe^{2+} -driven, one-step, and spontaneous fabrication method for a seawater-oxygen-evolution-active NiFe layered double hydroxide (LDH) at room temperature. The NiFe LDH was found to exhibit very high activity and stability toward the oxygen evolution reaction (OER) in an alkaline natural seawater electrolyte, delivering current densities of 100 and 500 mA/cm² at low overpotentials of 247 and 296 mV, respectively, and with no significant degradation observed over long-term stability testing of 96 h under a large current density of 500 mA/cm² in 1 M KOH seawater electrolyte. After coupling with a good hydrogen evolution reaction (HER) catalyst, NiMoN, the two-electrode electrolyzer was found to achieve current densities of 10, 100, and 500 mA/cm² at voltages of 1.477, 1.533, and 1.665 V, respectively, in alkaline natural seawater with good durability over 100 h at 500 mA/cm². The oxidation of Fe²⁺ is the driving force for the growth of NiFe LDH, and this mechanism is universal to the fabrication of other Fe-based hydroxides as efficient OER catalysts.

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1. Introduction

Hydrogen has been considered a promising energy resource to replace fossil fuel because of its high burning heat, low mass density, and, most importantly, carbon-free emissions. Water electrolysis is a sustainable way to produce hydrogen, but thus far most studies of water electrolysis have focused on fresh water, which is a scarce resource, especially in many arid zones [1–7]. Thus, seawater splitting is a more practical method for hydrogen production given the enormous amount of seawater. In addition, seawater electrolysis can not only generate clean energy, but also boosts the seawater desalination process because the product of hydrogen consumption is high-purity water [8,9]. That is, consuming energy from seawater electrolysis will help to generate fresh water and

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alleviate its scarcity [9–11].

However, seawater electrolysis is much more challenging than fresh water electrolysis due to the following: i) the presence of Clions in seawater will lead to the chlorine evolution reaction (CER), which is competitive with the oxygen evolution reaction (OER) [12,13]; ii) some impurity ions such as Mg²⁺ and Ca²⁺ will generate insoluble precipitates under alkaline conditions, and thus block the active sites of OER and hydrogen evolution reaction (HER) catalysts [14,15]; iii) the unavoidable poisoning effect by the complex organic and inorganic impurities in seawater [16,17]. In order to solve these challenges, great effort has been made to understand the underlying mechanism of seawater electrolysis, and some solutions corresponding to these challenges are listed below: i) Early studies showed that OER is more thermodynamically but less kinetically favorable than CER [12,18]. With a pH value higher than 7, the chemical potential between OER and CER (hypochlorite formation reaction in alkaline conditions) will be maximized, with an oxidation potential difference of about 480 mV [12,18]. That is to say, if an



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OER catalyst can generate meaningful current densities requiring overpotentials of less than 480 mV, the CER process will be thermodynamically suppressed. ii) The majority of insoluble precipitates can be removed by a simple filtration or centrifugation pretreatment prior to electrolysis. iii) While the poisoning effect by impurities is unavoidable in most situations, it is highly variable for different catalysts [9,11,19]. Thus, researchers can seek out impurity-resistant catalysts in order to minimize the poisoning effect.

NiFe layered double hydroxide (LDH) has been proved to be an efficient and stable OER catalyst under alkaline seawater conditions [9,10,20]. Currently, the most common methods to fabricate NiFe LDH are electrodeposition and hydrothermal techniques [21–25], which require either enormous energy input or elaborate equipment, and thus would introduce a financial burden to large-scale industrial application. Therefore, developing a rapid, facile, and low-energy-consumption method to fabricate NiFe LDH is of great significance for industrial application [26,27]. Recently, our group established an ultrafast room-temperature synthesis of highly active S-doped Ni/Fe (oxy)hydroxides based on the corrosion of nickel foam via Fe^{3+} and accelerated by the additive $Na_2S_2O_3$. Different from the previous work, here we further developed a onestep room-temperature spontaneous deposition of NiFe LDH nanosheets based on the oxidation of Fe²⁺ ions, which is a process that many electrodeposition researches tried to avoid [28,29]. However, in this research, we utilize the oxidation of Fe^{2+} ions to generate a highly active OER catalyst through a very facile method. Commercial nickel foam (NF) was selected as the substrate and was immersed in a Ni^{2+}/Fe^{2+} aqueous solution for several hours (1–5 h). A uniform layer of NiFe LDH nanosheets was subsequently found to have been successfully grown on the NF surface. Further electrochemical measurements showed that the NF/NiFe LDH electrode fabricated by this method exhibits very good OER activity and good stability under different seawater electrolytes. The NF/ NiFe LDH was then coupled with a state-of-art HER catalyst, NiMo nitride (NiMoN), to fabricate an outstanding seawater electrolyzer that delivers efficient and robust performance in alkaline seawater solutions.

