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PAPER

Carbon aerogels with atomic dispersion of binary iron-cobalt sites as effective oxygen catalysts for flexible zinc-air batteries

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Iron single atom catalysts have emerged as one of the most active electrocatalysts towards oxygen reduction reaction (ORR), but the unsatisfactory durability and limited activity for oxygen evolution reaction (OER) has hampered their commercial applications in rechargeable metal-air batteries. By contrast, cobalt-based catalysts are known to afford excellent ORR stability and OER activity, due to the weak Fenton reaction and low OER Gibbs free energy. Herein, a bimetal hydrogel template is used to prepare carbon aerogels containing Fe-Co bimetal sites (NCAG/Fe-Co) as bifunctional electrocatalysts towards both ORR and OER, with enhanced stability, as compared to the monometal counterparts. High-resolution transmission electron microscopy, elemental mapping and X-ray photoelectron spectroscopy measurements demonstrate homogeneous distribution of the metal centers within defected carbon lattices by coordination to nitrogen dopants. X-ray absorption spectroscopic measurements, in combination with other results, suggest the formation of FeN₃ and CoN₃ moieties on mutually orthogonal planes with a direct Fe-Co bonding interaction. Electrochemical measurements show that NCAG/Fe-Co delivers a small ORR/OER potential gap of only 0.64 V at the current density of 10 mA cm⁻², 60 mV lower than that (0.70 V) with commercial Pt/C and RuO₂ catalysts. When applied in a flexible Zn-air battery, the dual-metal NCAG/Fe-Co catalyst also shows a remarkable performance, with a high open-circuit voltage of 1.47 V, a maximum power density of 117 mW cm⁻², as well as good rechargeability and flexibility. Results from this study may offer an ingenious protocol in the design and engineering of highly efficient and durable bifunctional electrocatalysts based on dual metal-doped carbons.

Introduction

The non-renewability of fossil energy and growing environmental pollution have spurred the development of sustainable energy technologies, such as fuel cells and metal-air batteries.¹⁻⁶ Of these, zinc-air battery represents a promising energy technology for next-generation portable electronics, due to its good rechargeability and high theoretical density (1370 Wh kg⁻¹),^{7, 8} where the device performance is largely dictated by the reversible catalysts at the cathode for oxygen reduction (ORR) and oxygen evolution reactions (OER). Platinum-based nanoparticles have been the catalysts of choice for ORR, whereas Ir and Ru-based

nanoparticles for OER. Yet their high costs and low natural abundance have hindered the practical applications of the technology. Thus, development of low-cost and high-performance electrocatalysts for ORR and OER have been attracting extensive interest.⁹ Recent reports have shown that atomically dispersed metals (such as Mn, Fe and Co) within nitrogen-doped carbons, exhibit excellent electrocatalytic performance towards ORR and may even surpass the corresponding nanoparticle counterparts.^{10, 11} In both experimental and theoretical studies, Fe single atom catalysts (SACs) have been recognized as the most active catalysts towards ORR in alkaline media. Unfortunately, for the Fe-based SACs, Fenton reaction involving the Fe center and ORR byproduct H₂O₂ produces hydroxyl and oxygen radicals, which not only affect the durability of the catalysts by changing its chemical structure, but also damage the battery devices by corroding the ion membranes.¹² Additionally, theoretical and experimental studies have shown that the Fe-based SACs performs poorly towards OER, as compared to other 3d transition metals, such as Co and Ni.¹³ Therefore, it is critical to improve the ORR durability and OER activity of Fe SACs such that they may be used as the bifunctional oxygen catalysts in rechargeable Zn-air battery. Towards this end, the incorporation of Co atomic sites into Fe SACs represents a

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unique strategy. First of all, the weak Fenton activity between Co and H₂O₂ is anticipated to markedly enhance the ORR stability of Fe SACs.^{14, 15} In addition, prior studies have shown that Co-doped carbon exhibits a low overpotential and small Tafel slope towards OER.¹⁶ Thus, it is envisioned that atomically dispersing Co atoms into Fe-doped carbon may achieve a bimetal catalyst with excellent ORR/OER activity and enhanced durability, in comparison to the monometal counterparts.

Herein, modified gelatin hydrogels were used as 3D structural templates and precursors to synthesize N-doped carbon aerogels (NCAG/Fe-Co), whereby Fe and Co bimetal centers were atomically dispersed into the porous, defect-rich carbon matrix.¹⁷ This was evidenced in elemental mapping and inductively coupled plasma-optical emission spectrometry (ICP-OES) measurements. X-ray photoelectron spectroscopy (XPS) measurements suggest charge transfer between the Fe and Co centers, a unique feature that facilitated the catalytic reaction.^{18, 19} X-ray absorption spectroscopy (XAS) measurements, together with other results, suggest the formation of FeN₃ and CoN₃ moieties on orthogonal planes with a direct Fe-Co bonding linkage. The resulting bimetal NCAG/Fe-Co nanocomposite exhibited apparent electrocatalytic activity towards both ORR and OER. Notably, the incorporation of Co significantly improved both the ORR stability and OER activity of the Fe/carbon aerogel catalysts. With the excellent bifunctional catalytic performance, the NCAG/Fe-Co nanocomposite was used as the oxygen catalyst in a flexible Zn-air battery, which exhibited a high open circuit voltage, stable power density as well as good cycling stability, a performance even superior to that based on commercial Pt/C-RuO₂ catalysts. This suggests that atomic dispersion of dual metal sites in carbon is an effective strategy to boost the performance of carbon-based electrocatalysts for practical application in energy storage and conversion.²⁰

