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### Introduction

With the depletion of traditional fossil fuels and increasing concerns about serious environmental issues, the search for sustainable energy sources as alternatives has gained immense attention. Among the many new energy sources, hydrogen, wind, nuclear and solar energy are the main development goals at present.<sup>1-3</sup> Meanwhile, hydrogen  $(H_2)$  is an attractive energy carrier because of its high energy, and because of it being clean and pollution-free, and is expected to become one of the main energy sources in the future.4,5 Traditional hydrogen production methods mainly include methane reorganization, water gas and electrolytic water.6,7 Compared with the other two options, hydrogen production from electrolytic water is favored by researchers because it has no pollution and the products are only hydrogen and oxygen.<sup>8-10</sup> However, water splitting usually requires a huge amount of energy to start the two halfreactions, which include the oxygen evolution reaction (OER) and the hydrogen evolution reaction (HER).<sup>11,12</sup> The inert kinetics of these half-reactions can be effectively improved by

E-mail: zhangming@zstu.edu.cn



Xiao Li,<sup>a</sup> Yudong Wu,<sup>a</sup> Shanshan Li,<sup>a</sup> Yinchen Dai,<sup>a</sup> Jibiao Guan,<sup>a</sup> Baochun Guo<sup>b</sup> and Ming Zhang<sup>b</sup>\*<sup>a</sup>

Developing high-performance and earth-abundant electrocatalysts for hydrogen production by electrolysis of freshwater/seawater is desirable but remains a huge challenge, especially in seawater solution. Herein, we report an efficient catalyst for a cathode consisting of three-dimensional standing arrays of Mo-Ni<sub>2</sub>P/CC nanosheets uniformly grown on carbon cloth, in which the Mo doping improved the HER properties of Ni<sub>2</sub>P by providing applicable morphology, electronic properties and active sites. It is found that the as-obtained catalyst shows superior HER activity with a low overpotential of 113 and 154 mV at 10 mA cm<sup>-2</sup> in 1 M KOH and simulated alkaline seawater solution, respectively. Moreover, the Mo-Ni<sub>2</sub>P/CC catalyst exhibits favorable stability in 5000 CV cycles in 1 M KOH and reasonable stability in a 20 h stability test in alkaline, simulated seawater and alkaline seawater solution. This work may provide a feasible insight into the construction and development of high-efficiency HER electrocatalysts for freshwater/seawater electrolysis.

specific electrochemical catalysts. As of now, various Pt and Ir based catalysts are still a key measurement point for the HER and the OER, respectively. However, the scarcity and the prohibitive price of noble metals severely limit their extensive application for water splitting.<sup>13-16</sup> Therefore, it is imperative to exploit electrocatalysts with high cost-effectiveness, good catalytic activity and wide application in commercial fields, especially for hydrogen production in the HER.<sup>17,18</sup>

Depending on the type of metal used, electrocatalysts can be categorized into noble metal and transition metal (TM) catalysts. Currently, non-noble TM catalysts researched mainly include oxides (TMOs),<sup>19</sup> carbides (TMCs),<sup>20</sup> sulfides (TMSs),<sup>21</sup> and phosphides (TMPs).<sup>22</sup> Among these catalysts, TMPs have attracted extensive attention in recent years due to their low price, high stability and excellent electrochemical catalytic performance.<sup>23</sup> For example, Yang and co-workers fabricated a neoteric three-dimensional self-supporting Ni-P/Ni2P/CC supported on carbon cloth, reaching a current density of 10 mA cm<sup>-2</sup> in 1 M KOH at an overpotential of 95 mV.24 In addition, heteroatomdoping is an efficient way to maximize the electronic conductivity of electrocatalysts for enhancing the electrocatalytic performance.<sup>25</sup> Zhang and co-workers assembled self-supporting Ni<sub>2</sub>P nanosheets decorated with Ru nanoparticles (Ru-Ni2P/CC) exhibiting an ultralow overpotential of 23 mV to afford 10 mA cm<sup>-2</sup> for the HER.<sup>26</sup> Due to their suitable mechanisms and functional sites, many electrocatalytic materials can effectively help the HER to proceed and show better electrocatalytic properties.



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<sup>&</sup>lt;sup>a</sup> National Engineering Lab for Textile Fiber Materials and Processing Technology, Zhejiang Sci-Tech University, Hangzhou 310018, P. R. China.

