Hierarchical iridium-based multimetallic alloy with double-core-shell architecture for efficient overall water splitting

Jie Zhang¹, Zelin Chen¹, Chang Liu¹, Jun Zhao¹, Siliang Liu¹, Dewei Rao², Anmin Nie³, Yanan Chen^{1*}, Yida Deng^{1*} and Wenbin Hu^{1,4}

ABSTRACT The overall water splitting for hydrogen production is an effective strategy to resolve the environmental and energy crisis. Here, we report a facile approach to synthesize the Ir-based multimetallic, hierarchical, double-core-shelled architecture (HCSA) assisted by oil bath reaction for boosting overall water splitting in acidic environment. The IrNiCu HCSA shows superior electrocatalytic activity for hydrogen evolution reaction (HER) and oxygen evolution reaction (OER), which are comparable to commercial Pt/C and better than IrO₂. The IrNiCu HCSA exhibits remarkably catalytic efficiency as bifunctional catalyst for overall water splitting where a low cell voltage of 1.53 V is enough to drive a current density of 10 mA cm⁻² and maintains stable for at least 20 h. The presented work for the design and synthesis of novel Ir-based multimetallic architecture paves the way for high-performance overall water splitting catalysis.

Keywords: IrNiCu nanoframe, hierarchical structure, core-shell, oxygen evolution reaction, hydrogen evolution reaction

INTRODUCTION

Electrochemical water splitting is considered as one of the most promising way to produce hydrogen [1–3], which composes of hydrogen evolution reaction (HER) of cathodic half-reaction and oxygen evolution reaction (OER) of anodic half-reaction [4–11]. Acid polymer electrolyte membrane water electrolyzer (PEMWE) is the most popular technique towards the production of hydrogen and oxygen fuels [12–17]. Pt and Ir/Ru-based

nanocatalysts are emerging as the state-of-the-art metal catalysts for HER and OER in PEMWE, respectively [2,18–22]. However, these catalysts feature moderate intrinsic electrocatalytic activity with sluggish kinetics of HER and OER, and low durability in harsh acidic media and high cost, discouraging their large-scale applications [23–25]. Therefore, numerous scientific research efforts have been devoted to investigating and designing efficient noble metal nanocatalysts with high electrocatalytic activity, long-term stability and the use of non-noble metals. Alloying Ir with transition group metals [19,24–34] is generally regarded as an effective strategy that not only substantially reduces the usage of Ir but also facilitates the catalytic activity and stability for water splitting by tuning the d-band structure and oxygen adsorption energy on the surface of Ir. Another strategy to optimize the overall catalytic activity is to tune the geometric shape of the nanocatalysts [18,35–42]. A hierarchical alloy architecture is believed to show the capability of promoting the initial activity with more active surface area exposed to reactants [43]. The construction of a core-shell structure with a noble metal shell also demonstrates the enhancement of catalytic activity and stability, the core-shell structure maximizes valuable metal exposure to reactants and minimizes the amount of expensive metal used, and it boosts catalysis *via* core-shell synergistic interactions, such as tuning the electronic and surface strain effects [44,45]. However, it is still a huge challenge to synthesize a three-dimensional (3D), hierarchical, core-shell struc-

¹ School of Materials Science and Engineering, Key Laboratory of Advanced Ceramics and Machining Technology of Ministry of Education, Tianjin Key Laboratory of Composite and Functional Materials, Tianjin University, Tianjin 300072, China

² School of Materials Science and Engineering, Jiangsu University, Zhenjiang 212013, China

³ State Key Lab of Metastable Materials Science and Technology, Yanshan University, Qinhuangdao 066004, China

⁴ Joint School of National University of Singapore and Tianjin University, International Campus of Tianjin University, Fuzhou 350207, China

* Corresponding authors (emails: yida.deng@tju.edu.cn (Deng Y); yananchen@tju.edu.cn (Chen Y))

tured Ir-based multimetallic alloy with improved intrinsic activity and increased active sites as a highly efficient and stable bifunctional catalyst for both HER and OER.

