Neuron-Inspired Interpenetrative Network Composed of Cobalt– Phosphorus-Derived Nanoparticles Embedded within Porous Carbon Nanotubes for Efficient Hydrogen Production

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Supporting Information

ABSTRACT: The ongoing search for cheap and efficient hydrogen evolution reaction (HER) electrocatalysts to replace currently used catalysts based on Pt or its alloys has been considered as an prevalent strategy to produce renewable and clean hydrogen energy. Herein, inspired by the neuron structure in biological systems, we demonstrate a novel fabrication strategy via a simple two-step method for the synthesis of a neuronlike interpenetrative nanocomposite network of Co–P embedded in porous carbon nanotubes (NIN-Co–P/PCNTs). It is found that the interpenetrative network provides a natural transport path to accelerate the hydrogen production process. The embedded-type structure



improves the utilization ratio of Co–P and the hollow, tubelike, and porous structure of PCNTs further promote charge and reactant transport. These factors allow the as-prepared NIN-Co–P/PCNTs to achieve a onset potential low to 43 mV, a Tafel slope as small as 40 mV/decade, an excellent stability, and a high turnover frequency value of 3.2 s⁻¹ at $\eta = 0.2$ V in acidic conditions. These encouraging properties derived from the neuronlike interpenetrative network structure might offer new inspiration for the preparation of more nanocomposites for applications in other catalytic and optoelectronic field.

KEYWORDS: cobalt phosphorus, carbon nanotubes, neuronlike, electrocatalysts, hydrogen evolution reaction

INTRODUCTION

Hydrogen, famous as a renewable and clean energy resource, has been widely accepted as an alternative to substitute fossil fuels.^{1,2} Currently, the popular commercial technologies for producing hydrogen are partial oxidation, catalytic steam reforming, and coal gasification. However, these methods significantly increase global CO₂ emissions. Recently, water splitting using electrochemistry cells has been broadly investigated as a valid way for hydrogen evolution reaction (HER).^{3,4} So far, the most effective electrocatalysts for hydrogen production are platinum and its alloys.⁴ The high cost and relative rarity of these materials limit their applications and prohibit commercial deployment. Thus, considerable research interests have been made to develop the Pt-free catalysts with high-performing for HER. Currently, some transition-metal sulfides (MS), such as MOS_2 , ^{5–8} WS_2 , ^{9,10} and $CoS_{23}^{11,12}$ have demonstrated good results as HER catalysts. Substantial challenges must still be overcome to further improve their catalytic efficiency and meet the requirements of practical application.

Cobalt-phosphorus-derived compound (Co-P) is another type of promising low-cost HER catalysts.^{13,14} In theory, because Co-P contains a P atom or PO_x group, the catalyst forms a isotropic crystal structure, which is different from the layered structure of MS based crystals.¹⁵ The structural difference may result in that Co-P has more coordinatively unsaturated surface atoms than MS.¹⁶ Additionally, the phosphorus anions in Co-P have more electron-donating character than corresponding sulfur species, and thus demonstrate more thermoneutral hydrogen absorption at active sites, a positive indication of potential high HER catalytic activity. In recent reports, research involving Co-P catalysts, such as cobalt phosphide (CoP),¹⁷⁻¹⁹ cobalt phosphate, and cobalt phosphite,^{20,21} have demonstrated potential for use as effective HER or oxygen evolution (OER) catalysts. The strategies to improve catalytic performance in these reports are primarily focused on the hybridization of Co-P with conducting carbon nanostructures (e.g., carbon nanotubes or graphene) or metal substrate, as well as the formation of porous structures with large surface areas, such as nanosheets and nanowires.^{17,19} However, the improved performance produced by introducing the conductive supporter or simply adjusting the

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Scheme 1. Schematic Diagram to Illustrate the Operating Principle of the HER Based on NIN-Co-P/PCNTs Nanocomposites



structure is often limited, and further improvement remains an urgent task.

According to classic catalytic theory, an ideal HER electrocatalyst should feature three attributes: (1) high inherent catalytic activity; (2) abundant exposure of active sites; (3) excellent charge and reactant transport.²² Unfortunately, work in the past has usually emphasized only one or two of these three practical attributes.

