A facile strategy for ultrasmall Pt NPs being partially-embedded in N-doped carbon nanosheet structure for efficient electrocatalysis

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ABSTRACT A facile strategy is established for constructing composite nanostructure with ultrasmall Pt nanoparticles (NPs) of ~2 nm in diameter being homogeneously embedded in N-doped carbon nanosheets. The strong coordination between Pt atoms in cisplatin and N atoms in pyrrole contributes to the robust embedding of Pt NP into the N-doped carbon nanosheets after annealing. Such a unique partially-embedding structure facilitates the active site exposure while stabilizing the ultrasmall Pt NPs, leading to the comparable electrochemical activities for hydrogen evolution and oxygen reduction reactions, and substantially improves durability performance compared to that of the state-of-the-art Pt/C (20 wt%).

Keywords: ultrasmall Pt nanoparticles, *in situ* embedding, N-doped carbon nanosheet, electrocatalysis

INTRODUCTION

The platinum-based electrocatalysts is widely used to evaluate the electrocatalytic performances of alternative catalysts, which are designed for catalyzing electrochemical processes associated with energy conversion and storage, such as oxygen reduction reaction (ORR) and hydrogen evolution reaction (HER) [1–4]. The morphology and structure of catalyst play significant roles in determining their electrochemical properties. Typically, the small metal nanoparticle (NP) catalysts are supported on conductive supports, such as carbon, in order to expose as large specific surface areas as possible [5–7], which, however, leads to the susceptible growth and/or aggregation of the supported NPs and the consequent deteriorated electrochemical durability.

It is widely recognized that the long-term electro-

chemical stability of electrocatalyst under the corrosive operating conditions remains a major obstacle for large-scale practical applications [8–11]. As previously reported [12–14], the metal NP embedded in carbon support can achieve high electrocatalytic activity through altering the electronic structure of the active sites, and much enhanced durability performance as well. However, surfactants, organic stabilizing agents, and the complicated procedures are usually necessary to obtain the uniform distribution and embedding of metal NP onto/into the carbon supports matrix [15–18]. Although they could lead to excellent durability performance *via* stabilizing and steric effect, the confined Pt NPs in carbon surface layer will sacrifice a large proportion of active sites [19,20]. It is reported that the carbon support containing nitrogen groups can allow for the homogenous embedding of Pt NPs, facilitating electrons to transfer from Pt to carbon support, and the robust interaction between Pt and N atoms endows the catalysts with enhanced electrochemical activity and even durable catalytic performance [16,21]. Therefore, achieving Pt NPs homogeneously embedded in N-doped carbon materials through a facile and environment-friendly method is important for the electrochemical catalysts in energy conversion and storage technologies.

Herein, we constructed a nanostructure with ultrasmall Pt NPs partially-embedded in N-doped carbon nanosheets through a facile, controllable and surfactant-free strategy. The HER and ORR were employed to evaluate the electro-catalytic performances of the obtained catalysts. Compared to commercial 20% Pt/C, the optimized sample shows comparable electrochemical performance due to the homogeneous distribution and ultrasmall size

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of Pt NPs, and improved electro-catalytic stability due to the unique partially-embedding structure.

EXPERIMENTAL SECTION

Synthesis of Pt-based nanosheet catalysts

40 μL pyrrole was dissolved into 80 mL water, and then 15 mg cisplatin was added. After stirring for 30 min until the cisplatin was thoroughly dissolved, the solution was transferred into water bath at 60°C. After reaction for 12 h under rigorous stirring, the solution was centrifuged at 12,000 rpm and the products were rinsed with water and ethanol for more than three times. The precipitate was freezing-dried overnight and collected. The sample was subsequently annealed at 300, 500 or 700°C for 30 min in flowing N_2 atmosphere. The as-obtained catalysts are denoted as CpPy-NS, CpPy-NS@X (Cp, Py and X refer to cisplatin, pyrrole and annealing temperature, respectively, X=300, 500, 700).

Characterization of as-prepared catalysts

X-ray diffraction (XRD) pattern was recorded on a Rigaku D/Max-2550V X-ray diffractometer with a Cu K_α radiation. Transmission electron microscopy (TEM) was conducted on a JEOL-2100F and high resolution TEM (HRTEM) (200 kV). X-ray photoelectric spectroscopy (XPS) spectra were measured on a VG Micro MK II instrument using monochromatic Mg K_α X-rays (150 W, 1,253.6 eV), and the C 1s electron peak (BE=285 eV) was used as internal reference for spectrum calibration. The thickness of nanosheet was measured by atomic force microscopy (AFM, Nanonavi Probe Station and Nanoscope). A CHI760D electrochemical workstation (CH Instruments) and the PINE instrument were employed to evaluate the electrochemical properties of the samples.