2. Materials and method

2.1. Chemicals

Iron (II) sulfate heptahydrate (FeSO₄·7H₂O, \geq 99%, Sigma-Aldrich), iron (III) nitrate nonahydrate (Fe(NO₃)₃·9H₂O, \geq 98%, Alfa Aesar), nickel (II) nitrate hexahydrate (Ni(NO₃)₂·6H₂O, \geq 97%, Sigma-Aldrich), cobalt (II) nitrate hexahydrate (Co(NO₃)₂·6H₂O, \geq 98%, Sigma-Aldrich), ammonium fluoride (NH₄F, 96%, Alfa Aesar), sodium chloride (NaCl, Fisher Chemical), potassium hydroxide (KOH, 50% w/v, Alfa Aesar), urea (CO(NH₂)₂, Promega), ethanol (C₂H₅OH, Decon Labs, Inc.), and hydrochloric acid (HCl, 36.5–38.0% w/w, Fisher Chemical) were used without further purification. Ni foam (thickness: 1.6 mm, porosity: ~95%) pieces were applied as substrates. Deionized (DI) water was used for all of the aqueous solutions. Seawater was obtained from Galveston Bay, Galveston, Texas, USA (29.303° N, 94.772° W). Before usage, seawater was left standing for one week to settle the visible impurities, and the supernatant was collected afterward.

2.2. Growth of NiFe LDH on the surface of nickel foam

Before usage, the NF was immersed in 3 M HCl for 5 min to improve its hydrophilicity and then rinsed with DI water several times. Following this pretreatment, pieces of NF ($1.5 \times 3 \text{ cm}^2$) were immersed in 10 mL solution of 0.15 M Ni(NO₃)₂·6H₂O and 0.15 M

 $FeSO_4 \cdot 7H_2O$ at room temperature for different amounts of time (from 1 to 5 h). Finally, the NF pieces were removed and placed on filter paper to dry at room temperature. The resulting electrodes are denoted as NF/NiFe LDH.

2.3. Growth of CoFe LDH and FeOOH on the surface of nickel foam

The growth of CoFe LDH and FeOOH on the surface of NF generally follows the same procedure as that for NF/NiFe LDH. Solutions of 0.15 M Co(NO₃)₂·6H₂O + 0.15 M FeSO₄·7H₂O and of 0.15 M FeSO₄·7H₂O were employed as the reaction solutions for CoFe LDH and FeOOH, respectively. The reaction time for both CoFe LDH and FeOOH was set at 2 h. The resulting electrodes are denoted as NF/CoFe LDH and NF/FeOOH, respectively.

2.4. Material characterization

Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were conducted using a LEO 1525 SEM and a JEOL 2010F TEM, respectively. X-ray electron dispersive spectroscopy (EDS) was conducted using the JEOL 2010F TEM. X-ray photoelectron spectroscopy (XPS) was conducted using a PHI Quantera XPS scanning microprobe. Raman measurements were conducted using a homemade Raman microscope utilizing a light source of 532 nm with power of 10 mW and exposure time of 120 s.