In biological systems, a neuron is an electrically excitable cell that efficiently transports and processes information through electrical and chemical signals. External stimuli are accepted by the dendrite of neuron and efficiently transported into the soma through a neural network. We observe that interlaced carbon nanotubes (CNTs) have some morphological characteristics and functions similar to neural networks.^{23,24} Both are composed of quasi-one-dimensional fibers, and both demonstrate excellent charge transport properties. Therefore, we predicted that designing a Co–P/CNTs nanocomposite with a neuronlike network structure might be an ideal candidate material having high HER activity with Co–P.

In this report, we demonstrate a novel fabrication strategy via a simple two-step method for the synthesis of a neuronlike interpenetrative nanocomposite network of Co-P embedded in porous carbon nanotubes (NIN-Co-P/PCNTs). Such a design holds several advantages. Primarily, the neuronlike interpenetrative networks can provide a natural transport path to accelerate the hydrogen production process and facilitate the catalytic performance of Co-P. Second, in the embedded-type structure, the number of active sites in the catalytic system is increased remarkably. Finally, the hollow, tubelike, and porous structure of PCNTs further promotes the transport of both charge and reactants. These factors allow the as-prepared NIN-Co-P/PCNTs to achieve a onset potential low to 43 mV, a Tafel slope as small as 40 mV/decade, an excellent stability, and a high turnover frequency value of 3.2 s⁻¹ at $\eta = 0.2$ V in acidic conditions.

EXPERIMENTAL DETAILS

Synthesis of Porous Carbon Nanotubes (PCNTs). The raw carbon nanotubes (raw CNTs) were purchased from Cnano Technology (Beijing) Limited. Briefly, the porous CNTs (PCNTs) are obtained via a high temperature reaction between raw CNTs and a nebulized water stream, using a mild etch method that we reported previously.²⁵ In a typical process, water was first nebulized to create the atmosphere with vast droplets. The produced droplets were then

passed into a quartz tube loading with raw commercial CNTs in Arcarrying gas when the temperature of 850 $^{\circ}$ C was fixed. The water steams and furnace were turned off, and the sample was naturally cooled to room temperature. As control experiments, other carbon materials were synthesized in the same way under different etching time.

Electrode Preparation. Glassy carbon (GC) electrodes (diameter of 3 mm, CH instrument Inc.) were polished in 0.05 and 0.3 μ m alumina slurry (CH Instrument Inc.) and subsequently rinsed with ultrapure water and ethanol. Then, the GC electrodes were sonicated, rinsed thoroughly in ultrapure water and dried under a gentle nitrogen stream. In preparation of the working electrode, PCNTs and CNTs were ultrasonically dispersed in ethanol and equal amounts of suspension were dropped onto the surface of GC electrodes and dried naturally at room temperature. For comparison, a commercially available Pt/C-modified GC electrode (20 wt % Pt supported on carbon black) was prepared in the same process.

Synthesis of NIN-Co-P/PCNTs Nanocomposites. NIN-Co-P/ PCNTs nanocomposites were synthesized by a facile electrochemical deposition method. Briefly, the PCNT-modified glassy carbon electrodes were immersed in 0.3 M CoSO₄·7H₂O, 0.3 M NaH₂PO₂· H₂O solution containing 0.4 M H₃BO₃, and electrodeposited in the potential range from -1.8 to +0.5 V for cyclic voltammograms (CV) at a scan rate of 50 mV/s (Figure S1). After the electrochemical deposition, the working electrode was rinsed gently with water and dried overnight under vacuum at room temperature. In our experiment, all of the potentials are calibrated based on reversible hydrogen electrode (RHE) according to the Nernst equation. For comparison, bare glass carbon electrodes and the CNT-modified glassy carbon electrodes were also treated under the same synthesis conditions, and parallel experiments using various deposition cycles and precursor concentrations were also carried out. The obtained hybrids were denoted PCNTs-5cyc, PCNTs-10cyc, PCNTs-20cyc, CNTs-5cyc, CNTs-10cyc, and so on.

Electrochemical Measurements. All the electrochemical measurements were conducted in a typical three-electrode setup in 0.5 M H_2SO_4 , with a glassy carbon electrode as working electrode (3 mm diameter, CH instrument Inc.), a Pt electrode as counter electrode, and a Ag/AgCl electrode as reference electrode. The Ag/AgCl reference electrode was calibrated with respect to reversible hydrogen electrode (RHE) for the measurements. LSV measurements were also performed on CHI760 electrochemical workstation in 0.5 M H_2SO_4 . The polarization curves were corrected for the ohmic potential drop (*iR*) losses (Figure S2) and the potentials reported in our work were obtained vs the reversible hydrogen electrode (RHE). In 0.5 M H_2SO_4 , E(RHE) = E(Ag/AgCl) + 0.225 V.