In this work, we report a facile, one-pot strategy for a controllable synthesis of 3D hierarchical Ir-based multimetallic alloy nanoframes assembled by IrNiCu nanocrystals, with a Cu-rich@Ni-rich@Ir-rich multielement alloy and double-core-shell architecture (Fig. 1), as highly active and exceptionally stable bifunctional electrocatalysts for overall water splitting. The as-synthesized IrNiCu hierarchical double-core-shelled architecture (HCSA) exhibits remarkable electrocatalytic performance for both HER and OER in acidic environments. Specifically, the IrNiCu HCSA shows outstanding HER activity with a low overpotential of 41 mV at a current density of 10 mA cm^{-2} and a small Tafel slope of 21.4 mV/dec, which is comparable to commercial platinum/carbon (Pt/C) electrocatalysts (39 mV and 21.0 mV/dec). The IrNiCu HCSA displays the highest electrocatalytic activity for OER with only a 262 mV overpotential to attain 10 mA cm^{-2} and a 71.4 mV/dec Tafel slope, which outperforms the commercial IrO_2 (326 mV and 77.3 mV/dec), indicating that the IrNiCu HCSA is an excellent OER electrocatalyst in acidic electrolyte. It is noteworthy that the IrNiCu HCSA represents impressive electrocatalytic activity and superior durability for overall water splitting, achieving a 10 mA cm^{-2} current at a low cell voltage of 1.53 V and sustaining a negligible decay of polarized current after 1000 cycles. The present work provides possibilities in tuning the hierarchical and core-shell structure of Ir-based multimetallic nanocatalysts for promoting the electrocatalytic performance for overall water splitting.

EXPERIMENTAL SECTION

Chemicals

Iridium(III) 2,4-pentanedionate ($\text{Ir}(\text{acac})_3$, Ir 37.5%), nickel(II) 2,4-pentanedionate ($\text{Ni}(\text{acac})_2$, 96%), copper(II) acetylacetonate ($\text{Cu}(\text{acac})_2$, 98%), (1-hexadecyl)trimethylammonium chloride (CTAC, 96%), and 1,2-hexadecanediol (1,2-HDD, 98%) were purchased from Alfa Aesar. Oleylamine (80%–90%) was manufactured by Sigma-Aldrich Corporation. All the chemicals were used as purchased without further purification and deionized water was employed in these experiments.

Synthesis of the IrNiCu HCSA

The IrNiCu nanoframe structures were one-step synthesized with an oil bath method. A suspension containing 26.1 mg $\text{Ir}(\text{acac})_3$, 10.7 mg $\text{Ni}(\text{acac})_2$, 5.3 mg $\text{Cu}(\text{acac})_2$, 33.3 mg CTAC, 10.5 mg 1,2-HDD and 5 mL oleylamine was homogeneously dissolved with magnetic stirring at 60°C for 10 min in a round-bottom flask. After that, the round-bottom flask was transferred to a preheated silicone oil bath at 260°C for 40 min and then cooled to room temperature. The reacted mixture was collected by centrifugation with 5 mL methylbenzene and 10 mL methanol at 8000 revolutions per minute for 5 min. To further purify the precipitate, the centrifugation was performed twice more with 5 mL methylbenzene and 10 mL ethanol at 8000 revolutions per minute for 5 min. Finally, the purified IrNiCu nanoframe catalyst powder was redispersed in 1 mL ethanol for further use.

Synthesis of the IrNi and IrCu nanoarchitectures (NA)

The IrNi and IrCu were prepared and purified in the

Figure 1 Schematic illustration of the synthesis of IrNiCu HCSA.

same way, with $\text{Ir}(\text{acac})_3$, $\text{Ni}(\text{acac})_2/\text{Cu}(\text{acac})_2$, CTAC, 1,2-HDD and oleylamine as the reactants. Finally, the purified IrNi or IrCu nanocatalyst powder was redispersed in 1 mL ethanol for further use.

