High-performance self-supporting AgCoPO₄/CFP for hydrogen evolution reaction under alkaline conditions†

Wan Zhao,‡ Hongshuai Cao,‡ Liting Ruan, Shaoying He, Zhiai Xu † and Wen Zhang ‡*  

Electrochemical water decomposition to produce hydrogen is a promising approach for renewable energy storage. It is vital to develop a catalyst with low overpotential, low cost and high stability for hydrogen evolution reaction (HER) under alkaline conditions. Herein, we used a simple hydrothermal method to obtain a AgCo(CO)₄ precursor on the surface of carbon fiber paper (CFP). After thermal phosphorization, the self-supporting catalyst AgCoPO₄/CFP was obtained, which greatly improved the HER catalytic performance under alkaline conditions. At 10 mA cm⁻², it showed an overpotential of 32 mV. The Tafel slope was 34.4 mV dec⁻¹. The high catalytic performance of AgCoPO₄/CFP may be due to the hydrophilic surface promoting effective contact with the electrolyte and the synergistic effect of the two metals, which accelerated electron transfer and thus promoted hydrogen evolution reaction. In addition, it showed an outstanding urea oxidation reaction (UOR) activity. After adding 0.5 M urea, the overpotential of the AgCoPO₄/CFP assembled electrolytic cell was only 1.45 V when the current density reached 10 mA cm⁻², which was much lower than that required for overall water splitting. This work provides a new method for the design and synthesis of efficient HER electrocatalysts.

1. Introduction

Fossil fuel usage can produce carbon dioxide and other greenhouse gases, which are not friendly to the environment.¹,² Sustainable production of hydrogen is important for developing green energy.³–⁵ Electrocatalytic hydrogen evolution reaction (HER) is a crucial step in water splitting, which has been extensively studied in the last few decades.⁶,⁷ As with any other chemical reaction, an energy input is required to overcome the electrochemical process of producing hydrogen from water. Preparing catalysts with excellent catalytic activity to optimize the catalytic performance and reduce the overpotential is the key step for water splitting.⁸,⁹

Generally, platinum-based catalysts and their derivatives¹⁰,¹¹ have the best hydrogen binding energy (HBE) and Gibbs free energy (ΔG°H₂).¹²,¹³ However, precious metal catalysts in electrocatalytic HER have some disadvantages such as low reserves and high price.¹⁴–¹⁶ Therefore, the development of efficient, economic and long-life catalyst is the key factor to realize high-performance energy storage.¹⁷ Phosphate has attracted great attention because of its special structure and catalytic performance.¹⁸ Xiao reported a novel heterostructures named Co(Po₃)₄@NPC/MoS₂, where NPC was N-doped porous carbon.¹⁹ It clearly indicated that its electronic structure and HER performance was greatly ameliorated by interface of Co(Po₃)₄@NPC/MoS₂. In consequence, a lower overpotential of 119 mV was acquired in alkaline electrolyte at 10 mA cm⁻². However, catalysts synthesized by transition metals alone have limitations in reducing overpotential and maintaining stability. Various precious metal nanoparticles (such as Pt,²⁰ Ru,²¹,²² Ir,²³,²⁴ Au,²⁵ and Ag²⁶) usually combined with transition metal-based catalysts to improve HER catalytic performance. Among them, silver-based electrocatalysts have outstanding performance due to their low price and abundant natural reserves.²⁶ Xu’s group²⁷ prepared layered and porous Ag/Ag(SS) heterostructures. Ag⁺ acted as a regulator that competed with CoS linkers to control crystal growth rates and nucleation, adjusting pore size from micropore to macropore to achieve efficient mass transfer and to produce fully exposed active surfaces in porous frames. Thus, a better alkaline HER effect could be obtained. Therefore, combining the catalytic activity of noble metal with the stability of transition metal can effectively develop high-performance electrocatalysts.²⁸–⁴¹

Herein, in order to solve the problems of high overpotential and poor stability of HER catalyst, hydrophilic AgCo(CO)₄/CFP precursor was synthesized by hydrothermal synthesis on hydrophobic carbon fiber paper (CFP) and AgCoPO₄/CFP was obtained after thermal phosphorization. Compared with CFP...
and AgCo(CO)$_4$/CFP, AgCoPO$_4$/CFP had more favorable wettability, which can effectively contact the electrolyte and accelerate the reaction kinetics process. The synergistic effect of bimetal can accelerate the transmission of electrons and optimized the surface electronic structure of catalyst. Thus, the HER catalytic performance of AgCoPO$_4$/CFP was improved. In alkaline solution, the overpotential of AgCoPO$_4$/CFP was only 32 mV under the current density of 10 mA cm$^{-2}$, which was better than most non-noble-metal-based catalysts. In addition, AgCoPO$_4$/CFP can perform HER catalysis for up to 25 h at a faint voltage of 32 mV at a current density of 10 mA cm$^{-2}$, showing excellent catalytic durability. The AgCoPO$_4$/CFP assembled electrolytic cell also obtained excellent catalytic performance.