Structure Characterization. Scanning electron microscopy (SEM) images were carried out on a JSM-6700F field-emission scanning electron microscope. Transmission electron microscopy

(TEM) and high-resolution transmission electron microscopy (HRTEM) images were recorded upon a JEOL-3010 instrument. Xray photoelectron spectroscopy (XPS) measurements were carried out upon an ultrahigh vacuum setup, equipped with a monochromatic Al $K\alpha$ X-ray source and a high resolution Gammadata-Scienta SES 2002 analyzer. The specific surface area was calculated base on the Brunauer–Emmett–Teller (BET) equation. The nitrogen adsorption/desorption data were recorded at temperature of the liquid nitrogen (77 K) upon a Micromeritics ASAP 2020 M apparatus.

RESULTS AND DISCUSSION

Scheme 1 schematically illustrates the entire synthetic procedure for the NIN-Co-P/PCNTs. Briefly, the synthesis procedure can be conducted in a two-step process. First, the porous CNTs (PCNTs) are obtained via a high temperature reaction between the crude CNTs and a nebulized water stream.²⁵ Second, PCNT modified glass carbon electrodes are soaked in CoSO₄·7H₂O and NaH₂PO₂·H₂O aqueous solution. After an electrochemical deposition treatment (Figure S1), it can be observed that the current increases with subsequent CV cycles, which indicate that the Co-P can be directly grown onto the nodes of the interlaced PCNT networks. For comparison, the bare glass carbon electrode and glass carbon electrodes modified by CNT were also treated under the same synthetic conditions. Additionally, parallel experiments using various etch times and deposition cycles were also conducted. The resultant hybrids are denoted as PCNTs-5cyc, PCNTs-10cyc, PCNTs-20cyc, CNTs-5cyc, and CNTs-10cyc, and so on. The physical parameters and electrochemical properties for these obtained samples, as well as their corresponding experimental data are listed in Table 1 and 2.

Table 1. Comparison of Performance Parameters ofDifferent HER Catalysts

samples	CoP content (wt %)	onset η (mV)	Tafel slope (mV/dec)	exchange current density (mA/cm²)
PCNTs-5cyc	13.11	60	46	8.0×10^{-3}
PCNTs-10cyc	24.26	43	40	1.0×10^{-2}
PCNTs-20cyc	32.47	65	44	7.0×10^{-3}
CNTs-10cyc	23.89	95	49	6.3×10^{-3}
bare GC-10cyc		125	55	4.0×10^{-3}

Table 2. Porous Structure Properties of the Raw CNT andPCNT

samples	time (min)	specific surface area (m^2/g)	total pore volume (cm³/g)
raw CNTs		233.13	0.8
PCNTs-1	8	268.87	0.87
PCNTs	12	284.45	0.89
PCNTs-2	20	343.88	0.93

Figure 1 shows the nitrogen adsorption/desorption isotherms and pore size distribution curves of the as-prepared PCNTs. The specific surface area (SSA) and total pore volume $(V_{\rm T})$ of these PCNT samples with various etch times are summarized in Table 2. From Table 2, we observe that the values of SSA and $V_{\rm T}$ of these PCNTs are significantly increased comparing with the raw CNT values. While the electrochemical impedance spectroscopy (EIS) analyses in Figure S3 reveal that the PCNT samples etched at 8 and 12 min have a close value of interfacial charge-transfer resistance to the raw CNTs. Expecting that the PCNT samples etched at 12 min, having larger SSA and $V_{\rm T}$ values, should better retain their excellent catalytic properties, we selected the PCNT samples for the next electrochemical deposition experiment.

Furthermore, these results suggest that the optimized process involving a mild etch method can create porous structures on CNTs, while also preserving CNTs' intrinsic ability for charge transport.