Characterizations

The crystal structures of the as-prepared Ir-based catalysts were characterized by powder X-ray diffraction (XRD) conducted on a Bruker D8 Advance X-ray diffractometer (Cu K α radiation, 40 kV, 40 mA). Transmittance electron microscope (TEM) and high resolution TEM (HRTEM, JEOL JEM-2100F, 200 kV and JEM-ARM200F) were used to study the particle morphologies. The surface chemical valence state was characterized using X-ray photoelectron spectroscopy (XPS, Thermo ESCALAB 250XI, with an incident radiation of monochromatic Al K α X-rays). The element contents of the as-prepared nanoparticles were analyzed by inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7700x).

Electrochemical tests

All electrochemical measurements were conducted on a CHI 660E electrochemical workstation (Shanghai Chenhua, China). The catalytic performance of HER and OER was carried out in a three-electrode system containing 0.5 mol L⁻¹ H₂SO₄ solution at room temperature. A glassy carbon electrode with diameter of 5 mm, a graphite rod, and a Ag/AgCl electrode (3 mol L⁻¹ KCl) were serviced as the working, counter, and reference electrodes, respectively. Before every measurement, the glassy carbon electrode was polished with a 1.0 μm alumina suspension on a piece of moist chamois and then repolished with a 0.3 μm alumina suspension. Then, 8 μL of the aforementioned 1 mL catalyst-ethanol ink was dropped twice on the working electrode with a pipette gun and left alone until the liquid had evaporated and then 8 μL of a 0.2 wt% Nafion solution was dropped. The loading of Ir on the glassy carbon electrode was 10 $\mu\text{g cm}^{-2}$. The electrochemical potentials determined against the Ag/AgCl reference electrode were converted to a reversible hydrogen electrode (RHE) scale *via* the Nernst equation: $E_{\text{RHE}} = E_{\text{Ag/AgCl}} + 0.059\text{pH} + 0.197$, and the overpotential (η) for OER was calculated using the following equation: $\eta = E_{\text{RHE}} - 1.23 \text{ V}$ [25].

Cyclic voltammograms (CVs) were performed to activate the active substances on the working electrodes before the linear sweep voltammetry (LSV), which was conducted to obtain polarization curves of the aforementioned samples. For HER tests, the CVs were re-

corded in a N₂-saturated solution in the potential range of 0 to -0.4 V with scan rates of 100 and 20 mV s⁻¹ for four cycles. Then, the LSVs were subsequently performed in the same potential range with a scan rate of 5 mV s⁻¹ without *iR* compensation [28]. For the OER activity, the CVs were first recorded in a N₂-saturated solution in the potential range of 1.0 to 1.4 V at scan rates of 100 and 20 mV s⁻¹ for four cycles. Then, the LSVs were subsequently performed in the same potential range with a scan rate of 5 mV s⁻¹ without *iR* compensation. Electrochemical impedance spectroscopy (EIS) was conducted from 100 kHz to 0.01 Hz with an alternating current (AC) amplitude of 10 mV at -0.05 V *versus* RHE for HER and 1.5 V *versus* RHE for OER. Chronopotentiometry was employed to evaluate the stability of the as-prepared catalysts at a constant current density of 10 mA cm⁻². To estimate the electrochemical active surface areas (ECSAs), the electrochemical double-layer capacitance (C_{dl}) was determined by CVs tested at different scan rates (5, 10, 20, 40, 60, 80, and 100 mV s⁻¹) in the potential windows of 0.9 to 1.0 V *versus* RHE [46].

For the overall water splitting, a two-electrode system with 0.5 mol L⁻¹ H₂SO₄ solution was used, and two carbon papers with a size of 1 cm $\times$ 1 cm were used as the cathode and anode for HER and OER, respectively. The exact loading of the catalysts on the carbon papers was determined by ICP-MS. Polarization curves were carried out in the range of 1 to 2 V with a scan rate of 5 mV s⁻¹. The durability tests of the overall water splitting were recorded using chronopotentiometry at a constant current density of 10 mA cm⁻² for 20 h.