2. Experimental section

2.1 Chemicals and materials

The chemicals and reagents are shown in ESI.†

2.2 Preparation of AgCo(CO)$_4$/CFP

The thickness of CFP is 0.19 mm (HCP121). CFP was cut into a size of 1 cm $\times$ 1.5 cm, ultrasonic cleaned in 30 mL hydrochloric acid for 10 minutes, then in ethanol for 20 minutes, at last it was dried for later use. The precursor AgCo(CO)$_4$/CFP was prepared by a hydrothermal process. At the beginning, a CFP piece was mixed with 40 mL of a solution containing 0.9 mmol Co(NO$_3$)$_2$·6H$_2$O, 0.1 mmol AgNO$_3$, 5 mmol urea and 4 mmol NH$_4$F. The mixture was stirred for 5 h. Later, the solution including the CFP was heated up to 110 °C within a hydrothermal reactor for 10 h. After cooling naturally at room temperature, the crude product was washed with water and ethanol for 3 times. The precursor material produced by this hydrothermal reaction was known as AgCo(CO)$_4$/CFP.

2.3 Preparation of AgCoPO$_4$/CFP

AgCoPO$_4$/CFP was prepared from the precursor AgCo(CO)$_4$/CFP through a phosphorization step. At first, AgCo(CO)$_4$/CFP precursor and NaH$_2$PO$_2$·H$_2$O (1.0 g) were respectively put in a porcelain boat. NaH$_2$PO$_2$·H$_2$O was in a scan rate of 5 mV s$^{-1}$ after the phosphorization which was produced on the surface of CFP as AgCoPO$_4$/CFP. Note that the loading amount of the catalysts on CFP was around 0.6 mg cm$^{-2}$ after the phosphorization process.

2.4 Electrochemical measurements

All the electrochemical measurements were carried out on Ingens electrochemical workstation with a three-electrode system, in which a Hg/HgO electrode worked as the reference electrode, a carbon rod worked as the counter electrode and the catalyst was used as the working electrode. For comparison, HER was measured using Pt-C powder as the working electrode. Before electrochemical measurements, the electrolyte was absolutely eliminated dissolved gases by purifying with N$_2$ for 0.5 h. After stabilizing the current after 30 cycles of cyclic voltammetry (CV) tests, linear sweep voltammetry (LSV) with a scan rate of 5 mV s$^{-1}$ was conducted in 1.0 M NaOH for HER. As for urea oxidation reaction (UOR), the measurements were measured in 1.0 M NaOH containing 0.5 M urea with the same scan rate.

3. Results and discussion

3.1 Structure and morphology characterization of as-prepared materials

As illustrated in Scheme 1, the solution of Co(NO$_3$)$_2$ and AgNO$_3$ was thoroughly stirred and placed with CFP within a hydrothermal reactor at 110 °C for 10 h to obtain precursor AgCo(CO)$_4$/CFP. AgCo(CO)$_4$/CFP was phosphorized to form the final AgCoPO$_4$/CFP with PH$_3$, which was generated via decomposition of NaH$_2$PO$_2$·H$_2$O.

X-ray diffraction (XRD) analysis was firstly used for material characterization. Fig. 1a showed the XRD pattern of the precursor. The composite exhibited a pattern similar to the pattern of AgCo(CO)$_4$/CFP with major diffraction peaks. After comparing with the PDF standard card, we found that the main peaks at 17.9°, 21.3°, 33.3° and 35.8° was corresponding to the (2 2 0), (−1 3 1), (0 6 1), and (−3 5 1) planes of AgCo(CO)$_4$/CFP (PDF# 75-1810). In addition, the corresponding peaks of carbon fiber paper matched well with standard cards (PDF#75-2708). The morphology of the prepared product was then investigated by scanning electron microscope (SEM) (Fig. 1b and c). AgCo(CO)$_4$/CFP showed nanorod structure and the tip of the nanorods had large whiskers. In addition, the homogeneous distribution of AgCo(CO)$_4$ on CFP was proven by the corresponding elemental

![Scheme 1 Schematic illustration of the fabrication process of AgCoPO4/CFP nanorods.](image-url)
mapping images of Co, Ag, O, and C elements (Fig. 1d–h and S1†).