Experimental section

Chemicals

Gelatin, potassium hydroxide (KOH), iron(II) chloride tetrahydrate (FeCl₂·4H₂O), cobalt(II) acetate tetrahydrate (Co(Ac)₂·4H₂O), zinc(II) acetate dihydrate (Zn(Ac)₂·4H₂O), acrylamide, methylene bisacrylamide, potassium persulfate, and RuO₂ were purchased from Aladdin Reagents (Shanghai, China). Polytetrafluoroethylene (PTFE, 60 wt.%) was purchased from Japan DaJin. Perchloric acid (HClO₄), ammonium hydroxide, and ethanol were obtained from Chengdu Xiya Reagents Chemical Technology Co. Ltd. 1,10-phenanthroline (PM) monohydrate, acetylene black, 5% Nafion solution and RuO₂ were purchased from Sigma Aldrich. Commercial Pt/C (20 wt. %) was purchased from Johnson Matthey. All other reagents were of analytical grade, and ultrapure water (MilliQ, 18.2 MΩ cm) was used throughout this study.

Characterization

XPS spectra were acquired with an ESCALAB 250Xi instrument. X-ray diffraction (XRD) measurements were carried out with a

D/max 2550 X-ray Power Diffractometer. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) images were obtained on a Hitachi S-4800 field-emission SEM and FEI Talos F200S Field emission electron microscope. Raman spectra were collected with a Via-reflex instrument at the excitation of a 532 nm laser. ICP-OES analysis was performed with a SPECTRO BLUE SOP instrument. Nitrogen adsorption-desorption isotherms were acquired with a Micromeritics ASAP 2020 surface area and porosity analyzer. XAS measurements were performed in Shanghai Synchrotron Radiation Facility in the fluorescence mode at room temperature (298 K). Voltammetric measurements were performed with an RST 5200F electrochemical workstations (Zhengzhou, China). Rotating disk electrode (RDE, Pine Research Instrument) tests were carried out at the rotation rates of 400 to 1600 rpm.

Preparation of hydrogel precursors

Experimentally, 15 mg of PM was dispersed in 125 μL of FeCl₂·4H₂O (0.2 M) by ultrasound treatment to prepare a red Fe(PM)₃²⁺ solution. Similarly, 15 mg of PM was added in 125 μL of Co(Ac)₂·4H₂O (0.2 M) by ultrasound treatment to obtain an orange Co(PM)₃²⁺ solution. 60 mg of gelatin, 30 mg of SiO₂, and 2.51 mL of MilliQ water were then placed into a screw-cap vial, and mixed under magnetic stirring in a 60 °C water bath for 10 min, into which were added 125 μL of 0.2 M Fe(PM)₃²⁺, 125 μL of 0.2 M Co(PM)₃²⁺ and 80 μL of 1.0 M Zn(Ac)₂. The obtained hydrogels were subject to freezing-thawing three times, and denoted as G_{Si-Zn}/Fe@CoPM.

Preparation of NCAG/Fe-Co

The G_{Si-Zn}/Fe@CoPM hydrogels obtained above was freeze-dried overnight in vacuum, then pyrolyzed at 900 °C for 3 h in a tube furnace under a constant flow of 97% Ar + 3% H₂ at the heating rate of 5 °C min⁻¹. During this process, Zn atoms were vaporized, which formed atomic spaces to capture Fe or Co atoms. After being cooled down naturally to room temperature, the product was etched by HF to remove the SiO₂ nanoparticles, affording NCAG/Fe-Co. For comparison, two control samples, NCAG/Fe and NCAG/Co, were also prepared in the same fashion but without the addition of Co(PM)₃²⁺ and Fe(PM)₃²⁺, respectively, at the same total water volume of 3.56 mL.

Synthesis of polyacrylamide (PAM) hydrogel solid electrolyte

To prepare PAM hydrogel, 4 g of acrylamide was dissolved in 16 mL of MilliQ water under vigorous magnetic stirring at room temperature, into which were then added 4 mg of methylene bisacrylamide and 10 mg of potassium persulfate. The obtained clear solution was injected into a glass plate mold and placed overnight in a 60 °C oven. The as-prepared PAM sheet was removed from the mold and dried naturally, then immersed in a mixed solution containing 6 M KOH and 0.2 M Zn(Ac)₂ for 48 h before use.