RESULTS AND DISCUSSION

The morphology of IrNiCu HCSA synthesized by the one-step oil bath method was characterized by TEM. As shown in Fig. 2a, b and Fig. S1, the typical IrNiCu HCSAs were 3D polyhedron nanoframes composed of IrNiCu nanocrystals with diameters of 40–80 nm. The HRTEM image of the IrNiCu HCSA (Fig. 2c) reveals that the lattice spacing is 0.221 nm, between 0.222 nm (Ir, JCPDS card No. 06-0598), 0.203 nm (Ni, JCPDS card No. 04-0850), and 0.209 nm (Cu, JCPDS card No. 04-0836), indicating the formation of the (111) plane of IrNiCu [18]. High-angle annular dark field scanning tunneling electron microscopy (HAADF-STEM) and energy dispersive X-ray spectroscopy (EDX) (Fig. 2d, e) were utilized to probe the elemental mapping of the IrNiCu HCSA structure. From the higher magnification of the HAADF-STEM images, the iridium, nickel, and copper elements are distributed in a specific manner. The copper is most

Figure 2 (a) TEM, (b) high-magnification TEM, (c) HRTEM, (d, e) HAADF-STEM image and corresponding EDX elemental mapping, and (f) linear scan element distribution of the as-synthesized IrNiCu HCSA.

concentrated in the middle, suggesting a preferential nucleation of copper during the synthesis process as the center of the whole structure. Then, nickel coats on the copper-rich phase and forms a certain orientation. Finally, iridium grows at the outermost layers of the CuNi-rich 3D polyhedron. On the whole, iridium, nickel and copper synergistically form the Cu-rich@Ni-rich@Ir-rich multielement alloy double-core-shell architecture, consistent with the linear scan of the elements (Fig. 2f). The crystal structure of the IrNiCu HCSA was analyzed by XRD. As shown in Fig. S2, the spectrum exhibits four main diffraction peaks matching the typical fcc crystalline structure of Ir (PDF #06-0598), corresponding to the (111), (200), (220) and (311) crystal planes. Furthermore, the doping of Ni and Cu atoms with smaller radii results in a shift of the spectrum to a higher angle, and this shift reveals the formation of a well-defined IrNiCu structure. The EDX spectroscopy of the IrNiCu HCSA (Fig. S3) further attests to the coexistence of all the elements with the Ir weight percentage of 61.9%, same as the initial loading percentage. According to the XPS results (Table S1), the percentage of Ir atoms in IrNiCu HCSA is 76.2%, larger than that in EDS (33.9%), indicating that there are more Ir atoms on the surface, consistent with the element mapping results.

To further analyze the ternary IrNiCu HCSA, two binary IrNi and IrCu NA were prepared for comparison. Fig. S4a shows a typical TEM image of an IrNi NA, composed of many small particles interlaced and stacked. The lattice spacing was measured to be between 0.216 and

0.218 nm (Fig. S4b). Fig. S4c shows the element distribution of the IrNi NA. It can be seen that the Ni is concentrated in the center, while the Ir distributes in the periphery, indicating that the Ni first nucleates and then the Ir grows during the synthesis process. The element linear scan distribution (Fig. S4d) further proves the above conclusion. According to the particle size analysis in Fig. S5, the particle size of the IrNi NA is concentrated between 25 and 40 nm, smaller than that of the IrNiCu HCSA. The XRD pattern (Fig. S6) shows that the four major peaks of the corresponding Ir are all offset to a high angle, indicating that the IrNi alloy is well formed with the addition of Ni. Fig. S7 shows that the Ir weight percentage is 76.2% in the IrNi NA. The morphology of the IrCu NA (Fig. S8a) is a membrane-like polyhedron structure, and the crystal plane spacing (Fig. S8b) is between 0.210 and 0.220 nm, assigned to the (111) crystal plane. Fig. S8c shows that the element distribution of the IrCu is relatively uniform, with no obvious area of concentration, which is consistent with the linear scan element distribution (Fig. S8d). In addition, its particle size (Fig. S9) is smaller than that of the IrNi NA. The XRD results of the IrCu are similar to those of the IrNi NA (Fig. S10).