After phosphorization, the main diffraction peaks were consistent with the pattern of AgCoPO4. The main diffraction peaks at 14.2°, 25.2°, 30.5°, 35.8° and 38.3° can be assigned to the (0 0 1), (0 −3 1), (−2 0 2), (0 1 2), and (−2 1 2) planes of AgCoPO4 (PDF#83-1628) (Fig. 2a). The corresponding peaks of CFP matched well with standard cards. These results demonstrated that AgCo(CO)4/CFP precursor had been transformed into AgCoPO4/CFP after phosphorization. Fig. 2b and c showed that the AgCoPO4/CFP nanostructure obtained by thermal phosphorization. It was composed of randomly oriented nanorods with a regular rhomboid structure at the top and a rhomboid side length was 1.1 μm. The whisker structure on
tip of the precursor nanorods was transformed into a smooth diamond tip after phosphorization (Fig. 2b, c and S2†). The change had little effect on the thickness and width of nanorods (Fig. S3†). Transmission electron microscopy (TEM) and high resolution TEM (HRTEM) images of AgCoPO4/CFP revealed the edge of nanorods and well-resolved interplanar distance between faces of the lattice fringes of 0.273 and 0.180 nm, which were indexed to the (1 0 2) and (0 – 3 1) plane, and their facet angle was 80.0° (Fig. 2d–f). High magnification element plotting showed that O (Fig. 2h), Ag (Fig. 2i), Co (Fig. 2j), and P (Fig. 2k) were evenly distributed on the whole nanorods.

3.2 Electrochemical performances of AgCoPO4/CFP

Linear sweep voltammetry (LSV) measurements in a three-electrode system (reference electrode: Hg/HgO electrode, counter electrode: carbon electrode) were performed to study the HER properties of the prepared materials. The HER activities of the catalyst with various Co : Ag ratios were firstly tested. The HER catalytic activity was related to silver loading, where the catalytic activity reached the highest performance at the Co : Ag mole ratio of 9 : 1 (Fig. 3a). After determining the optimal ratio (Co : Ag = 9 : 1), we performed linear sweep voltammetry (LSV) measurements to study the HER properties of AgCo(CO)₄/CFP, AgCoPO4/CFP and Pt–C/CFP samples in 1 M NaOH electrolyte. As expected, at 10 mA cm⁻², Pt–C/CFP showed an overpotential (η) of about 0 mV (vs. RHE), which was consistent with the reported value.¹⁰⁻¹² AgCo(CO)₄/CFP showed poor activity with an overpotential of about 250 mV. The performance of AgCoPO₄/CFP could be greatly improved, for which a current density of 10 mA cm⁻² only needed an overpotential of 32 mV (Fig. 3b). It was better than most phosphate catalysts in alkaline medium (Tables S1 and S2†). A plot known as the Tafel plot using the logarithmic relationship between η and current density is commonly used to assess electrode performance. The Tafel slope was considered as the growth ratio of the current to the overpotential, mainly determined by the transfer coefficient. Hereby, from the LSV polarization curve we got the Tafel slope in Fig. 3c. The experimental data of all tested catalysts was consist with the Tafel equation η = b log(j + a), where b was the Tafel slope and j was the current density in different overpotential ranges.³²⁻³³ The as-obtained AgCoPO₄/CFP possessed a Tafel slope of 34.4 mV dec⁻¹, which was close to that of Pt/C (30.0 mV dec⁻¹), greatly lower than those of AgCo(CO)₄/CFP (237.9 mV dec⁻¹) and CFP (447.8 mV dec⁻¹), suggesting that the kinetics toward the HER was greatly improved (Fig. 3c).

In order to further study the high HER activity of AgCoPO₄/CFP nanorods, the reaction resistance was studied by electrochemical impedance spectroscopy (EIS), which reflected the charge transfer ability of the electrocatalyst. EIS was operated at the fixed voltage of 0.55 V (Fig. 3d and S4†). Rₚ represents ohm resistance, and Rₜ represents charge transfer resistance between AgCoPO₄/CFP and electrolyte interface. Nyquist plots showed that AgCoPO₄/CFP presented lower semicircle diameter.
than that of AgCo(CO)₄/CFP and CFP, indicative of the improved charge transfer property of the AgCoPO₄/CFP electrode.