Electrochemical measurements

All electrochemical tests were carried out in a three-electrode configuration. To prepare the catalyst inks, 3 mg of the catalyst powders obtained above was added to a vial containing 475 μL

of a H₂O and C₂H₅OH mixture (v:v = 1:1) and 25 μ L of a Nafion solution (5%). Cyclic voltammetry (CV) measurements were carried out on an RST 5200F electrochemical workstation with a KCl-saturated Ag/AgCl electrode as the reference electrode, a Pt wire as the counter electrode and a glassy carbon disk electrode, with a catalyst loading of 0.255 mg cm⁻², as the working electrode. Oxygen-saturated 0.1 M KOH or 0.1 M HClO₄ was used as the electrolyte.

Rotating disk electrode (RDE) and rotating ring-disk electrode (RRDE) tests were carried out to assess the ORR activity with a Pine Research Instrument bipotentiostat. A KCl-saturated Ag/AgCl electrode was used as the reference electrode, a Pt plate as the counter electrode and a glassy carbon electrode at the catalyst loading of 0.425 mg cm⁻² as the working electrode.

The OER polarization curves were acquired with an RST 5200F electrochemical workstation in 1 M KOH electrolyte, with the KCl-saturated Ag/AgCl electrode as the reference electrode, a graphite rod as the counter electrode, and a carbon paper at the catalyst loading of 1 mg cm⁻² as the work electrode. To prepare the working electrode, 1.5 mg of the catalysts obtained above, 2 mg of acetylene black and 1.3 μ L of PTFE (60 wt%) were evenly mixed and coated on a piece of carbon paper (1.5 \times 1.0 cm²), which was then vacuum-dried for 3 h at 60 $^{\circ}$ C. The carbon paper was cut into 0.5 \times 0.5 cm² pieces and used as the working electrode.

The Ag/AgCl electrode was calibrated against a reversible hydrogen electrode (RHE), and all potentials in the present study were referenced to this RHE.

Fabrication and testing of liquid and solid Zn-air batteries

Liquid rechargeable Zn-air batteries were assembled with a homemade cell. A zinc sheet (purity 99.9 wt.%) was used as the anode, which was polished with sandpaper before use. A mixed solution of 6 M KOH and 0.2 M Zn(Ac)₂ was used as the electrolyte. The air cathode was composed of three layers, including a catalyst layer, a nickel foam layer and a gas diffusion layer. The catalytic layer was fabricated by homogeneously mixing the NCAG/Fe-Co catalyst, acetylene black, PTFE (60 wt.%) at the mass ratio of 6:1:3. The nickel foam was treated with 0.2 M HCl, water and ethanol for 20 min, successively, and then vacuum dried at 60 $^{\circ}$ C before use. The three layers were compressed with a roll press to obtain the cathode, which was then vacuum dried at 60 $^{\circ}$ C for 3 h.

Solid-state Zn-air battery with a sandwich structure was assembled by replacing the zinc sheet and liquid electrolyte with a zinc foil (purity 99.9 wt.%) and the as-fabricated PAM sheet, respectively.

For comparison, Zn-air batteries were also assembled in the same manner, except that the oxygen cathode was based on the mixture of commercial Pt/C:RuO₂ catalysts (1:1 by mass).

In all zinc-air battery performance tests, the mass loading of the catalysts (i.e., NCAG/Fe-Co, and Pt/C:RuO₂ mixture) was 1 mg cm⁻².

Results and discussion

Characterization and structural analysis

The synthetic procedure for the NCAG/Fe-Co carbon aerogel entails two major steps: (a) a freeze-dried hydrogel network was prepared and used as the 3D structural template, where gelatin-Zn, bimetal-PM complex and SiO₂ nanoparticles served as the sources of N-doped carbon, metal centers, and porogens, respectively; and (b) subsequent pyrolysis and acid etching led to the facile production of N-doped carbon aerogels with atomic dispersion of Fe and Co (NCAG/Fe-Co, Figure 1a).²¹ The monometal counterparts (NCAG/Fe and NCAG/Co) were prepared in the same manner. The sample structures were first examined by SEM measurements. From Figure 1b and S1, the freeze-dried gelatin hydrogels can be seen to exhibit a network of micron-sized pores. Upon pyrolysis and HF etching, the resulting NCAG/Fe-Co aerogels contained abundant mesopores (Figure 1c). From the HRTEM image in Figure 1d, one can see a highly disordered carbon structure and plentiful micropores, and a number of metal atoms were randomly distributed in the carbon lattices (marked by red circles). Note that no nanoparticle or nanocluster species were found. Elemental mapping analysis (Figure 1e) shows that the distinct signals of N, O and C were distributed evenly across the entire carbon matrix, whereas those for Fe and Co were rather scattered. These results suggest the successful production of dual metals and N doped carbon aerogels from a hydrogel template/precursor.