The electronic structures of the IrNiCu HCSA, IrNi NA and IrCu NA were investigated by XPS. The XPS survey scan spectra suggest the existence of iridium, nickel and copper in the samples (Fig. 3a). Fig. 3b depicts the core level spectra of the Ir 4f electrons of the three different samples. For IrNiCu HCSA, the Ir 4f_{5/2} and Ir 4f_{7/2} peaks

Figure 3 (a) XPS survey spectra, and core levels spectra of (b) Ir 4f, (c) Ni 2p, and (d) Cu 2p for the IrNiCu HCSA, IrNi NA and IrCu NA samples.

are deconvoluted into two sets of peaks centered at 63.8 and 60.8 eV for the Ir^0 and at 64.4 and 61.4 eV for the Ir^{4+} [47,48]. The presence of iridium at a high chemical valence is due to its oxidation in the air. For IrNi NA and IrCu NA, their Ir 4f peaks show the same rule as that of IrNiCu HCSA, but there are slight differences. Specifically, the Ir $4f_{5/2}$ and Ir $4f_{7/2}$ peaks of the IrNi NA are both shifted by 0.2 eV in the direction of low binding energy, while the IrCu NA is shifted by 0.4 eV in the same direction, meaning the Ir in IrNi NA and IrCu NA has a lower valence state. The deconvoluted Ni 2p is shown in Fig. 3c, the binding energies of 855.6 and 873.4 eV can be attributed to Ni^{2+} (NiO or Ni(OH)_2), and the peaks at 852.8 and 869.9 eV correspond to Ni^0 [49]. The same rule is applied to IrNi NA, except that all the corresponding peaks of IrNi NA are shifted by 0.2–0.6 eV in the direction of low binding energy. Fig. 3d shows that the binding energy of $\text{Cu } 2p_{3/2}$ of IrNiCu HCSA shifts to a lower value (932.1 eV) compared with standard $\text{Cu } 2p_{3/2}$ (933 eV), while the binding energy of $\text{Cu } 2p_{3/2}$ in IrCu NA decreases slightly (932.3 eV), indicating that the partial charge transfer from Cu to Ir results in a lower d-band center of Ir, improving its electrochemical properties [50]. The peaks at 952.0 and 952.3 eV represent the $2p_{1/2}$ peaks of Cu in IrNiCu HCSA and IrCu NA, respectively. The above four peaks represent the zero valence state of copper in the samples [51,52]. Cu^{2+} still exists in the

samples evidenced by the corresponding binding energy (~ 933.5 eV) [53].

The HER electrocatalytic properties of the IrNiCu HCSA were evaluated in 0.5 mol L^{-1} H_2SO_4 solution. The polarization curves of HER indicate that the overpotentials of IrNiCu HCSA, IrNi NA, IrCu NA and Pt/C are 41, 55, 70 and 39 mV, respectively, at a current density of 10 mA cm^{-2} (Fig. 4a), revealing the superior catalytic activity of the IrNiCu HCSA compared with the Pt/C. The corresponding Tafel plots are illustrated in Fig. 4b, where the IrNiCu HCSA shows the lowest Tafel slope (21.4 mV/dec) and is almost the same as the commercial Pt/C (21.0 mV/dec). The HER kinetics of the catalysts at the electrode/electrolyte interface were further established by EIS measurements at -0.05 V (vs. RHE) (Fig. 4c). The Pt/C and IrNiCu HCSA exhibit the smallest resistance, possessing a lower charge-transfer resistance and faster charge transfer rate [19]. CV curves under different scanning rates (5, 10, 20, 40, 60, 80 and 100 mV s^{-1}) in the voltage range of 0.9–1.0 V (vs. RHE) were performed as shown in Figs S11–S15. Under the same voltage, the current density of the IrNiCu HCSA is the maximum value. Meanwhile, the ECSA was estimated by the C_{dl} using a CV measurement in Fig. S16. The C_{dl} of IrNiCu HCSA is 71.19 mF cm^{-2} , much larger than those of IrNi NA (41.24 mF cm^{-2}) and IrCu NA (22.64 mF cm^{-2}), indicating that the hierarchical structure

Figure 4 (a, d) LSV curves for HER and OER performance of IrNiCu HCSA, IrNi NA, IrCu NA, Pt/C and IrO₂ in N₂-saturated 0.5 mol L⁻¹ H₂SO₄ solution at the potential scan rate of 5 mV s⁻¹, (b) Tafel plots and (c) EIS of IrNiCu HCSA, IrNi NA, IrCu NA and Pt/C for HER at -0.05 V (vs. RHE). (e) Tafel plots and (f) chronopotentiometry curve of IrNiCu HCSA, IrNi NA and IrCu NA in 0.5 mol L⁻¹ H₂SO₄ at a constant current density of 10 mA cm⁻².

offers vast active sites for catalytic performance improvement.