Evaluation of electrochemical properties

In electrochemical measurements, 8 mg of catalyst and 50 μL of 5% Nafion solution (DuPont) were mixed into 950 μL of mixed solution of absolute ethanol and deionized water ($v/v=1:1$). Then the mixture was sonicated for 30 min to form a homogeneously dispersed ink. An aliquot of 6.94 μL of the ink was pipetted onto a glassy carbon electrode, yielding a catalyst loading of 0.28 mg cm^{-2} . The preparation of commercial Pt/C (20%) ink followed the same procedure as above with the same loading amount of Pt. The catalysts were activated for 50 cycles at a scan rate of 50 mV s^{-1} via cyclic voltammetry (CV) method before linear sweep voltammetric (LSV) measurement.

In HER measurements, a three-electrode configuration was equipped with rotating disk electrode (PINE, diameter in 5 mm), saturated $\text{Hg/Hg}_2\text{SO}_4$ electrode and graphite rod as working electrode, reference electrode and counter electrode, respectively. CV and LSV tests were conducted in 0.5 mol L^{-1} H_2SO_4 with a continuous flow of N_2 at a rotating rate of 1,600 rpm. The obtained potentials were all referenced to that of the reversible hydrogen electrode (RHE) ($E_{\text{RHE}}=E_{\text{Hg/Hg}_2\text{SO}_4}+0.059\text{pH}+0.652\text{ V}$, the $E_{\text{Hg/Hg}_2\text{SO}_4}$ refers to the potential relative to the $\text{Hg/Hg}_2\text{SO}_4$ electrode.). The double layer capacitance (C_{dl}) was calculated from the slope of capacitive current ($\Delta J=J_a-J_c$) versus scan rate (ν) in the non-Faradaic region (where ΔJ is the current density difference between anode and cathode) [22]. The CVs were measured from 60–200 mV s^{-1} in static solutions. Electrochemical impedance spectra (EIS) were recorded from 0.01 Hz to 100 kHz with an amplitude of 5 mV at a constant voltage of -0.058 V (vs. RHE). Accelerated degradation testing (ADT) was performed ranging from -0.34 to -0.65 V (vs. RHE) in N_2 -saturated 0.5 mol L^{-1} H_2SO_4 at a scan rate of 50 mV s^{-1} .

In ORR measurements in 0.1 mol L^{-1} KOH, a three-electrode configuration was equipped with rotating disk electrode (PINE, diameter in 5 mm), 3 mol L^{-1} Ag/AgCl electrode and graphite rod as working electrode, reference electrode and counter electrode, respectively. The LSV test was carried out with a continuous flow of O_2 at a rotating rate of 1,600 rpm. The obtained potentials were all referenced to that of the reversible hydrogen electrode ($E_{\text{RHE}}=E_{\text{Ag/AgCl}}+0.059\text{pH}+0.193\text{ V}$, the $E_{\text{Ag/AgCl}}$ refers to the potential relative to the Ag/AgCl electrode. The EIS were collected at a frequency range from 0.01 Hz to 100 kHz with an amplitude of 5 mV at a constant voltage of 0.831 V (vs. RHE). The stability test was performed between 0.46 V and 0.96 V (vs. RHE) in O_2 -saturated 0.1 mol L^{-1} KOH at a scan rate of 50 mV s^{-1} .

ORR measurements in 0.1 mol L^{-1} HClO_4 was performed in a procedure similar to that in 0.1 mol L^{-1} KOH as described above. The EIS test was performed in a frequency range from 0.01 Hz to 100 kHz with an amplitude of 5 mV at a fixed voltage of 0.822 V (vs. RHE). The ADT was performed ranging from 0.55 to 1.05 V (vs. RHE) in O_2 -saturated 0.1 mol L^{-1} HClO_4 at a scan rate of 50 mV s^{-1} . To measure the effective electrochemical active surface area (ECSA), CV curve was recorded in N_2 -saturated 0.1 mol L^{-1} HClO_4 solution (0.05 to 1.05 V vs. RHE) with a sweep rate of 50 mV s^{-1} . The ECSA was calculated based on the hydrogen adsorption-desorption region from 0.05 V to 0.4 V (vs. RHE) [2,23].

Figure 1 Schematic illustration of the extremely facile synthesis of Pt NPs-embedded nanosheet materials.

RESULTS AND DISCUSSION

Characterization of as-prepared catalysts

Pt NPs embedded in N-doped carbon nanosheet are synthesized using pyrrole and cisplatin as precursors *via* a coordination-assembly strategy under a mild condition. The facile synthesis procedure is illustrated in Fig. 1.