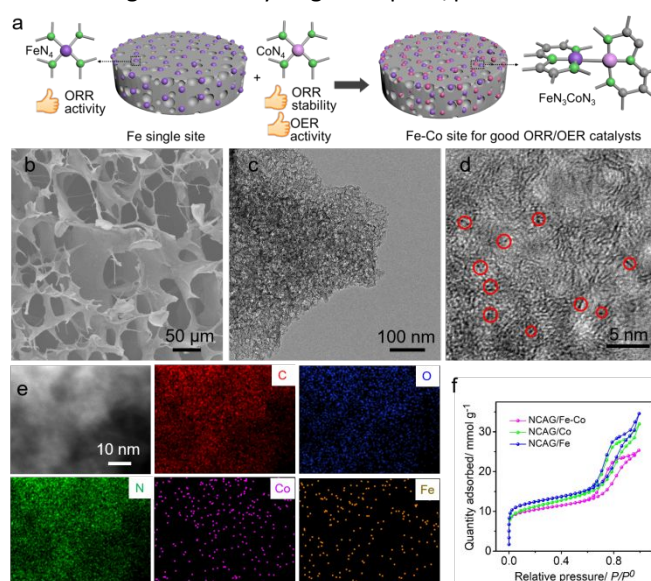


Figure 1. (a) Schematic illustration of the combination of Fe and Co single atom catalysts into Fe-Co dual metal-doped carbon aerogel. (b) SEM image of the freeze-dried G_{Si-Zn}/Fe@CoPM hydrogel. (c) TEM image of the NCAG/Fe-Co aerogel. (d) HRTEM image of the NCAG/Fe-Co aerogel. The red circles indicate metal clusters. (e) HAADF-STEM image and elemental maps of NCAG/Fe-Co. (f) Nitrogen adsorption-desorption isotherms of NCAG/Fe-Co, NCAG/Fe, NCAG/Co.

N₂ absorption-desorption isotherms were then acquired to investigate the porosity of the obtained nanocomposites (Figure 1f). Table S1 lists the calculated specific surface areas and pore volumes. One can see that all samples are mainly

composed of micropores and mesopores (Figure S2) with a close surface area ranging from 748.2 to 893.3 m² g⁻¹, a feature that is conducive for mass transfer during catalytic reactions. Of note is that NCAG/Fe-Co displays the largest fraction of micropores (32.1%), suggestive of rich edge defects for capturing individual metal atoms.²²

Further structural insights were obtained in XRD and Raman measurements. From Figure 2a, all three samples can be seen to show only a broad peak between 2 θ = 20° and 30°, which is attributed to the (002) plane of graphitic carbon (PDF 656212). Notably the peak position varies slightly among the three NCAG samples, at 2 θ = 23.9° for NCAG/Fe, 24.6° for NCAG/Fe-Co and 25.5° for NCAG/Co, with the corresponding interplanar spacing of 3.7 Å, 3.6 Å and 3.5 Å, respectively. Note that no other diffraction patterns can be resolved, consistent with the absence of metal (oxide) nanoparticles in the samples (Figure 1c and 1d). Successful graphitization of the hydrogels by pyrolysis is also evidenced in Raman measurements (Figure 2b), where all samples exhibited a well-defined D band (sp² hybrid carbon) at 1347 cm⁻¹ and G (sp³ hybrid carbon) band at 1595 cm⁻¹, with a low D band to G band intensity ratio ($I_{D/G}$) at 0.83, 0.89, and 0.77, respectively.

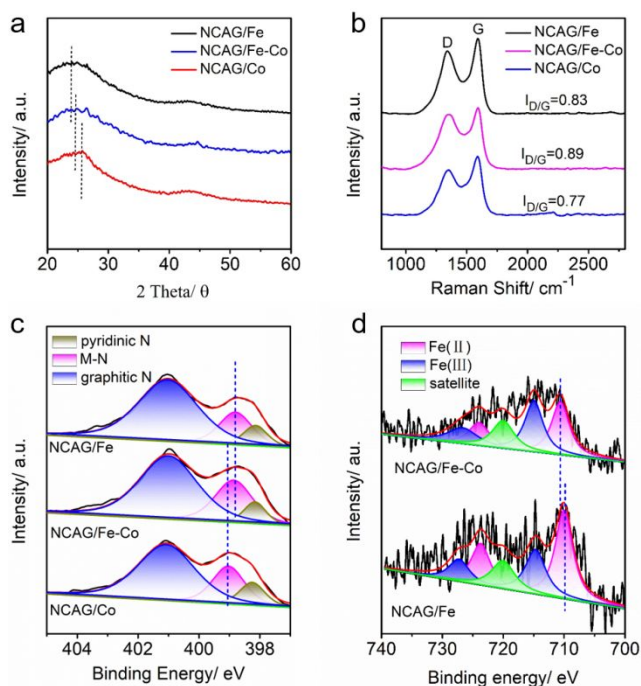


Figure 2. (a) XRD patterns of NCAG/Fe-Co, NCAG/Fe, NCAG/Co. (b) Raman spectra of NCAG/Fe-Co, NCAG/Fe, NCAG/Co. (c) XPS spectra of the N 1s electrons in NCAG/Fe-Co, NCAG/Fe, NCAG/Co. (d) High-resolution XPS scan of the Fe 2P electrons of NCAG/Fe-Co, NCAG/Fe.