<sup>&</sup>lt;sup>b</sup> Department of Polymer Materials and Engineering, South China University of Technology, Guangzhou 510640, P. R. China

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However, another concern is that fresh water is widely used in the laboratory to study water electrolysis, which is scarce in some countries around the world and the total fresh water resources are limited.<sup>27,28</sup> If the route of electrolytic freshwater is adopted on a large scale, it will be an inevitable problem in the future. At the same time, seawater resources account for about 96.5% of the total water resources, which can be regarded as an unlimited resource.<sup>29-31</sup> Some marine related renewable power generation technologies, such as tidal energy, wind energy and solar energy, can be effectively combined with electrochemical seawater decomposition to achieve clean and sustainable energy technologies.32,33 Recently, Zhang and co-workers constructed Cu<sub>2</sub>S nanorod arrays for enhancing the HER performance via Ni-S interaction. The fabricated electrocatalyst showed a preferable HER activity within 200 mV at a current density of 500 mA cm<sup>-2</sup> in alkaline seawater.<sup>34</sup> Although many noble metal catalysts maintain good electrocatalytic performance in alkaline solution, their overpotential exceeds 490 mV at a current density of 300 mA cm<sup>-2</sup>.33,35 Consequently, it is not desirable to exceed 490 mV at high current density (300 mA  $cm^{-2}$ ), because once the potential exceeds 490 mV, the chloride electro-oxidation reaction (CIER) will occur at the same time as the OER at the anode.36 In addition, corrosive Cl<sup>-</sup> in seawater will also corrode the electrocatalyst and affect the stability of the catalyst.<sup>37</sup> Therefore, the construction and development of a high-efficiency electrocatalyst for industrial H2 production in seawater electrolyte has become an urgent problem.

In this work, we reported a simple and economic electrocatalyst (denoted Mo–Ni<sub>2</sub>P/CC) for the HER in freshwater/seawater solution through a facile hydrothermal and phosphating approach. The incorporation of Mo into Ni<sub>2</sub>P can not only adjust the electronic structure but also generate a lower crystallinity for facilitating the electronic transmission, thus enhancing the HER process with a low overpotential of 113 and 154 mV at 10 mA cm<sup>-2</sup> in KOH and simulated seawater solution. Furthermore, the Mo–Ni<sub>2</sub>P/CC electrocatalyst exhibited a favorable durability for 20 h in an alkaline electrolyte, simulated alkaline seawater and real alkaline seawater solution. This work will shed new light on the design of metal phosphides as efficient electrocatalysts for H<sub>2</sub> production.

### Experimental

#### Chemicals

Carbon cloth (CC, WOS1009) was bought from China Power Technology Co., Ltd. Nickel nitrate hexahydrate (Ni(NO<sub>3</sub>)<sub>2</sub>·6H<sub>2</sub>O), sodium molybdate dihydrate (Na<sub>2</sub>MoO<sub>4</sub>·2H<sub>2</sub>O), ammonium fluoride (H<sub>4</sub>FN), urea (CH<sub>4</sub>N<sub>2</sub>O) and sodium hypophosphite (NaH<sub>2</sub>PO<sub>2</sub>) were used without further purification.

#### Preparation of Mo-Ni<sub>2</sub>P/CC

In this experiment, the Mo–Ni $_2$ P/CC nanosheet arrays on the CC were prepared by a facile hydrothermal and phosphating procedure. Prior to synthesis, the substrate CC was cut into

pieces of  $1 \times 4$  cm in dimension. These small pieces were first etched with nitric acid solution at 90 °C for about 2 h, after which it was ultrasonicated in ethanol and water for 15 min, respectively. In a typical synthesis, 2 m mol of Ni(NO<sub>3</sub>)<sub>2</sub>·6H<sub>2</sub>O, 0.1 m mol of Na<sub>2</sub>MoO<sub>4</sub>·2H<sub>2</sub>O, 10 m mol of CO(NH<sub>2</sub>)<sub>2</sub> and 6 m mol of H<sub>4</sub>FN were stirred with 30 mL of deionized water until they completely dissolved. After that, the mixed solution was introduced into a 40 mL Teflon-lined stainless steel autoclave with washed CC and maintained at 120 °C for 6 h in an electric oven. After cooling down to room temperature, the precursor was fully washed with deionized water, and then dried at 60  $^{\circ}$ C for 4 h under vacuum. Next, NaH<sub>2</sub>PO<sub>2</sub> and the precursor were placed upstream and downstream, respectively. Subsequently, the tube furnace was calcined at 350 °C under an Ar atmosphere and maintained at this temperature for 2 h to obtain the final sample. The final catalyst was named Mo-Ni<sub>2</sub>P/CC and the mass loading of the active material was obtained as 3.05 mg cm<sup>-2</sup>. For comparison, pure Ni<sub>2</sub>P/CC and Mo<sub>x</sub>-Ni<sub>2</sub>P/CC (x represents the doping level of Mo, x = 0.04, 0.05 and 0.06) were also synthesized via the above procedure.