2.5. Electrochemical characterization

Electrochemical measurements were obtained using a Gamry Reference 600 electrochemical workstation. Linear sweep voltammetry (LSV), OER stability testing and electrochemical impedance spectroscopy (EIS) were conducted on a three-electrode configuration in which a graphite electrode served as the counter electrode, a Hg/HgO electrode served as the reference electrode, and a synthesized sample served as the working electrode. The scan rate for the activity tests was 2 mV/s and the back scanning (from high to low potential) was utilized during LSV in order to characterize the activity and avoid overestimation. The current-interrupt (CI) method was utilized to introduce iR compensation. All potentials were converted into the reversible hydrogen electrode (RHE) by the equation: $E_{RHE} = E_{Hg/HgO} + 0.098 + 0.0591 \times \text{pH}$ for the convenience of comparison. The pH value of each of the different electrolytes (1 M KOH, 1 M KOH and 0.5 M NaCl, 1 M KOH nd 1 M NaCl, and 1 M KOH and seawater) was approximately 14. The chronopotentiometric technique was applied to measure the stability of the asprepared samples under current densities of 200 and 500 mA/ cm² in different electrolytes. EIS was performed at the overpotential of 300 mV for OER from 0.1 Hz to 100 kHz and data of R_{ct}, Rex and C were acquired from the Zview fitting. In the twoelectrode configuration, NF/NiMoN and NF/NiFe LDH were used as the cathode and the anode, respectively.

3. Results and discussion

The spontaneous growth of NiFe LDH at room temperature is schematically illustrated in Fig S1. In general, a piece of NF was immersed in a solution of 0.15 M Ni(NO₃)₂·6H₂O and 0.15 M FeS-O₄·7H₂O for several hours at room temperature and NiFe LDH was spontaneously grown on the NF surface based on the mechanism shown in Fig S1, in which the oxidation of Fe²⁺ is the main driving force for the spontaneous growth. Optical images of samples prepared with different amounts of immersion time are displayed in Fig S2, which shows the apparent color changes with increasing immersion time. Scanning electron microscopy (SEM) was employed to characterize the nanostructure of the as-prepared

samples. Fig S3 shows the three-dimensional (3D) porous framework of the NF substrate in general, and its smooth surface was further confirmed under higher magnifications, as shown in Fig. 1a and b. After the NF was immersed in the solution of 0.15 M Fe^{2+} and 0.15 M Ni^{2+} for 2 h, a thin layer of nanosheets was uniformly grown on its surface, as shown in Fig. 1c and d. The surface features of the samples prepared with different amounts of reaction time (1, 3, and 4 h) are presented in Fig S4. With increasing amounts of reaction time, aggregation of NiFe LDH on the NF surface continually increased, indicating the increased loading of the NiFe LDH.

Transmission electron microscopy (TEM) was applied to further reveal the nanosheet structure and crystalline features of the asprepared NiFe LDH (2 h sample). As shown in Fig. 1e and f, the typical nanosheet structure of NiFe LDH was verified at different magnifications. The selective area electron diffraction (SEAD) pattern displayed in Fig. 1g shows well-resolved diffraction rings corresponding to the (012), (015) and (113) planes of NiFe LDH. The high-resolution TEM image displayed in Fig. 1h shows the lattice fringes of the NiFe LDH planes with an interplanar distances of 0.25 nm. To determine the elemental distribution in these samples, energy-dispersive X-ray microscopy (EDX) elemental mapping was conducted and the results are shown in Fig. 1i-m. The EDX elemental mapping images clearly prove the uniform distribution of elemental Ni, Fe, and O. Moreover, the map sum spectrum of EDX mapping displayed in Fig S5 shows that the Ni/Fe ratio of our sample is about 5/3.

We then utilized X-ray photoelectron spectroscopy (XPS) to explore the surface composition and elemental states of this NF/ NiFe LDH electrode. The survey spectrum in Fig S6 confirms the coexistence of elemental Ni, Fe, and O on the surface of the NF/NiFe LDH electrode. In Fig. 2a, the peaks at 855.8 and 873.6 eV correspond to the Ni $2p_{3/2}$ and Ni $2p_{1/2}$ orbits, respectively, and two satellite peaks at 861.5 eV and 879.3 eV can also be observed, and these results indicate the Ni²⁺ oxidation state [30]. The Fe 2p spectrum (Fig. 2b) shows two dominant peaks at 713.1 eV (Fe $2p_{3/2}$) and 725.5 eV (Fe $2p_{1/2}$) and two satellite peaks at 718.9 and 727.5 eV, which are the typical characteristics of the Fe³⁺ oxidation state [31]. The O 1s spectrum in Fig. 2c displays metal-O (M – O) and metal-OH (M – OH) peaks located at 531.0 and 532.7 eV, respectively, indicating the existence of the LDH species [32]. To further confirm the successful fabrication of NiFe LDH, Raman spectroscopy was employed, and the results were analyzed. As shown in Fig. 2d, three bands located at around 276, 442, and 531 cm⁻¹ are contributed by metal-O-metal (the metal can be Ni or Fe) species [33,34]. The bands at around 966 and 1063 cm⁻¹ are ascribed to the metal-OOH active species [35]. The Raman spectroscopy results correspond to the typical brucite-like LDH structure.