The elemental compositions were then analyzed by ICP-OES and XPS measurements. The results of the ICP-OES measurements are summarized in Table S2, where the total metal content is estimated to be 0.6 wt.% for NCAG/Fe, 1.0 wt.% for NCAG/Co, and 1.8 wt.% for NCAG/Fe-Co (including 0.7 wt.% Fe and 1.1 wt.% Co). XPS measurements show that the carbon aerogels consisted of ca. 89 wt.% C, 5 wt.% O, 5 wt.% N and 1 wt.% metals (Table S3), in good agreement with the ICP-OES results. Note that in comparison with NCAG/Fe, NCAG/Fe-

Co and NCAG/Co exhibit a slightly higher content of N and lower content of O, suggesting a higher degree of graphitization by Co, which may facilitate electron transfer during electrocatalytic reactions. The high-resolution scan of the N 1s electrons are depicted in Figure 2c and S3. From deconvolution, one can see that the majority of the N species in the carbon aerogels is graphitic N, with a minority of metal N (M–N) and pyridinic N. As listed in Table S4, the M–N species in NCAG/Fe-Co is 1.4 wt.%, much higher than those of NCAG/Fe (0.8 wt.%) and NCAG/Co (1.0 wt.%). Intriguingly, the ratio between N in M–N species (1.5 at.%) and the metal content (0.5 at.%) in NCAG/Fe-Co is about 3:1, suggesting the formation of MN₃ coordination moieties in the sample.

Furthermore, from Table S4, the N 1s binding energy of M–N in NCAG/Fe-Co (398.9 eV) can be seen to be ca. 0.1 eV higher than that of NCAG/Fe (389.8 eV), but 0.1 eV lower than that of NCAG/Co (399.0 eV), consistent with the higher electron affinity of cobalt than that of iron. For the binding energy of the metal 2p electrons (M = Fe or Co), M(II/III) turns out to be the predominant species in these carbon aerogels (Figure 2d and S4). In comparison to NCAG/Fe, the binding energy of Fe(II) and Fe(III) for NCAG/Fe-Co show a positive shift of +0.5 eV and +0.3 eV, respectively (Table S5). On the contrary, the binding energy of Co(II) for this dual-metal catalyst shows a negative shift of 0.2 eV, compared to that of NCAG/Co. These variations in binding energy suggest electron transfer from the Fe to Co sites in NCAG/Fe-Co. It has been known that the poor durability of Fe-based ORR catalysts is mainly due to the Fenton reaction, where the Fe(II) centers act as the reductant. The reduced electron density of the Fe centers in NCAG/Fe-Co observed above may therefore hinder the Fenton reaction, and enhance the ORR durability, as observed below in electrochemical measurements.

XAS measurements were then conducted to investigate the chemical states and coordination configurations of the metal atoms in the aerogel catalysts. From Figure 3a, one can see that the Fe K-edge X-ray absorption near-edge structure (XANES) spectrum of the dual-metal NCAG/Fe-Co catalyst resembles that of FePc, but is apparently different from that of the Fe foil. This indicates that the valence state of Fe in NCAG/Fe-Co is close to +2, in good agreement with results from XPS measurements (Table S5).

The corresponding extended X-ray absorption fine structure (EXAFS) spectra at the Fe K edge are depicted in Figure 3b. To construct a starting structure, we use two results obtained above: (i) the relative atomic fractions of N to metals is 3:1, suggesting the formation of MN₃ moieties, and (ii) the apparent change in binding energies for Fe when Co is present suggests charge transfer between Fe and Co and hence pairing of Fe and Co atoms in a fairly close proximity. This leads to a structure similar to that in Figure 1a. The first broad peak at about 1.5 Å can be observed for both FePc and NCAG/Fe-Co (Figure 3b, S5 and Table S6), which is ascribed to the nearest Fe–N coordination; this indicates a Fe–N bond length close to 2 Å (note that there is a well-known and calculable phase shift in EXAFS that shifts the peaks of an EXAFS profile to a shorter R). However this peak is unusually broad and has a significant

shoulder near 1.9 Å, suggestive of another Fe-N peak near 2.4 Å.

The second well-defined peak at 2.4 Å is attributed to a Fe-M pair (where M could be either Co or Fe; note that neighbors in the periodic table cannot be distinguished easily in EXAFS measurements). However, based on points (i) and (ii) mentioned above, M is most likely Co; and in the structure shown in Figure 1a, the FeN₃ and CoN₃ coordination moieties all have a comparable M-N bond length of ca. 2 Å. However, this structure does not provide an explanation for the peak near 2.4 Å, as the distance from Fe to the N atoms bonded to Co is 3.4 Å. To obtain a Fe-N distance near 2.4 Å, the Co-N vertical bonds in Figure 1a are tilted towards Fe by 30°, as shown in Figure 3d (the atomic positions of this cluster are provided in the Table S7).