#### Characterization

X-Ray diffraction (XRD) patterns of the as-prepared Mo–Ni<sub>2</sub>P/ CC electrocatalysts were tested on a Bruker AXS GmbH with a working voltage of 40 kV. The surface morphologies were examined using scanning electron microscopy (SEM, JSM-6700, JEOL, Japan). The microstructure was characterized by energy dispersive X-ray spectroscopy (EDX) and transmission electron microscopy (TEM, JSM-2100, JEOL, Japan). X-Ray photoelectron spectroscopy (XPS) was carried out with an Al (mono) K source (1486.6 eV).

#### **Electrochemical measurements**

Electrochemical measurements were carried out on a CHI 660D electrochemical workstation (CH Instruments, Inc., Shanghai, China) in a standard three-electrode system. For all of the hydrogen evolution reaction (HER) experiments, we conducted the tests in three different electrolytes, which included 1 M KOH (pH = 14), 1 M KOH + 0.5 M NaCl (pH = 14), and 1 M KOH + Seawater (pH = 13.6). In addition, the catalysts grown on carbon cloth, a graphite rod, and a saturated calomel electrode were used as the working electrode, counter electrode, and reference electrode, respectively. Linear sweep voltammetry (LSV) tests were conducted with a scan rate of 1 mV s<sup>-1</sup>. Afterwards, all the potentials were then transformed from the saturated calomel electrode (SCE) into a reversible hydrogen electrode (RHE) through the following formula:  $E_{RHE} = E_{SCE} +$  $0.098 + 0.0592 \times \text{pH}$ . Based on the polarization curves, the Tafel slope was determined using the equation  $(\eta = b \log |j| + a, \eta)$ denotes overpotential, *j* denotes current density and *b* denotes the Tafel slope). The electrochemical impedance spectra (EIS) measurements were conducted with the frequencies ranging from 100 kHz to 0.01 Hz. Chronoamperometry was carried out to test the stability of the electrocatalyst. Using the cyclic voltammogram (CV) curves at different scan rates (10 mV s<sup>-1</sup>

to 100 mV s<sup>-1</sup>), the double-layer capacitance ( $C_{dl}$ ) values can be determined for the as-prepared samples.

### Results and discussion

In Fig. 1a, it is shown that the Mo-Ni<sub>2</sub>P/CC catalyst was fabricated using two main steps. In the first step, the Mo-Ni<sub>2</sub>P/CC precursor was supported on carbon cloth (CC) through a simple hydrothermal method. Next, the sample was dried overnight at 60 °C, and then the as-fabricated precursor was reacted with NaH<sub>2</sub>PO<sub>2</sub>, which acted as a phosphorus source, to obtain the Mo-Ni<sub>2</sub>P/CC. Then scanning electron microscopy (SEM) was used to examine the morphologies of catalysts. As revealed in Fig. S1a and b (ESI<sup>+</sup>), nickel phosphide nanosheets grown on the CC are uniform and compact, and the surface of the nanosheets is obviously rough. Compared with pure nickel phosphide, the size of nanosheets (Fig. 1b and c) gets smaller and the surface becomes smoother after Mo doping. Moreover, high-resolution transmission electron microscopy (HRTEM) was further used to monitor the micromorphology of the asprepared samples. Interestingly, the TEM image in Fig. 1d uncovers that the nanosheets of Mo-Ni<sub>2</sub>P/CC are composed of many nanoparticles. The HRTEM image in Fig. 1e shows two fringes with an interplanar spacing of 0.225 and 0.332 nm, corresponding to the (111) and (301) planes of Ni<sub>2</sub>P, respectively. Moreover, the relevant energy dispersive X-ray (EDX)



Fig. 1 (a) Schematic illustration of the formation of  $Mo-Ni_2P/CC$ ; SEM (b and c) and TEM (d and e) images of the  $Mo-Ni_2P/CC$  electrocatalyst; (f–i) TEM image and the corresponding elemental mapping of Mo, Ni and P for the  $Mo-Ni_2P/CC$  electrocatalyst.

elemental mapping in Fig. 1f–j shows that Mo, Ni and P are uniformly distributed throughout  $Mo-Ni_2P/CC$  and the composition of the catalyst is presented in Table S1 (ESI†), which further verified that Mo was successfully introduced into the  $Ni_2P/CC$ .