The electrochemical OER performance of these samples were first investigated in a three-electrode system using 1 M KOH as the electrolyte. Linear sweep voltammetry (LSV) with iR compensation was carried out to characterize the OER activity [36]. The LSV curves of NF/NiFe LDH electrodes prepared with different amounts of reaction time displayed in Fig S7 show that there was no significant improvement in the OER performance after 2 h immersion. Since further increasing the immersion time will be time consuming, so 2 h immersion was determined to be the optimal reaction time and was used for further analysis unless otherwise indicated. It is also worth mentioning that the loading of NiFe LDH on the surface of NF reached saturation after 2 h of immersion, so further increasing the loading does not help to increase extra active sites and the OER performance. To verify the versatility of the Fe²⁺-driven fabrication, NF/CoFe LDH and NF/FeOOH samples were fabricated as examples and their OER performance is shown in Fig S8, which confirms the very good activity of the catalysts fabricated in this way. The SEM images of NF/CoFe LDH and NF/FeOOH samples are provided in Fig S9 to further confirm the successful deposition of CoFe LDH and FeOOH on the surface of nickel foam.

The OER activity values of different electrodes are also compared in Fig. 3a. After 2 h treatment at room temperature, NF/NiFe LDH was found to exhibit a significant OER enhancement compared with the original NF, and it is also superior to the benchmark



Fig. 1. (a), (b) SEM of pure NF at different magnifications. (c), (d) SEM of NF/NiFe LDH at different magnifications. (e), (f) TEM of NiFe LDH at different magnifications. (g) SAED pattern and (h) HRTEM of NiFe LDH. (i) TEM image of NiFe LDH for EDX mapping. (j) Ni, (k) Fe, (l) O, and (m) overview elemental mapping.



Fig. 2. High-resolution XPS spectra of (a) Ni 2p, (b) Fe 2p, and (c) O 1s. (d) Raman measurement of NF/NiFe LDH.

catalyst IrO₂. Note that the reduction peak of NF/NiFe LDH around 1.35 V vs. RHE in Fig S7, S8, and 3a is originated from Ni³⁺ to Ni²⁺ transformation [10]. NF/NiFe LDH requires only a very low overpotential of 202 mV to reach a current density of 10 mA/cm², while overpotentials of 304 mV and 331 mV are required for NF/IrO₂ and nickel foam, respectively, in order to reach the same current density. To achieve higher current densities of 100, 200, and 500 mA/ cm², the needed overpotentials are 237, 251, and 274 mV, respectively, for NF/NiFe LDH, which significantly outperforms both NF/ IrO₂ and NF, as shown in Fig. 3a and b. The LSV curve of NF/NiFe LDH without iR compensation is also shown in Fig S10 for comparison. The Tafel slopes of the three electrodes are shown in Fig. 3c, in which NF/NiFe LDH exhibits the lowest Tafel slope of 32.8 mV/dec, indicating its outstanding intrinsic activity. Remarkably, the OER activity of the NF/NiFe LDH in this work makes it among the best transition-metal-based OER catalysts in alkaline electrolyte (1 M KOH), as shown in Table S1. More importantly, compared with those for other state-of-the-art transition-metal catalysts, the synthetic process used for our samples is much more cost effective since it does not require high energy input or any other additives. The main driving force for the fabrication is the oxidation of Fe^{2+} at room temperature, which is a process that many researches try to avoid [28,37]. To further prove the advantages of our NiFe LDH catalyst prepared by this method, we also synthesized NiFe LDH on Ni foam via electrodeposition method (ED) and hydrothermal method (HT) for comparison [29,38]. In Fig S11, the OER performances of NF/NiFe LDH fabricated by the three methods are provided and the NF/NiFe LDH fabricated by Fe²⁺-driven method is significantly better than the other than electrodes fabricated by electrodeposition and hydrothermal methods, which verified the extremely good OER activity of NiFe LDH prepared in this work.