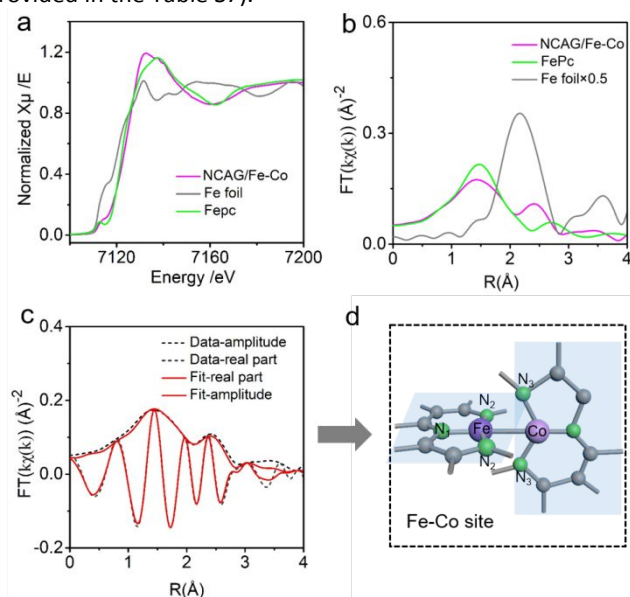


Figure 3. (a) Fe K-edge XANES and (b) EXAFS of NCAG/Fe-Co, Fe foil and FePc. (c) Fe K-edge EXFAS of NCAG/Fe-Co and the fitting curve. (d) Schematic illustration of the structure of the Fe-Co dual metal sites in NCAG/Fe-Co.

Using the cluster structure depicted in Figure 3d, theoretical EXAFS functions for Fe-N and Fe-Co were calculated using FEFF7 (phase shifts were included in the calculations).²³ The data were then fitted to a sum of five peaks: three Fe-N peaks (for N atoms N₁, N₂, and N₃), one Fe-Co peak for the Co neighbour, and one multi-scattering (MS) peak involving scattering from Fe to N₂ to N₃ to Fe. In these fits the number of neighbors was fixed according to the model and only the pair distance and pair distribution width (σ) varied for each peak. The distance for the MS peak is sensitive to the configuration of N atoms about Fe. The sum of the three Fe-N EXAFS functions fit the broad peak very well including the shoulder near 1.9 Å, while the Fe-Co function models the 2nd main peak (Figure 3c). The fitting results are summarized in Table S8. The MS peak is quite small but did not shift much from the starting value, indicating that the relative positions of N₂ and N₃ are close to that in Figure 3d.

These results are consistent with an N₃Fe-CoN₃ structure as depicted in Figure 3d, where the FeN₃ and CoN₃ moieties are on mutually orthogonal planes, with a direct Fe-Co bonding linkage and a tilted N-Co bond. The synergistic interaction arising from the dual metal sites can reduce the free energy of the rate-determining step in ORR/OER, leading to enhanced electrocatalytic activity, as observed below.^{13, 20, 24}

ORR electrocatalysis

The ORR activity and durability were then examined by CV measurements in O₂-saturated 0.1 M KOH at the potential scan rate of 50 mV s⁻¹ (Figure 4a). The NCAG/Fe-Co sample shows a cathodic peak at +0.881 V, close to that of NCAG/Fe (+0.885 V) but much higher than that of NCAG/Co (+0.817 V). Further insights were acquired in linear sweep voltammetry (LSV) measurements with a rotating (ring) disk electrode (RDE/RRDE). One can see that all samples apparently outperformed commercial Pt/C, and NCAG/Fe-Co stood out as the best among the series. For instance, the onset potential (E_{onset}) and half-wave potential ($E_{1/2}$) were estimated to be +1.04 V and +0.89 V for NCAG/Fe-Co, +1.01 V and +0.89 V for NCAG/Fe, +1.00 V and +0.83 V for NCAG/Co, as compared to +0.96 V and +0.83 V for Pt/C (Figure 4b and 4c). The kinetic current density (J_k) at the potential of +0.85 V shows a similar variation, 8.5 mA cm⁻² for NCAG/Fe-Co, 8.9 mA cm⁻² for NCAG/Fe, and 2.1 mA cm⁻² for NCAG/Co, highlighting the unique ORR activity of Fe SACs (Figure S6). In addition, RRDE studies showed that the NCAG/Fe-Co sample produced a low H₂O₂ yield of 0.1 % within a wide potential range from +0.2 V to +0.9 V, indicating four-electron reduction of oxygen (Figure 4d and S7).