Figure 2a and b shows the scanning electron microscopy (SEM) images of the PCNTs. In these images, no obvious distinction in morphology is observed between the CNTs before and after etching. Figure 2c-f shows typical SEM images for the PCNTs-10cyc, where abundant catalyst particles are now interspersed in the PCNT networks. The highlighted dots in the scanning transmission electron microscopy (STEM) and corresponding elemental mappings in Figure 2c display a uniform spatial distribution of the nanoparticles comprising Co and P atoms for PCNTs, indicating successful synthesis of Co-P grown on PCNTs. The enlarged SEM (Figure 2f) and transmission electron microscopy (TEM) images (Figure 3a,b) show that most of these particles are decorated on the nodes of the interlaced PCNTs and a neuronlike morphology is present, where the nanoparticles seem to act as a soma, while the PCNTs are similar to a neural dendrite. Considering that the nodes of the interlaced PCNTs should have larger chargedischarge currents during the electrochemical deposition process than other positions on PCNTs, we infer that the inductive effect rooted in the production of large currents may be the main reason for the formation of this neuronlike morphology.

To further explore these nodes, close-up TEM studies were performed. Typical TEM images shown in Figures 3c-e and S5clearly reveal that the PCNTs have been embedded into the Co–P nanoparticles. The high resolution TEM (HRTEM) image in Figure 3f shows typical lattice fringes. The fringe spacing of 0.37 and 0.25 nm represent the spacing of the (011) and (200) plane of the CoP cubic structures. The 0.34 nm fringe spacing indicates the interlayer distance of the (002) plane for PCNTs. The selected-area electron-diffraction (SAED) characterization in the inset of Figure 3f shows several bright rings consisting of discrete spots, which are attributed to the (011), (111), (200) planes of CoP.¹⁷ We thus conclude that a neuronlike interpenetrative nanocomposite network composed of Co–P embedded with porous carbon nanotubes was successfully prepared via this simple two-step method.

The elemental compositions of the PCNTs-10cyc nanocomposites were also investigated by X-ray photoelectron spectroscopy (XPS). The XPS survey spectra of the catalyst in Figure 4a displays a predominant C 1s peak (~284.5 eV), an O 1s peak (~532.0 eV), two Co 2p_{3/2} peaks (~779.1, ~782.3 eV), and two P 2p peaks (~129.8, ~134.1 eV), which further confirm the presence of cobalt and phosphorus in the nanocomposites. These results are consistent with the elemental mapping analysis, HRTEM, and SAED results described above. Moreover, more surface configuration details involving the cobalt and phosphorus atoms can also be seen from XPS high-resolution Co $2p_{3/2}$ and P 2p spectra as shown in Figure 4b and c. It is interesting that the peaks (779.1 and 129.8 eV) are shifted to the binding energies (BEs) for Co and P in CoP, suggesting that the Co atom in the Co-P has a partial positive charge (δ^+) , while the P atom shows a partial negative charge (δ^{-}). The peaks (782.3 and 134.1 eV) are ascribed to the oxidized Co and the PO_x species originating

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Figure 1. Nitrogen adsorption/desorption isotherms (a) and pore size distribution curves (b) of PCNTs at various etch times.



Figure 2. SEM images of PCNTs (a,b) and PCNTs-10cyc (d-f). (c) STEM and corresponding element mapping of PCNTs-10cyc.



Figure 3. TEM images of (a, b) PCNTs-10cyc. HRTEM image of (c-f) PCNTs-10cyc. Corresponding SAED pattern of (f, inset) PCNTs-10cyc.

from superficial oxidation of CoP. This result is similar to the previous reports involving CoP synthesis.^{26,27}

The HER activities of various NIN-Co–P/PCNTs nanocomposites were evaluated in 0.5 M $\rm H_2SO_4$ solution with a typical three-electrode configuration, with a glassy carbon electrode (GCE) modified by various NIN-Co–P/PCNTs as the working electrode. For comparison, other electrodes, such as PCNTs, PCNTs-Scyc, PCNTs-10cyc, PCNTs-20cyc, CNTs-



Figure 4. XPS spectra of the PCNTs-10cyc nanocomposites: (a) survey, (b) Co(2p_{3/2}) regions, and (c) P(2p) regions.



Figure 5. (a) Polarization curves for different deposition cycles in H_2SO_4 solution (0.5M). (b) Electrochemical impedance spectra of NIN-Co-P/PCNTs nanocomposites. (c) Tafel plots of PCNTs-10cyc, CNTs-10cyc, and Pt/C. (d) Polarization curves of PCNTs initially and after 1200, and 2000 CV scans at 50 mV/s.