Electrochemical active surface area (ECSA) is an effective method to estimate the relative activity of electrocatalysts. CV was used to measure the double-layer capacitance (Cₐdl) between −1.0 and −0.6 V and to evaluate the ECSA. As shown in Fig. 3e, the Cₐdl of AgCoPO₄/CFP nanorods was 69.27 mF cm⁻², which was larger than that of AgCo(CO)₄/CFP (11.56 mF cm⁻²) (Fig. S5†), suggesting that the rod-like nanostructures had more active sites for contact with electrolyte after thermal phosphorization. In addition, it can be seen from the current–time (I−t) curve that AgCoPO₄/CFP electrode’s catalytic performance showed little change after continuous operation for 25 h (Fig. 3f), indicating that the AgCoPO₄/CFP electrode had good stability in 1.0 M NaOH solution.

3.3 The mechanism of the excellent catalytic performance

In order to explore the mechanism for the excellent catalytic performance of AgCoPO₄/CFP, the hydrophilicity, chemical environment and corresponding electronic states of the catalyst before and after hydrogen evolution reaction were thoroughly discussed. The contact angle of AgCoPO₄ with water was 32.3°. However, the contact angle of CFP with water was 145.9°. Through the contact angle measurements, it was proved that the surface wettability of the CFP was enhanced (Fig. 4a–c). In addition to the surface wettability, the introduction of phosphate is also very important for improving the catalytic performance of HER. Although the precursor AgCo(CO)₄ showed good wettability, the catalytic effect was not ideal. Not only did the introduction of phosphate group act as a proton acceptor, facilitating the oxidation of the metal species, but also it promoted metal synergistic catalysis and further facilitated hydrogen evolution reaction. The decent surface wettability of AgCoPO₄/CFP was good for the adsorption of electrolyte on the electrode surface, and further promoted the hydrogen precipitation.

The chemical states of AgCoPO₄/CFP and surface composition were analyzed by XPS before and after HER (Fig. 5)†. Two doublets can be observed before and after alkaline HER reaction. The two peaks at binding energies of 74.4 and 368.4 eV can be assigned to Ag 3d₃/₂ and 3d₅/₂. According to the calculation of peak area, Ag³⁺/Ag⁰ (area ratio) increased markedly from 1.29 to 1.45 (Fig. 5a). Especially, the binding energy also changed greatly, indicating that the coulomb or polarographic interaction between Ag and Co led to the increase of electron transfer.

Fig. 5b showed the Co 2p spectrum had high resolution XPS and Co 2p₃/₂ peaks at 782.3 eV, which were assigned to Co⁵⁺ and Co²⁺. Small peaks located at 783.5 eV and 786.9 eV are designated as satellite peaks. The ratio of Co⁵⁺ and Co²⁺ for AgCoPO₄/CFP was about 1.32 before the reaction, and it changed to 1.50 after the reaction for 25 h. Thus, the Co on the surface was oxidized to a higher state during HER, which is favorable for HER. This can also be confirmed from the activation process of CV curves. The peak of the oxidation from Co²⁺ to Co⁵⁺ appeared near 0.3 V and 1.25 V. Compared with the raw material at the Co : Ag mole ratio of 10 : 0, more obvious oxidation peak appeared. When Ag was introduced into the material, the new peak value in the vicinity of 1.25−1.5 V belonged to the oxidation from Ag to Ag⁺. The high valence state of metal played a major role in the catalytic reaction, promoting the rapid progress of catalytic reaction (Fig. S7†). The high resolution XPS spectra showed three oxygen components of O 1s: oxygen within a metal oxide environment (Co−O at 530.6 eV and 530.8 eV), oxygen in phosphate environment (O−H at 531.4 eV) and oxygen vacancy (Ov at 532.5 eV). Before the alkaline HER, the oxygen in different states was Co−O: O−H: Ov = 1 : 1.2 : 1.0, but it changed to Co−O: O−H: Ov = 1 : 1.2 : 0.8 after alkaline HER (Fig. 5c). The peak analysis after fitting of P 2p displayed different P−O bindings (PO₃⁻ at 135.0 eV, M−P−O (M = Co, Cu) at 133.6−134.2 eV). Here, the PO₃⁻ belonged to the AgCoPO₄ phase (Fig. 5d).