Electrochemical impedance spectroscopy (EIS) was employed to characterize the charge-transfer kinetics of different catalysts. In Fig. 3d and Fig S12, NF/NiFe LDH shows the lowest charge transfer resistance (R_{ct}) of about 0.564 Ω , which is much lower than that of NF/IrO₂ (~6.42 Ω) and pure NF (~13.4 Ω), demonstrating its more efficient charge transfer between the electrolyte and the catalyst surface.

We then evaluated the OER performance of our NF/NiFe LDH electrode in alkaline simulated seawater (1 M KOH and 0.5 M NaCl, and 1 M KOH and 1 M NaCl) and alkaline natural seawater (1 M KOH and seawater) electrolytes. As displayed in Fig. 3e and f, compared with its activity in 1 M KOH, NF/NiFe LDH exhibits no obvious degradation in alkaline simulated seawater, and even shows slightly better performance in higher salinity (1 M KOH and 1 M NaCl), likely due to the higher ionic concentration that contributes to higher conductivity. In alkaline natural seawater, the activity of OER catalysts usually suffers due to the poisoning effect of the complex soluble and insoluble impurities in natural seawater [9,19]. Notably, the NF/NiFe LDH electrode was found to exhibit good resistance to the poisoning effect of natural seawater and the additional overpotentials required to achieve current densities of 100, 200, and 500 mA/cm² are only 10, 15, and 22 mV, respectively, compared with those for 1 M KOH electrolyte. Most importantly, the overpotential required to achieve a large current density of 500 mA/cm² in alkaline natural seawater electrolyte (1 M KOH and seawater) is only 296 mV, far below the CER threshold of 480 mV, so hypochlorite formation can be thermodynamically suppressed [12,20].

In addition to electrochemical activity, the electrochemical stability of electrodes is also of great significance for practical applications. To evaluate the electrochemical stability of our catalyst,

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Fig. 3. (a) OER performance, (b) overpotentials required to achieve different current densities, (c) Tafel slopes, and (d) EIS for different electrodes in 1 M KOH. (e) OER performance of NF/NiFe LDH in different electrolytes. (g) Long-term OER stability tests of NF/NiFe LDH at different current densities in different electrolytes.

stability tests were conducted on NF/NiFe LDH at a large current density of 200 mA/cm² over 100 h in alkaline fresh water (1 M KOH) and in alkaline natural seawater (1 M KOH and seawater). The OER performance remained highly stable throughout the long-term continuous testing in both electrolytes, as shown in the top and middle panels of Fig. 3g. Additionally, the SEM, TEM, and XPS of NF/ NiFe LDH were measured after the stability test in alkaline natural seawater electrolyte. The SEM images in Fig S13a and S13b, along with the TEM image in Fig S13c show that the nanosheet structure of the NF/NiFe LDH was well maintained after the stability test. In addition, we can also detect the lattice fringe of (012) plane for NiFe LDH in Fig S13d after the stability test. In Fig S13e and S13f, the Ni 2p and Fe 2p XPS spectra of our sample show no significant change before and after the stability test, indicating no chemical state change after seawater OER catalysis. Therefore, these results further verify the robust physical and chemical stability of the NF/NiFe LDH in this work. We then measured the stability of our sample under an even larger current density of 500 mA/cm² over 96 h in different electrolytes, and the results are presented in the bottom panel of Fig. 3g. Clearly, the NF/NiFe LDH electrode still exhibits good durability in the four different electrolytes under a very large

current density, demonstrating its good potential for real application. As shown in Table S1, the stability of our sample is among the best in comparison with that of other recently reported transitionmetal-based OER catalysts for water oxidation. More importantly, the synthetic process for this NF/NiFe LDH electrode is facile and cost-effective, not relying on any energy input or additives, which makes it more meaningful for practical applications.