The OER activity of the IrNiCu HCSA was also investigated in 0.5 mol L⁻¹ H₂SO₄, as illustrated in Fig. 4d. The IrNiCu HCSA exhibits the lowest overpotential (262 mV), and the IrCu NA shows the highest overpotential (296 mV) at a current density of 10 mA cm⁻². In addition, the electrochemical performance of the IrNiCu HCSA, IrNi NA and IrCu NA are all better than that of commercial IrO₂ (326 mV). Fig. S17 shows the overpotentials of the various specimens at different current densities. It can be seen that the corresponding overpotential of IrNiCu HCSA is the lowest at 1, 10 and 20 mA cm⁻², showing the best catalytic property for OER. The IrNiCu HCSA exhibits the lowest Tafel slope of 71.4 mV/dec (Fig. 4e), lower than that of IrO₂ (77.3 mV/dec), confirming its impressive OER electrocatalytic activity. The EIS results at 1.5 V (vs. RHE), as shown in Fig. S18, demonstrate that the IrNiCu HCSA displays the smallest impedance and lowest charge transfer resistance compared with the IrNi NA, IrCu NA and IrO₂. Durability is an important parameter to evaluate the catalytic performance. The stability of the catalysts was investigated by a chronopotentiometry measurement at a constant current density of 10 mA cm⁻² in 0.5 mol L⁻¹ H₂SO₄ solution (Fig. 4f). After a con-

tinuous 20 h test, the voltage of IrNiCu HCSA increases by only 2% compared with the initial one, while that of IrCu NA increases by 5%, indicating the excellent durability of IrNiCu HCSA in acidic solution. We also investigated the TEM of the IrNiCu HCSA, IrNi NA and IrCu NA catalysts after the OER stability test (Figs S19–S21), indicating that the morphology had no obvious change. The corresponding EDX (Table S2) shows that its composition has not significantly changed, indicating the morphology and composition remained.

To investigate the possibility of simultaneously employing the IrNiCu HCSA as an efficient bifunctional catalyst for both HER and OER, an electrode of the catalysts coated on carbon paper (1 cm×1 cm) was fabricated and tested as both the anode and cathode in a two-electrode system in acidic solution (Fig. 5d). The electrolysis that applied the IrNiCu HCSA as bifunctional catalysts exhibits exceptional performance for overall water splitting. When the current density was 10 mA cm⁻², the voltages of IrNiCu HCSA, IrNi NA and IrCu NA were 1.56, 1.62 and 1.65 V, respectively (Fig. 5a). The stability of the IrNiCu HCSA for overall water splitting was evaluated by a chronopotentiometry measurement at a constant current density of 10 mA cm⁻² in 0.5 mol L⁻¹ H₂SO₄ solution (Fig. 5b). The IrNiCu HCSA has the lowest voltage, at ~ 1.53 V, and after 20 h of continuous

Figure 5 Overall-water-splitting performance of IrNiCu HCSA, IrNi NA and IrCu NA. (a) Polarization curves of IrNiCu HCSA, IrNi NA and IrCu NA in 0.5 mol L⁻¹ H₂SO₄ solution at a scan rate of 5 mV s⁻¹. (b) Chronopotentiometry curve of IrNiCu HCSA, IrNi NA and IrCu NA in 0.5 mol L⁻¹ H₂SO₄ at a constant current density of 10 mA cm⁻². (c) Polarization curves of IrNiCu HCSA, IrNi NA and IrCu NA for overall water splitting after 10, 500, and 1000 cycles. (d) Optical image of electrocatalytic water electrolysis.