The TEM images after alkaline recycling were presented in Fig. 6a. They possessed similar nanorod-like structure, which indicated that AgCoPO₄/CFP after alkaline recycling still possessed intrinsic stability. HRTEM image showed a nanorod-like structure which is in agreement with the TEM image. A high-resolution TEM image of AgCoPO₄/CFP revealed well-reconstructed nanorods with the thickness of 3.41 nm, indicating high crystallinity.
like structure of AgCoPO₄/CFP on the edge (Fig. 6b). Moreover, the lattice spacing of 0.267 and 0.288 nm belonged to (1 2 0) and (2 1 /C0 2) planes in AgCoPO₄, their facet angle was 66.7° (Fig. 6c). Furthermore, the corresponding elemental mappings demonstrated the uniform distribution of Ag, Co, P, and O elements in AgCoPO₄ (Fig. 6d–h). Therefore, the change of hydrophilicity and surface electronic structure caused by the synergistic effect of bimetal and the exposure of catalytic active sites contributed to the high catalytic activity of AgCoPO₄/CFP in HER.

3.4 Excellent urea oxidation reaction (UOR) activity

The traditional catalysts for HER and OER are RuO₂ and Pt on the basis of extremely rare and expensive precious metals. It is important to develop alternative electrolytic cells. AgCoPO₄/CFP not merely had good HER catalytic activity. Urea is notorious for environmental problems, but it is a promising option for producing H₂ in electrolytic cell. After UOR, urea decomposes into inert N₂ and carbon dioxide. When UOR is applied to replace OER, energy consumption and security problems can be solved. We also tested different UOR and OER processes with different proportions of Ag, and the results proved that Co : Ag = 9 : 1 [AgCoPO₄/CFP] had the best performance (Fig. S8†). The electrochemical properties of AgCoPO₄/CFP on OER and UOR were tested respectively in 0.5 M urea + 1.0 M NaOH electrolyte. The electrode potential of AgCoPO₄/CFP for UOR at 15 mA cm⁻² was 1.43 V (Fig. 7a), which had a low Tafel slope at 49.1 mV dec⁻¹ (Fig. 7b). At 10 mA cm⁻², the potential of UOR is 180 mV lower than OER, the energy required for urea oxidation was significantly lower than that for water oxidation. We had developed an electrolytic cell using AgCoPO₄/CFP as anode and cathode electrocatalysts (Fig. S9† and 7a). As we can see in Fig. 7c, the cell voltage needed by the AgCoPO₄/CFP||AgCoPO₄/CFP electrolyzer in 1 M NaOH + 0.5 M urea at 10 mA cm⁻² was 1.45 V (Fig. 7c), lower than that of water splitting (1.54 V), which proved that urea oxidation assisting hydrogen production can reduce the energy consumption of hydrogen production. In addition, to evaluate the stability of AgCoPO₄/CFP in HER-UOR cell, a constant current test was performed. Fig. 6d showed that after 18 h of electrolysis, the cell voltage had no obvious attenuation, indicating that AgCoPO₄/CFP had good durability as the bifunctional electrode for urea-assisted electrochemical hydrogen production.

4. Conclusions

In this work, a simple and controllable self-supported method was used for the synthesis of AgCoPO₄/CFP nanorods. The synthesized AgCoPO₄/CFP nanorods exhibited excellent alkaline hydrogen evolution catalytic performance and remarkable long-term durability. Under 10 mA cm⁻² of 1 M NaOH, it showed an overpotential decrease of 32 mV and the Tafel slope was 34.4 mV dec⁻¹. The rod-like nanostructures had significant electrical conductivity, which promoted the complete contact between the active site and electrolyte, and further accelerated the gas desorption process through the conversion of hydrophobic and hydrophilic properties. It also could be used as the anode and cathode of the electrolytic cell and had decent overall water separation performance. This study on the structure–performance relationship shed light on the controllable design of low-cost and efficient transition metal phosphorylation catalysts in the future. In addition, the AgCoPO₄/CFP nanorods synthesis method mentioned in this study had low requirement preparation conditions, which holds the promise of achieving relatively large-scale industrial production and applying it to emerging energy technologies.

Conflicts of interest

There are no conflicts to declare.
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Notes and references