The crystalline structures and surface chemical states of the synthesized catalysts were further analyzed through X-ray diffraction (XRD) and X-ray photoelectron spectroscopy (XPS). As displayed in Fig. 2a, the main diffraction peaks of nickel phosphide correspond to Ni<sub>2</sub>P (PDF#74-1385). And the typical diffraction peaks at 40.7°, 44.6°, 47.4°, and 54.2° appear for Mo-Ni<sub>2</sub>P/CC, which are indexed to the (111), (201), (210) and (300) planes of Ni<sub>2</sub>P crystals, respectively. After the introduction of Mo into Ni<sub>2</sub>P, the peaks of the material exhibit little change except a low degree of crystallinity, implying that no new phase is produced.<sup>38,39</sup> In addition, different molybdenum doping levels were also measured, which confirms that molybdenum has been successfully incorporated and no molybdenum compounds are present. Fig. S2 (ESI<sup>+</sup>) depicts the XPS survey spectrum of Mo-Ni<sub>2</sub>P/CC, demonstrating the presence of the Ni, Mo and P elements in the catalyst, consistent with the EDX results. XPS analysis for the Ni 2p signal (Fig. 2b) in Mo-Ni<sub>2</sub>P/ CC nanosheets demonstrates that the Ni 2p spectrum could be distributed into two parts (Ni  $2p_{3/2}$  and Ni  $2p_{1/2}$ ) and two satellite peaks.<sup>40,41</sup> The other two peaks (880.9 and 862.1 eV) can be attributed to the co-occurrence of photoexcitation and photoionization.<sup>35</sup> With the addition of Mo, the positions of the Ni  $2p_{3/2}$  and Ni  $2p_{1/2}$  peaks shifted towards the higher energy region, demonstrating that the Mo-Ni<sub>2</sub>P/CC contributed to electron interactions between Ni and Mo. In the Mo 3d region, Fig. 2c shows that the binding energy of two characteristic peaks at 227.7 eV and 230.8 eV belongs to Mo 3d<sub>5/2</sub> and Mo  $3d_{3/2}$ , respectively.<sup>42,43</sup> The peak located at 233.9 eV can be ascribed to Mo<sup>6+</sup> due to surface oxidation.<sup>44</sup> As presented in Fig. 2d, two sharp peaks at around 129.5 and 130.6 eV belong to P 2p in the Mo-Ni<sub>2</sub>P/CC catalyst, and correspond to P 2p<sub>3/2</sub> and P  $2p_{1/2}$ , respectively.<sup>45,46</sup> Additionally, the peak at 134.4 eV may have come from the phosphorus oxide that resulted from the partial surface oxidation of the electrocatalyst.47 Compared to pure Ni<sub>2</sub>P, Ni and P in Mo-Ni<sub>2</sub>P/CC show a positive shift in binding energy, suggesting that the addition of molybdenum increased the electronic interactions of Ni<sub>2</sub>P, thereby enhancing the HER of the catalyst.<sup>48</sup> The above discussion illustrates that the element Mo is successfully doped into Ni<sub>2</sub>P/CC and causes a change of the electronic system.

Finally, the HER activities of the as-obtained materials were obtained using a typical three-electron system through linear sweep voltammetry (LSV) in alkaline electrolyte at room temperature. The results show the polarization curves of  $Mo_x$ -Ni<sub>2</sub>P/CC (x = 0, 0.04, 0.05 and 0.06) in Fig. 3a. Not unexpectedly, Pt/C possesses the lowest overpotential. Meanwhile, as a metal dopant, the Mo center has excellent adsorption performance for hydrogen, and the synergistic interaction between Mo and Ni can effectively accelerate the HER kinetics in alkaline solution.<sup>49,50</sup> In Fig. 3a, the pure Ni<sub>2</sub>P/CC shows poor HER properties with a high overpotential of 166 mV at a current



Fig. 2 (a) XRD patterns of Mo<sub>x</sub>-Ni<sub>2</sub>P/CC (x represents the doping amount of Mo); XPS spectra of Mo-Ni<sub>2</sub>P/CC in (b) Ni 2p, (c) Mo 3d and (e) P 2p.