catalysis, the voltage increases by only 0.8%, demonstrating the excellent stability of IrNiCu HCSA. A homemade exhaust device was set up to collect the gas products (H₂ and O₂) to detect the catalytic efficiency of IrNiCu HSCA for overall water splitting in Fig. S22. The faradaic efficiencies of IrNiCu HCSA are almost 100% for both HER and OER. We further evaluated the long-term stability of IrNiCu HCSA, IrNi NA and IrCu NA toward water splitting by cycling the potential between 1.0 and 2.0 V for 10, 500 and 1000 cycles, respectively. It can be clearly seen from Fig. 5c that IrNiCu HCSA has the best stability, and the polarization curve basically does not change even after 1000 cycles, compared with the serious changes observed in that of the IrNi and IrCu NA.

CONCLUSIONS

In summary, we demonstrated a simple, one-step method for the synthesis of IrNiCu nanoframes with hierarchical features and double core-shell structures assisted by oil bath reactions and applied it as an efficient bifunctional catalyst for overall water splitting catalysis in acidic environments. By comparing various Ir-based alloy specimens, we found that the IrNiCu HCSA exhibited excellent performance with an OER activity superior to that of IrO₂ (overpotential of 262 mV and Tafel slope of 71.4 mV/dec vs. 326 mV and 77.3 mV/dec at a current

density of 10 mA cm⁻²) and a HER activity close to that of Pt/C (41 mV and 21.4 mV/dec vs. 39 mV and 21.0 mV/dec). An outstanding overall water splitting performance was also observed with a current density that reached 10 mA cm⁻² at a potential of only 1.53 V and remained stable for a long time. The exceptional electrochemical performances are mainly attributed to the large electrochemical active areas brought by the hierarchical nanoframe architecture and the synergistic effect from the three elements of Ir, Ni and Cu and the double core-shell structure. This work illustrates a novel strategy to design Ir-based multimetallic HCSA as a bifunctional catalyst with remarkable electrocatalytic activity and robust durability for water splitting in an acidic solution and provides a very broad prospect for practical application in a PEMWE.

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Supplementary information Supplementary data including TEM images, EDS pattern, XRD pattern and supplementary electrochemical properties data are available in the online version of the paper.

Jie Zhang obtained her Bachelor's degree from the School of Materials Science and Engineering, Chang'an University in 2017. She is now a graduate student in the School of Materials Science and Engineering, Tianjin University. Her main research focuses on the synthesis and characterization of iridium nanomaterials for electrocatalysis.

Zelin Chen received his Bachelor and Master degrees from Nanjing Tech University in 2012 and 2015, respectively. Now, he is a PhD candidate majored in material science under the supervision of Prof. Wenbin Hu and Prof. Yida Deng at Tianjin University. His research interests focus on the design and controllable synthesis of noble-metal-based nanomaterials and their electrocatalytic applications in fuel cells.

Yida Deng is a Professor in the School of Materials Science and Engineering, Tianjin University. He received his PhD from Shanghai Jiao Tong University in 2006. His research interests include the metal and metal oxide nanostructures for electrochemical and energy applications.

分级双核壳架构铱基多金属合金催化剂的高效全解水研究

张洁¹, 陈泽霖¹, 刘畅¹, 赵君¹, 刘思靓¹, 饶德伟², 聂安民³, 陈亚楠^{1*}, 邓意达^{1*}, 胡文彬^{1,4}

摘要 电解水制氢是解决环境和能源危机的一种有效策略。本文采用简便的一步油浴法合成分级双核壳架构(HCSA)铱基多金属合金催化剂, 并将其应用于酸性环境中的全解水。所制备的IrNiCu HCSA表现出可以与Pt/C相媲美的氢析出(HER)性能和优于IrO₂的氧析出(OER)性能。IrNiCu HCSA作为一种双功能催化剂也显示出卓越的全解水性能, 在酸性环境中当电流密度为10 mA cm⁻²时电压仅为1.53 V, 并且在持续催化20 h后性能基本不变, 具有很好的稳定性。本研究为新型铱基多金属合金结构的设计与合成奠定了基础, 有望应用于电催化水分解领域。