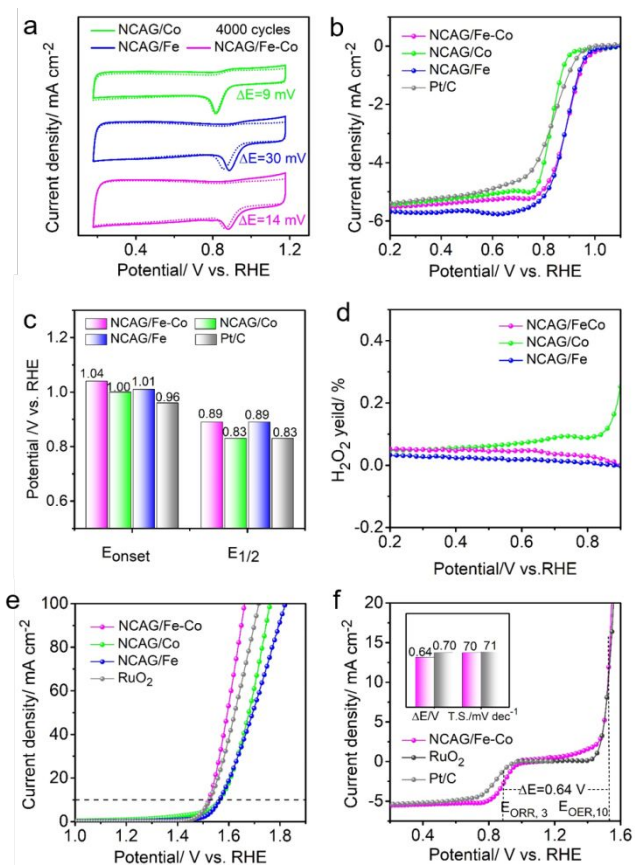


Figure 4. (a) CV curves of the various catalysts after 4000 cycles in O₂-saturated 0.1 M KOH (scan rate: 50 mV s⁻¹). (b) LSV curves of the various ORR catalysts at 1600 rpm and 5 mV s⁻¹. (c) H₂O₂ yield of the various catalysts. (d) E_{onset} and E_{1/2} of the various catalysts. (e) OER polarization curves of the various catalysts. (f) ΔE of NCAG/Fe-Co and Pt/C-RuO₂.

In addition to the excellent activity towards ORR, NCAG/Fe-Co also displayed good stability. As shown in Figure 4a, after 4,000 continuous potential cycles, the CV peak exhibited only a negative shift of 14 mV, which is close to that of NCAG/Co (9 mV), but much lower than that of NCAG/Fe (30 mV). The NCAG/Fe-Co also exhibited a better ORR activity in acid than NCAG/Fe and NCAG/Co (Figure S8).

Taken together, these results show that the incorporation of Co into the NCAG/Fe aerogel nanocomposite leads to marked enhancement of both the ORR activity and durability, most likely due to the synergistic interactions between the Fe and Co centers, as manifested in XPS and EXAFS measurements (Figure 2 and 3).

OER electrocatalysis and flexible Zn-air battery

As reversible oxygen catalytic activity is necessary for a rechargeable metal-air battery, the obtained carbon aerogels were then deposited onto carbon paper to examine the OER performance in 1 M KOH. Figure 4e depicts the OER polarization curves. One can see that to reach the anodic current density of 10 mA cm⁻², the required overpotential ($\eta_{\text{OER},10}$) was only +293 mV for NCAG/Fe-Co, very close to that of commercial RuO₂ (+297 mV), but markedly lower than those of NCAG/Co (+336 mV) and NCAG/Fe (+335 mV),

demonstrating the unique advantage of the synergistic interaction between Fe and Co that boosted the OER activity in NCAG/Fe-Co.⁸ The corresponding Tafel slope for NCAG/Fe-Co is estimated to be 70 mV dec⁻¹, close to that of RuO₂ (71 mV dec⁻¹), again, revealing favorable OER kinetics (Figure 4f inset).

Generally, the overall reversible ORR/OER catalytic activity is evaluated by the potential gap (ΔE) between the ORR potential at 3 mA cm⁻² (E_{ORR,3}) and OER potential at 10 mA cm⁻² (E_{OER,10}). Thanks to the excellent ORR and OER activity, NCAG/Fe-Co affords a small ΔE of only 0.64 V, 60 mV lower than that (0.70 V) with commercial Pt/C and RuO₂ as the ORR and OER catalysts, respectively (Figure 4f).

In view of the excellent reversible ORR/OER catalytic performance of the NCAG/Fe-Co aerogels, a rechargeable Zn-air battery was assembled using the NCAG/Fe-Co as the oxygen catalysts, and the performance was compared to that based on a mixture of commercial Pt/C-RuO₂ catalysts (mass ratio = 1:1). As shown in Figure S8, the liquid Zn-air batteries assembled with NCAG/Fe-Co and Pt/C-RuO₂ display an open circuit voltage (OCV) of 1.51 V and 1.44 V, respectively, manifesting excellent practicability of the dual-metal carbon aerogels as oxygen catalysts. When a PAM hydrogel was employed as the solid electrolyte to assemble a solid Zn-air battery instead of a KOH solution (Figure 5a and 5b), the NCAG/Fe-Co solid battery can be observed to show an OCV of 1.47 V and a maximum power density of 117 mW cm⁻², about 110 mV and 25 mW cm⁻² higher than those based on commercial Pt/C-RuO₂ catalysts, and markedly better than most leading results with relevant catalysts reported in the literature (Table S9).²⁵⁻³¹ After 1,000 cycles of discharge-charge tests, the NCAG/Fe-Co solid battery exhibited a much smaller discharge-charge voltage gap, indicating its excellent rechargeability (Figure 5c). Significantly, when the PAM thickness was compressed by 20% and 60%, the solid battery can still retain 96% and 92% of the maximum power density (Figure 5b). In addition, this solid-state device exhibited a high OCV of about 1.47 V when bended at 120° to 180° (Figure 5d). These compression and bending experiments indicate good flexibility of the NCAG/Fe-Co solid battery. It is notable that only two NCAG/Fe-Co solid batteries are needed in series to light up 10 LEDs with a rated voltage of about 3.0 V, indicating great potential for practical applications.