1 H. A. Gasteiger and N. M. Markovic, Just a dream-or future reality?, Science, 2009, 48, 324.
2 Q. Fu, T. Wu, G. Fu, T. Gao, J. Han, T. Yao, Y. Zhang, W. Zhong, X. Wang and B. Song, Skutterudite-type ternary Co3+2NiP3 nanoneedle array electrocatalysts for enhanced hydrogen and oxygen evolution, ACS Energy Lett., 2018, 3, 1744–1752.
3 S. A. Chala, M. C. Tsai, W. N. Su, K. B. Ibrahim, A. D. Duma, M. H. Yeh, C. Y. Wen, C. H. Yu, T. S. Chan, H. Dai and B. J. Hwang, Site activity and population engineering of NiRu-layered double hydroxide nanosheets decorated with silver nanoparticles for oxygen evolution and reduction reactions, ACS Catal., 2019, 9, 117–129.
4 Z. W. Seh, J. Kibsgaard, C. F. Dickens, I. b. Chorkendorff, J. K. Nørskov and T. F. Jaramillo, Combining theory and experiment in electrocatalysis: Insights into materials design, Science, 2017, 355, 6321.
5 Q. Gong, Y. Wang, Q. Hu, J. Zhou, R. Feng, P. N. Duchesne, P. Zhang, F. Chen, N. Han, Y. Li, C. Jin, Y. Li and S. T. Li, Ultrasmall and phase-pure W6C nanoparticles for efficient electrocatalytic and photoelectrochemical hydrogen evolution, Nat. Commun., 2016, 7, 13216.
6 N. S. Lewis and D. G. Nocera, Powering the planet: Chemical challenges in solar energy utilization, Proc. Natl. Acad. Sci. U.S.A., 2006, 103, 15729.
7 H. B. Gray, Powering the planet with solar fuel, Nat. Chem., 2009, 1, 7.
8 V. Krubel and X. L. Hu, Molybdenum boride and carbide catalyze hydrogen evolution in both acidic and basic solutions, Angew. Chem., Int. Ed., 2012, 51, 12875–12878.
9 X. D. Jia, Y. F. Zhao, G. B. Chen, L. Shang, R. Shi, X. F. Kang, G. I. N. Waterhouse, L. Z. Wu, C. H. Tung and T. R. Zhang, NiFe-P nanoparticles derived from ultrathin NiFe-Layered double hydroxide nanosheets: an efficient overall water splitting electrocatalyst, Adv. Energy Mater., 2016, 6, 1502585.
10 H. Yin, S. Zhao, K. Zhao, A. Muqsit, H. Tang, L. Chang, H. Zhao, Y. Gao and Z. Tang, Ultrathin platinum nanowires grown on single-layered nickel hydroxide with high evolution activity, Nat. Commun., 2015, 6, 6430.
11 Y. Wang, L. Chen, X. Yu, Y. Wang and G. Zheng, Superb alkaline hydrogen evolution and simultaneous electricity generation by Pt-decorated Ni3N nanosheets, Adv. Energy Mater., 2017, 7, 1601390.
12 X. Han, X. Ling, D. Yu, D. Xie, L. Li, S. Peng, C. Zhong, N. Zhao, Y. Deng and W. Hu, Atomically dispersed binary Co-Ni sites in nitrogen-doped hollow carbon nanocubes for reversible oxygen reduction and evolution, Adv. Mater., 2019, 31, 1905622.
13 H. B. Wu, B. Y. Xia, L. Yu, X. Y. Yu and X. W. Lou, Porous molybdenum carbide nano-octahedrons synthesized via confined carburization in metal–organic frameworks for efficient hydrogen production, Nat. Commun., 2015, 6, 6512.
14 N. M. Marković, B. N. Grgr and P. N. Ross, Temperature-dependent hydrogen electrochemistry on platinum low-index single-crystal surfaces in acid solutions, J. Phys. Chem. B, 1997, 101, 5405–5413.
15 X. X. Zou and Y. Zhang, Noble metal-free hydrogen evolution catalysts for water splitting, Chem. Soc. Rev., 2015, 44, 5148–5180.
16 S. M. Li, K. Kang and H. Jang, Environmental friendly synthesis of hierarchicalmesoporous platinum nanoparticles templated by fucoidan biopolymer for enhancedhydrogen evolution reaction, J. Mater. Sci. Lett., 2020, 46, 185–190.
17 D. H. Ha, B. Han, M. Risch, L. Giordano, C. Yao, P. Karayaylali and Y. Shao, Activity and stability of cobalt phosphides for hydrogen evolution upon water splitting, Nano Energy, 2016, 29, 37–45.
18 X. Yang, A. Y. Lu, Y. Zhu, M. N. Hedhili, S. Min, K. W. Huang, Y. Han and L. J. Li, CoP nanosheet assembly grown on carbon cloth: A highly efficient electrocatalyst for hydrogen generation, Nano Energy, 2015, 15, 634–641.
19 H. Zheng, Y. Li, Y. Wang and P. Gao, Fabrication of Co(PO3)3@NPC/MoS2 heterostructures for enhanced electrocatalytic hydrogen evolution, J. Alloys Compd., 2022, 894, 162411.
20 Y. Wang, L. Chen, X. Yu, Y. Wang and G. Zheng, Superb alkaline hydrogen evolution and simultaneous electricity generation by Pt-decorated Ni3N nanosheets, Adv. Energy Mater., 2017, 7, 1601390.
21 Q. Q. Chen, X. Yang, C. C. Hou, K. Li and Y. Chen, Inlay of ultrafine Ru nanoparticles into a self-supported Ni(OH)2 nanoarray for hydrogen evolution with low overpotential and enhanced kinetics, J. Mater. Chem. A., 2019, 7, 11062–11068.
22 S. A. Chala, M. C. Tsai, W. N. Su, K. B. Ibrahim, A. D. Duma, M. H. Yeh, C. Y. Wen, C. H. Yu, T. S. Chan, H. Dai and B. J. Hwang, Site activity and population engineering of NiRu-layered double hydroxide nanosheets decorated with silver nanoparticles for oxygen evolution and reduction reactions, ACS Catal., 2019, 9, 117–129.
23 L. M. Leng, J. Li, X. Y. Zeng, X. L. Tian, H. Y. Song, Z. M. Cui, T. Shu, H. S. Wang, J. W. Ren and S. J. Liao, Enhanced cyclability of LiO2 batteries with cathodes of Ir and MnO2 supported on well-defined TiN arrays, Nanoscale, 2018, 10, 2983–2989.
enhanced oxygen evolution reaction, Angew. Chem., Int. Ed., 2020, 59, 7245.