density of 10 mA  $cm^{-2}$ . As for the molybdenum doped sample, the as-prepared Mox-Ni2P/CC catalysts all show better HER performance than pure Ni<sub>2</sub>P/CC. In particular, Mo-Ni<sub>2</sub>P/CC only needs 113 mV at 10 mA cm<sup>-2</sup>, which was superior to those of the others. Additionally, the performance of other electrocatalysts for the HER are shown in Table 1. The results show that the value of the overpotential is smaller than or comparable to those of the recently reported non-noble metal catalysts, such as N-Ni<sub>3</sub>S<sub>2</sub>/NF (155 mV), <sup>51</sup> Ni<sub>2</sub>Mn<sub>1</sub>P PNAs (120 mV)<sup>52</sup> and other catalysts. The favorable HER activity of the Mo-Ni<sub>2</sub>P also indicates that doping can improve the deficiency of the catalytic performance of transition metals. In order to further investigate the effect of mass loading on the electrode activity, we measured the mass loading of different catalysts as in Table S2 (ESI<sup>†</sup>). The results demonstrate that the values of mass loading are all within one order of magnitude, and the difference is not significant due to the small doping amount. Therefore, it can be seen that the effect of the active material loaded on the electrode on the performance is negligible. So next we primarily explore the influence of doping on the catalytic properties. As presented in Fig. 3b, the Tafel slopes of Mo-Ni<sub>2</sub>P/CC, pure Ni<sub>2</sub>P/CC, Mo<sub>0.04</sub>-Ni<sub>2</sub>P/CC, Mo<sub>0.06</sub>-Ni<sub>2</sub>P/CC and Pt/C were 80, 96, 94, 94, and 35.9 mV dec<sup>-1</sup>, respectively. According to the Volmer-Tafel mechanism,<sup>53</sup> a smaller Tafel slope indicates a faster increase with increasing overpotential, which means better activity of a catalyst. In addition, doping Mo atoms can

change the HER active site and increase the electrocatalytic activity.<sup>54</sup> That is to say, with the introduction of Mo, the Volmer–Heyrovsky mechanism is beneficial to the HER process.

To further understand the catalytic behavior of the HER process, we perform electrochemical impedance spectroscopy (EIS) and use the corresponding potential at a current density of 10 mA cm<sup>-2</sup>. Typically, the Nyquist plot of Mo-Ni<sub>2</sub>P/CC (Fig. 3c) shows the smallest semicircle diameter compared to the other samples, which means that it has faster kinetics and lower charge transfer resistance as well as more favorable catalytic kinetics during the HER process after Mo doping. Besides, the electrochemical active surface area (ECSA) was calculated from the double-layer capacitance  $(C_{dl})$  through the calculation (ECSA =  $C_{dl} \times S/C_s$ , S denotes the geometric area and  $C_s = 0.040 \text{ mF cm}^{-2}$  in 1 M KOH solution<sup>55</sup>).  $C_{dl}$  was obtained from CV curves, and the CV curves of the catalyst with different doping amounts are shown in Fig. S3 (ESI<sup>†</sup>). As expected, the Mo-Ni<sub>2</sub>P/CC electrocatalyst showed a largest  $C_{\rm dl}$  of 33.7 mF cm<sup>-2</sup> in the HER (Fig. 3d). Based on these results, the catalyst will contain more active sites with the addition of Mo, and the electrocatalytic performance will be further improved. In addition, stability should also be considered as an important factor when evaluating a catalyst. The as-prepared Mo-Ni<sub>2</sub>P/CC exhibits outstanding durability for HER performance as shown in Fig. 3e and f. There is a negligible degradation after 2000 and 5000 cycles. Moreover,

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**Fig. 3** HER catalytic performance of  $Ni_2P/CC$  and  $Mo_x - Ni_2P/CC$  (*x* represents the doping amount of Mo) in 1 M KOH. (a) LSV curves; (b) Tafel plots came from LSV; (c) Nyquist plots; (d)  $C_{d1}$  measurements; (e) LSV curves of Mo $-Ni_2P/CC$  before and after the CV test of the accelerated stability test; and (f) the chronopotentiometric curve for 20 h.

 $Mo-Ni_2P/CC$  displays favorable stability for 20 h (the degradation rate is about 54%) and the SEM images are basically similar to the original one after the I-T test (Fig. S4, ESI†). In addition, after the stability test, the XRD image (Fig. S5, ESI†) reveals that the phase structure is well preserved, thus indicating its long-term durability.