To evaluate the OER performance of NF/NiFe LDH in overall seawater splitting, we coupled it with one of the most efficient transition-metal HER catalysts, NiMoN (Fig. 4a), in order to construct a two-electrode electrolyzer. iR-corrected LSV curves were obtained for the NF/NiFe LDH||NF/NiMoN two-electrode configuration in different electrolytes and are presented in Fig. 4b and c. In the 1 M KOH electrolyte, the voltage required to deliver a current density of 10 mA/cm² was found to be only 1.464 V, making this one of the most efficient among the reported transition-metal-catalyst-based alkaline water electrolyzers (Fig. 4d). In the alkaline simulated seawater electrolytes (1 M KOH and 0.5 M NaCl, and 1 M KOH and 1 M NaCl), no obvious activity degradation was observed for our electrolyzer compared with that in alkaline fresh water, as shown in Fig. 4b and c. In the alkaline natural seawater electrolyte



Fig. 4. (a) HER performance and (inset) Tafel slope of NF/NiMoN in 1 M KOH. (b) Overall seawater splitting performance of, and (c) voltages required to drive different current densities by, NF/NiFe LDH||NF/NiMoN in different electrolytes. (d) Voltages required by different water electrolyzers to reach a current density of 10 mA/cm² in 1 M KOH [24,39–48]. (e) Faradaic efficiency measurement and (f) long-term overall seawater splitting test of NF/NiFe LDH||NF/NiMoN in alkaline natural seawater.

(1 M KOH and seawater), this electrolyzer was able to deliver current densities of 10, 100, and 500 mA/cm² at small voltages of 1.477, 1.533 and 1.665 V, respectively, which is the best alkaline seawater splitting performance reported to date. At an industry-standard current density of 500 mA/cm², the activity degradation in alkaline natural seawater was found to be only about 21 mV compared with the result in alkaline fresh water, indicating the high impurity tolerance of this electrolyzer. For comparison, the overall seawater splitting performance without iR compensation is shown in Fig S14. To study its selectivity during seawater electrolysis, we further measured the Faradaic efficiency of this electrolyzer using a sealed two-electrode configuration in 1 M KOH and seawater. A chronopotentiometric test at a constant current density of 250 mA/cm² was conducted to generate hydrogen and oxygen, and the asgenerated gas products were collected in graduated cylinders filled with water (see the Experimental section in supporting information for details). As shown in Fig. 4e, the detected amounts of hydrogen and oxygen match well with the theoretical values, indicating a Faradaic efficiency close to 100%. Therefore, the hypochlorite formation reaction was effectively suppressed under a current density as high as 250 mA/cm², demonstrating the excellent selectivity for OER by our anode catalyst.

Finally, to measure the stability of the NF/NiFe LDH||NF/NiMoN electrolyzer, we conducted overall seawater splitting at an

industry-standard current density of 500 mA/cm² for 100 h in 1 M KOH and seawater electrolyte. As shown in Fig. 4f, the NF/NiFe LDH||NF/NiMoN electrolyzer very encouragingly exhibited highly stable overall alkaline seawater splitting performance during 100 h electrolysis, and the voltage increase after the stability test was only about 0.047 V, demonstrating this electrolyzer's good resistance to poisoning and corrosion during alkaline seawater splitting.

4. Conclusions

In summary, we have developed a cost-effective way to fabricate a very efficient OER catalyst, NiFe LDH, at room temperature. The NF/NiFe LDH catalyst was found to exhibit high activity and good stability towards OER in both alkaline fresh water and alkaline natural seawater. After coupling it with a NF/NiMoN cathode, we obtained an outstanding seawater electrolyzer, NF/NiFe LDH||NF/ NiMoN, which displayed excellent activity for alkaline natural seawater splitting, as well as good durability and high selectivity. The Fe²⁺-driven synthesis of layered double hydroxides may pave a new way to fabricate other good catalysts for water splitting at a very low cost, and we believe this method will help to lower investment requirements, thus boosting the industrial application of fresh water and seawater splitting.

Credit author statement

Minghui Ning: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Libo Wu: Formal analysis, Resources, Fanghao Zhang: Formal analysis, Resources, Dezhi Wang: Resources, Shaowei Song: Formal analysis, Tian Tong: Resources, Jiming Bao: Resources, Shuo Chen: Formal analysis, Luo Yu: Formal analysis, Resources, Writing – review & editing, Supervision, Zhifeng Ren: Writing – review & editing, Supervision.

Declaration of competing interest

There are no conflicts of interest to declare.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.mtphys.2021.100419.

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