27 R. Liu, K. Ye, Y. Gao, W. Zhang, G. Wang and D. Cao, Ag supported on carbon fiber cloth as the catalyst for hydrazine reduction in alkaline medium, Electrochim. Acta, 2015, 186, 239–244.

28 H. Xu, X. Niu, Z. Liu, M. Sun, Z. Liu, Z. Tian, X. Wu, B. Huang, Y. Tang and C. Yan, Highly controllable hierarchically porous Ag/Ag$_2$S heterostructure by cation exchange for efficient hydrogen evolution, Small, 2021, 17, 2103064.

29 Z. Cui, Y. Li, G. Fu, X. Li and J. B. Goodenough, Robust Fe$_3$Mo$_2$C supported IrMn clusters as highly efficient bifunctional air electrode for metal-air battery, Adv. Mater., 2017, 29, 1702385.

30 Y. Tan, H. Wang, P. Liu, C. Cheng, F. Zhu, A. Hirata and M. Chen, 3D nanoporous metal phosphides toward high-efficiency electrochemical hydrogen production, Adv. Mater., 2016, 28, 2951.

31 E. J. Popczun, C. G. Read, C. W. Roske, N. S. Lewis and R. E. Schaak, Highly active electrocatalysis of the hydrogen evolution reaction by cobalt phosphide nanoparticles, Angew. Chem., Int. Ed., 2014, 53, 5427.

32 Y. Jiao, Y. Zheng, M. T. Jaroniec and S. Z. Qiao, Design of electrocatalysts for oxygen- and hydrogen-involved energy conversion reactions, Chem. Soc. Rev., 2015, 44, 2060–2086.

33 H. S. Cao, Y. Xie, H. L. Wang, F. Xiao, A. P. Wu, L. Li, Z. K. Xu, N. Xiong and K. Pan, Flower-like Co$_3$P microballs assembled with [002] facet nanowires via precursor route: Efficient electrocatalysts for hydrogen and oxygen evolution, Electrochim. Acta, 2018, 259, 830–840.

34 T. Wu, M. Pi, D. Zhang and S. Chen, 3D structured porous CoP$_3$ nanoneedle arrays as an efficient bifunctional air catalyst for the evolution reaction of hydrogen and oxygen, J. Mater. Chem. A., 2016, 4, 14539–14544.

35 Y. P. Zhu, Y. P. Liu, T. Z. Ren and Z. Y. Yuan, Self-supported cobalt phosphide mesoporous nanorod arrays: A flexible and bifunctional electrode for highly active electrocatalytic water reduction and oxidation, Adv. Funct. Mater., 2015, 25, 7337–7347.

36 H. Wu, X. Lu, G. Zheng and G. W. Ho, Topotactic engineering of ultrathin 2D nonlayered nickel selenides for full water electrolysis, Adv. Energy Mater., 2018, 8, 1702704.

37 Y. Li and C. Zhao, Enhancing water oxidation catalysis on a synergistic phosphorylated NiFe hydroxide by adjusting catalyst wettability, ACS Catal., 2017, 7, 2535–2541.