10cyc, bare GC-10cyc, and 20 wt % Pt/C, were also measured at a constant active mass loading. As a typical reference metric for electrochemical catalytic performance, PCNTs-10cyc achieved a onset overpotential as small as 43 mV (Figure S6) and current densities (*j*) of 2, 10, and 20 mA/cm² at overpotentials of 99.5, 150.6, and 177.6 mV, respectively.

This is comparable to or better than those of all reported Pt-free HER catalysts (Table S1).

For the bare GC-10cyc electrode, a very negative onset potential of 125 mV and a low catalytic current can be observed, indicating inferior HER performance. After combining PCNTs and Co-P, we observed that all of the NIN-Co-P/ PCNTs catalysts demonstrate more positive onset potentials and higher catalytic currents than the PCNT or bare GC-10cvc electrode, these experimental results indicate the positive synergistic effect involving hybridization of Co-P with PCNTs for enhancing HER activity. Furthermore, from Figures 5a and S7, it can also be seen that the PCNTs-10cyc sample obtained in 0.3 M CoSO₄·7H₂O, 0.3 M NaH₂PO₂·H₂O solution containing 0.4 M H₃BO₃ has the most positive onset potential and the highest catalytic current of all of the NIN-Co-P/PCNTs samples. In this case, increasing or decreasing the deposition cycles leads to a decrease in the activity of these NIN-Co-P/PCNTs hybrid catalysts. To further reveal the effect of the deposition cycles on the HER performance, the EIS analysis of the NIN-Co-P/PCNTs catalysts with various deposition cycles in 5 mM H₂SO₄ was preformed. The Nyquist plots are shown in Figure 5b, and their electrical equivalent circuit diagram shown in Figure S8 is used to model the solidliquid interface after the experimental data were well fitted. The impedance parameters are listed in Table S2. It is noted from Table S2, PCNTs-10cyc have a low R_{ct} value of 34.2 Ω , and the largest C_{dl} value among all the NIN-Co-P/PCNTs catalysts. The low R_{ct} value indicates its faster surface charge transfer and higher reaction rate in the electrocatalysis kinetics. The large C_{dl} value corresponds to its high active surface area, which can strongly promote the HER performance. These may be the main reason that PCNTs-10cyc has the highest HER activity among all the NIN-Co-P/PCNTs catalysts. In other words, the varying activity of these counterparts may be the result of their various loading and surface electrocatalysis kinetics. The NIN-Co-P/PCNTs nanocomposites with fewer deposition cycles (less than 10 cycles) are expected to have fewer active sites. Longer cycles (beyond 20 cycles) are expected to lead to the formation of larger Co–P agglomerations (Figure S9), thus decreasing the density of the edge activity sites and increasing resistance. The measurements of inductively coupled plasmaatom emission spectroscopy and elemental analysis also confirm this hypothesis, as the loading values for the samples obtained using deposition cycles of 5, 10, and 20 are 13.11, 24.26, and 32.47 wt %, respectively (Table 1).

In addition, the effect of the porous structure on the HER performance has also been investigated. From Figure S10, it can be seen that CNTs-10cyc has the most HER performance among all of these Co-P/CNTs samples. The measurements of inductively coupled plasma-atom emission spectroscopy and elemental analysis confirm that the Co-P loading value for the PCNTs-10cyc sample is close to that of the CNTs-10cyc sample (Table 1). Furthermore, as shown in Figure 5a,c, it can also be found that Co-P nanoparticles grown on PCNTs show a higher HER activity than corresponding Co-P on CNTs. We hypothesize that some opened structure in the inner cavity or created pores on the walls of PCNTs from water etching may play a crucial role in promoting charge and reactant transport.

To further reveal the detailed mechanism behind its HER activity of the NIN-Co–P/PCNTs catalysts, Tafel slopes were derived from polarization curves (Figures 5c and S11). A Tafel slope of 40 mV/decade was obtained for PCNTs-10cyc, similar to that reported for the Pt/C catalyst of 30 mV/decade, while

lower than that for the bare GC-10cyc of 55 mV/decade. The Tafel slope of 40 mV/decade suggests that the electrochemical desorption of hydrogen is the rate-limiting step in the HER.^{5,6} To the best of our knowledge, this Tafel slope of 40 mV/ decade is also comparable to or lower than those for all the previously reported Pt-free HER catalysts (Table S1). The exchange current densities (j_0) were determined by fitting polarization data according to the Tafel equation ($\eta = b \log j + a$, in which j is the current density and b is the Tafel slope) in Table 1. The PCNTs-10cyc electrode exhibits a remarkable exchange current density of 0.01 mA/cm², which is almost 3 times larger than the value of bare GC-10cyc, and better than that of most non-Pt catalysts (Table S1), suggesting excellent activity of PCNTs-10cyc for HER catalysis.