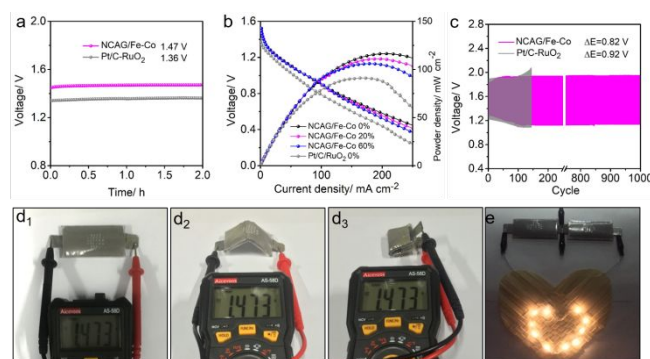


Figure 5. (a) Open circuit voltage of a solid Zn-air battery with NCAG/Fe-Co as the oxygen electrode catalysts, in comparison to that

with a mixture of commercial Pt/C-RuO₂ (mass ratio 1:1). (b) Discharge polarization and corresponding power density curves at 0%, 20%, and 60% compressive strains with a PAM hydrogel as the electrolyte. (c) Long-term cycling performance of the solid Zn-air batteries at 5 mA cm⁻² with NCAG/Fe-Co and Pt/C-RuO₂ as the oxygen electrode catalysts. (d) Photographs of the solid Zn-air battery with NCAG/Fe-Co as the oxygen electrode catalysts showing an open-circuit voltage of 1.473 V under various bending conditions. (e) Photograph of two solid Zn-air batteries connected in series lighting up 10 LEDs, with NCAG/Fe-Co as the oxygen electrode catalysts.

Conclusions

In this study, carbon aerogels with atomic dispersion of Fe-Co dual sites (NCAG/Fe-Co) were prepared by controlled pyrolysis of a hydrogel precursor. HRTEM and elemental mapping analysis revealed homogeneous distribution of the metal sites within the defected carbon lattices. XPS measurements suggested charge transfer from the Fe to Co sites and the metal centers were mostly involved in MN₃ coordination. Consistent results were obtained in XAS measurements where the FeN₃ and CoN₃ moieties were arranged in an orthogonal configuration, with a direct Fe-Co bonding interaction. Such a unique structure was found to facilitate the electrocatalysis of both ORR and OER. Electrochemically, the NCAG/Fe-Co nanocomposites exhibited an apparent electrocatalytic activity towards both ORR and OER, and a performance was superior to leading results of relevant catalysts reported in the literature. The bifunctional electrocatalytic activity and stability was also found to be markedly enhanced, as compared to the monometal counterparts, with a small ORR/OER potential gap (ΔE) of 0.64 V, 60 mV lower than that (0.70 V) with commercial Pt/C and RuO₂ catalysts. When NCAG/Fe-Co was used as the oxygen electrode catalysts for a Zn-air battery with either a liquid or solid electrolyte, the device showed a drastically better performance than that based on a mixture of commercial Pt/C-RuO₂, in terms of OCV, maximum power density, and rechargeability. Notably, the solid-state Zn-air battery exhibited excellent retention of the performance under various compressions and bending, suggesting great potential as a flexible power device. Taken together, results from this study open up an ingenious pathway in the rational design and engineering of highly efficient and durable oxygen electrocatalysts based on dual metal-doped carbon aerogels for flexible metal-air batteries.

Conflicts of interest

There are no conflicts to declare.

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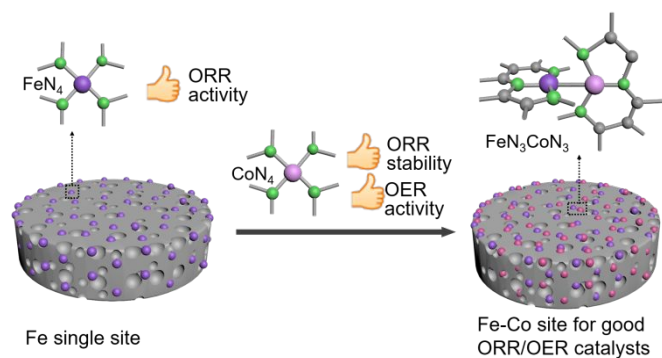
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TOC graph



A dual-metal hydrogel is used as a structural template and precursor to prepare carbon aerogels doped with Fe-Co bimetal sites as bifunctional electrocatalysts towards both ORR and OER, which exhibit enhanced stability and activity, as compared to the monometal counterparts.