Utilizing the most abundant seawater resources on earth as the source of electrolytic water without additional treatment can alleviate the tension of water resources. Hence, it is crucial to develop an electrical catalyst suitable for seawater splitting so that  $H_2$  can be produced on a large scale to meet the increasing energy demand. In this work, we further study the electrochemical HER properties of Mo–Ni<sub>2</sub>P/CC in simulated alkaline seawater and real alkaline seawater solution. It can be observed from Fig. 4a that the Mo–Ni<sub>2</sub>P/CC catalyst exhibits a lower overpotential in simulated alkaline seawater and real alkaline seawater solution than pure Ni<sub>2</sub>P/CC. And the Tafel slope shown in Fig. 4b also further confirmed that Mo doping can accelerate electron transfer. This performance boost implies an optimum electronic structure in combination with molybdenum doping. Furthermore, in Fig. 4c and d, the

 Table 1
 Comparison of HER performances of different catalysts in 1 M

 KOH
 KOH

Catalysts	Overpotential at 10 mA cm <sup><math>-2</math></sup> (mV)	Tafel slope (mV dec $^{-1}$ )	Ref.
Mo-Ni <sub>2</sub> P/CC	113	80	This work
N-Ni <sub>3</sub> S <sub>2</sub> /NF	155	113	51
Ni <sub>2</sub> Mn <sub>1</sub> P PNAs	120	82	52
Ni <sub>2</sub> P/CNT	137	71.3	56
W-Ni <sub>12</sub> P <sub>5</sub>	172	75	57
NiFe/Ni/Ni	132	107.7	58
Ni <sub>0.7</sub> Fe <sub>0.3</sub> S <sub>2</sub> @NF	155	109	59
CoFeZr/NF	159	132.7	60
Co-Ni <sub>3</sub> N	194	156.0	61
CoP/Co2P@NC	198	82	62
CoP/NiCoP	133	88	63
$Mo_2(CN)$	80	40	64
Mo-Ni-S NSs	83	66	65
Np- $\alpha$ -MoC <sub>1-x</sub> NSs	147	43.6	66

long-time stability of Mo–Ni<sub>2</sub>P/CC is evaluated as observed through chronoamperometry for 20 h continuous operation in simulated alkaline seawater and real alkaline seawater, respectively. After the operation, the current density of Mo–Ni<sub>2</sub>P/CC exhibits some degradation. This can be attributed to the addition of other ions in seawater, which expands the resistance of the solution interface.<sup>67</sup> From the inset of Fig. 4c and f, reasonable CV cycling stability is observed in the 5000 cycle operation, which is almost unchanged. In addition, the SEM images of the catalyst after the stability test in different solutions are presented in Fig. S6 (ESI†), which further indicate favorable stability of Mo–Ni<sub>2</sub>P/CC. Overall, a facile hydrothermal-phosphorization method for the preparation of a novel Mo–Ni<sub>2</sub>P/CC was developed for an efficient HER in alkaline seawater solution, and so it was supposed to be one of the most ideal candidates for seawater splitting.

### Conclusions

In conclusion, molybdenum was doped into the crystal lattice of nickel phosphide through a facile hydrothermal and phosphorization method. For determining the optimum experimental conditions, various comparison experiments were conducted. The as-obtained electrocatalyst displayed an overpotential of 113 and 154 mV at 10 mA cm<sup>-2</sup> in 1 M KOH and the simulated alkaline seawater, respectively. In addition, Mo–Ni<sub>2</sub>P/CC exhibits favorable stability after 5000 CV cycles and a 20 h stability test in alkaline solution. Furthermore, reasonable stability was also determined in simulated seawater and real alkaline seawater. By completing this work, we can explore many new possibilities for the economic



Fig. 4 Comparative HER performance between simulated seawater and alkaline seawater electrolytes. (a) LSV polarization curves; (b) Tafel plots; the chronopotentiometric curve for 20 h in (c) simulated seawater (inset of (c), LSV after the 5000 cycle test) and (d) alkaline seawater (inset of (d), LSV after the 5000 cycle test).

synthesis of heteroatom doped metallic phosphide electrocatalysts for high-efficiency hydrogen production in freshwater/seawater electrolytes.

### Author contributions

Xiao Li: Conceptualization, methodology, writing – original draft. Yudong Wu: resources, data curation. Shanshan Li: formal analysis, writing – review & editing. Yinchen Dai: investigation. Jibiao Guan: writing – review & editing. Baochun Guo: methodology. Ming Zhang: supervision.

### Conflicts of interest

There are no conflicts of interest to declare.

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