To further explore the origin of the observed HER performance, the electrochemical capacitance surface area measurements were conducted to estimate the active surface area of the nanocomposites. The obtained data were also adopted to work out the average activity of each site, namely, the per-site turnover frequency (TOF) (calculations detailed in Figure S12). Figure S12a shows the cyclic voltammogram measurements in the range from 0 to 0.3 V versus RHE for the PCNTs-10cyc. As summarized in Table 3, the electrochemically

Table 3.	Calculated	Values o	f Turnover	Frequency	v (TOF))
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samples	surface sites $(10^{16}/\text{cm}^2)$	TOF (s ⁻¹) at η = 0.2 V
PCNTs-5cyc	2.35	2.7
PCNTs-10cyc	2.96	3.2
PCNTs-20cyc	2.87	1.7
CNTs-10cyc	2.42	2.9
bare GC-10cyc	2.93	0.4

accessible sites density of PCNTs-10cyc catalyst is estimated to be ~2.96 × 10^{16} /cm². The corresponding TOF for each active site is derived to be as high as 3.2 s⁻¹ upon η = 0.2 V and pH = 0, which is superior to most reported Pt-free catalysts (Table S1).

To better understand the origin of this high TOF value, some samples including PCNTs-5cyc, PCNTs-10cyc, PCNTs-20cyc, CNTs-10cyc, and bare GC-10cyc are compared. From Table 3, it can be seen that the PCNTs-10cyc has a relatively high surface active sites compared to CNTs-10cyc, despite their close Co-P loading values. This further indicates that the porous and embedded structure in the PCNTs-10cyc can generate more active sites, and thus improve the utilization ratio of catalysts. Furthermore, it is also found that the PCNTs-10cyc have an obviously higher TOF value than CNTs-10cyc or bare GC-10cyc. After referencing their different morphological and structural characterizations, and coupling with the face that the PCNTs-10cyc has a more positive onset potential (Figure 5a) and a lower Tafel slope (Figures 5c, S10, and S11) than the CNTs-10cyc or bare GC-10cyc sample, it is believed that the hollow, tubelike, and porous structure of PCNTs should be one of the most important factors affecting the high TOF value.

The long-term cycling stability of PCNTs-10cyc was assessed by performing continuous linear sweep voltammetry at 50 mV/ s. The polarization curve of PCNTs-10cyc catalyst after 1200 cycles covers almost exactly the initial curve (Figure 5d), with negligible current loss. This suggests that the catalyst is highly stable. After the extension of 2000 cycles, it is found that the overpotential only has a slight increase. The high durability is comparable to or higher than most previously reported Co–P/

C hybrid catalysts.^{17,19,28,29} The exceptional long-term durability as well as the superior HER activity described above makes the PCNTs-10cyc a promising HER catalyst for practical applications.

CONCLUSIONS

In summary, we demonstrate a novel fabrication strategy via a simple two-step method for NIN-Co-P/PCNTs nanocomposites. In this work, the as-prepared NIN-Co-P/PCNTs composites exhibit a excllent HER catalytic performance, with a small onset overpotential of 43 mV, a low Tafel slope of 40 mV/dec, and a high turnover frequency value of 3.2 s⁻¹ at η = 0.2 V in acidic conditions. We attribute this high activity to the neuronlike morphology. We suggest that the interpenetrative network provides a natural transport path to accelerate the hydrogen production process. The embedded-type structure improves the utilization ratio of Co-P and the hollow, tubelike, and porous structure of PCNTs further promote charge and reactant transport. These encouraging properties derived from the neuronlike interpenetrative network structure might offer new inspiration for the preparation of more nanocomposites for applications in other catalytic and optoelectronic field.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsami.6b04718.

Experimental section, images of supplementary electrodeposition, morphological, and structural characteristics, performance, and calculation of TOF of the material (PDF)

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Notes

The authors declare no competing financial interest.

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