38 X. Zhang and X. Yu, Hopsphide/Carbon nanotube hybrids as pH-universal electrocatalysts for hydrogen evolution reaction, Adv. Funct. Mater., 2018, 28, 1706523.

39 C. V. Babahmadi, M. Montazer and W. Gao, Low temperature welding of graphene on PET with silver nanoparticles producing higher durable electro-conductive fabric, Carbon, 2017, 118, 443.

40 X. Song, Z. Y. Zhao, X. X. Sun, Y. H. Zhou, Y. Wang and D. B. Wang, In situ growth of Ag nanodots decorated Cu$_2$O porous nanobelts networks on copper foam for efficient HER electrocatalysis, Small, 2019, 15, 1804268.

41 Y. Y. Feng, T. Zhang, J. H. Zhang, H. Fan, C. He and J. X. Song, 3D 1T-MoS$_2$/Co$_3$S$_2$ heterostructure via interface engineering for ultrastable hydrogen evolution reaction, Small, 2020, 16, 2002850.

42 X. Chen, M. Cheng, D. Chen and R. Wang, Shape-Controlled Synthesis of Co$_3$P Nanostructures and Their Application in Supercapacitors, ACS Appl. Mater. Interfaces, 2016, 8, 3892–3900.

43 Y. Pan, Y. Liu and C. Liu, Metal doping effect of the MC$_2$P/Nitrogen-doped carbon nanotubes [M = Fe, Ni, Cu] hydrogen evolution hybrid catalysts, ACS Appl. Mater. Interfaces, 2016, 8, 13890–13901.

44 R. Vittal and H. Gomathi, Prabhakara Rao, Derivatised nickel and cobalt oxide modified electrodes: effect of surfactant, Electroanal. Chem., 2001, 497, 47.

45 C. Barbem, G. A. Planes and M. C. Miras, Redox coupled ion exchange in cobalt oxide films, Electrochem. Comm., 2001, 3, 113.

46 I. G. Casella, Electrodeposition of cobalt oxide films from carbonate solutions containing Co(II)-tartrate complexes, Elecraonal Chem., 2002, 520, 119.

47 I. G. Casella and M. J. Gatta, Study of the electrochemical deposition and properties of cobalt oxide species in citrate alkaline solutions, Electrochim. Acta, 2012, 530, 44.

48 P. Elumalai, H. N. Vasan and N. Munichandmiah, Electrochemical studies of cobalt hydroxide — an additive for nickel electrodes, Power Sources, 2001, 93, 201.

49 Y. M. Xia, Z. M. He, K. J. Hu, B. Tang, J. B. Su, Y. Liu and X. P. Li, Fabrication of n-SrTiO$_3$/p-Cu$_2$O heterojunction composites with enhanced photocatalytic performance, J. Alloy Compd., 2018, 753, 356.

50 C. Yuan, J. Li, L. Hou, X. Zhang, L. Shen and X. Lou, Ultrathin mesoporous NiCo$_2$O$_4$ nanosheets supported on Ni foam as advanced electrodes for supercapacitors, Adv. Funct. Mater., 2012, 22, 4592–4597.

51 H. Cao, Z. Li, Y. Xie, F. Xiao, H. Wang, X. Wang, K. Pan and A. Cabot, Hierarchical CoP nanostructures on nickel foam as efficient bifunctional catalysts for water splitting, ChemSusChem, 2021, 14, 1094.

52 H. Q. Zhou, F. Yu, J. Y. Sun, R. He, S. Chen, C. W. Chu and Z. F. Ren, Highly active catalyst derived from a 3D foam of Fe(Po$_3$)$_3$/Ni$_2$P for extremely efficient water oxidation, Proc. Natl. Acad. Sci. U.S.A., 2017, 114, 5607–5611.

53 Y. Li, Z. Wang, J. Hu, S. Li, Y. Du, X. Han and P. Xu, Metal–organic frameworks derived interconnected bimetallic metaphosphate nanoarrays for efficient electrocatalytic oxygen evolution, Angew. Chem., 2014, 126, 6828–6832.

54 S. Chen, J. Duan, A. Vasilieff and S. Z. Qiao, Size fractionation of Two-dimensional sub-nanometer thin manganese dioxide crystals towards superior urea electrocatalytic conversion, Angew. Chem., 2016, 55, 3804–3808.

55 K. Geng, Y. Zheng, S. Q. Li, H. Su, X. Zhao, J. Hu, H. B. Shu, M. Jaroniec, P. Chen, Q. H. Liu and S. Z. Qiao, Nickel ferrocyanide as a high-performance urea oxidation electrocatalyst, Nat. Energy., 2021, 6, 904–912.