As depicted in Fig. 2a, the CpPy-NS without annealing shows no significant diffraction signals belonging to platinum, being characteristic of an amorphous phase. With pyrolysis temperature increasing, the sharp diffraction peaks are found at 39.76°, 46.24°, 67.45°, 81.28° and 85.71°, which can be indexed to the lattice planes of (111), (200), (220), (311) and (222) of metal platinum (PDF-#04-0802), respectively.

A few nanoparticles can be identified in Fig. S1a and S1e on the as-assembled nanosheet CpPy-NS without lattice fringe in the HRTEM images, which implies an amorphous state in accordance with the XRD result. After

annealed at 700°C, the particle size grew larger from 1.4–1.8 nm to 2.5–4.5 nm, accompanying the emergence of distinct lattice fringes (Fig. 3 and Fig. S1). Typically, Pt NPs are about 2 nm in diameter on average in CpPy-NS@500. Surprisingly, the crystallized Pt NP, though substantially grown, still remain uniformly distributed in the integral nanosheet structure even at 700°C. The thickness of the as-fabricated nanosheets was further characterized by AFM. As depicted in Fig. 2b, c, it is approximately 5–6 nm, proving its ultrathin nature. Therefore, it is reasonable to infer that these nanosheets are carbon or carbon analogues derived from the polymerization/carbonization of pyrroles, meanwhile the Pt NPs are generated *via* the *in-situ* reduction of Pt (II) by pyrrole molecules and uniformly distributed in the nanosheets *via* partially-embedding mode owing to the robust coordination between N atoms in pyrrole molecules and Pt (II) in cisplatin molecules. Also from the high-angle annular dark field scanning transmission electron microscopy (HAADF-STEM) and elemental mapping (Fig. S2), it is clear that Pt, C and N elements are uniformly dispersed and distributed on the nanosheets, indicating the high exposure of active species. The energy-dispersive X-ray spectroscopy (EDS) analysis exhibits the elemental compositions of 4.26 at% of Pt and 1.72 at% of N (Fig. S2e).

XPS analysis was carried out to further elucidate the chemical composition and environment. Four distinct peaks are centered at ca. 285, 531, 72, 399 eV, which are attributed to the C 1s, O 1s, Pt 4f and N 1s, respectively, in Fig. 4a. Additionally, the signals of Pt 5s (102 eV), Pt

Figure 2 XRD patterns of CpPy-NS, CpPy-NS@X (X= 300, 500 and 700); AFM image (b) and corresponding height profile (c) of the CpPy-NS@500 nanosheet.

Figure 3 TEM images and corresponding particle size distributions of CpPy-NS (a, e), CpPy-NS@300 (b, f), CpPy-NS@500 (c, g) and CpPy-NS@700 (d, h).

4p (521 eV) and Pt 4d (316 and 333 eV) also appear [15,24]. The average contents of elements in CpPy-NS and CpPy-NS@500 are summarized in Table S1, from which the atomic percentage of N decreases after being annealed at 500°C due to the dissociation of ammonia molecule coordinated to Pt in cisplatin upon heating at elevated temperatures. Meanwhile, a slight increase of Pt content occurs after being heat-treated, which can be ascribed to the gradual crystallization of metallic Pt on the surface of material. From the deconvoluted XPS spectra of Pt 4f in CpPy-NS@500 (Fig. 4b), six peaks located at ca. 71.6/74.9 eV, 72.6/75.8 eV and 74.0/77.5 eV are found, which can be attributed to metallic Pt (0), Pt (II) and Pt (IV), respectively [25,26]. As displayed in Fig. 4c, the C 1s in CpPy-NS@500 can be deconvoluted to four types of peaks centered at ca. 284.8, 286.0, 288.2 and 291.7 eV, which can be assigned to C=C, C-N, C=O, and $\pi-\pi^*$, respectively [27–30]. In Fig. 4d, the deconvoluted N 1s contains three peaks positioned at 399.2, 400.9 and 402.4 eV, which can be respectively ascribed to pyrrolic N, graphitic N and oxidized N [31] derived from N elements in pyrrole upon heat treatment. Among them, the pyrrolic and graphitic N species can promote the oxygen reduction *via* changing the chemical/electronic environment of the neighboring carbon atoms [32–34]. Besides, a lower binding energy of 398.5 eV may be attributed to the interaction between Pt and N atoms [15,16].

HER performance evaluation of as-synthesized catalysts

As shown in Fig. 5a, CpPy-NS@500 exhibits better performance with a lower overpotential of 71.4 mV than that

of Pt/C (72.3 mV) to achieve a current density of 10 mA cm^{-2} . Meanwhile, CpPy-NS@500 shows much higher electrocatalytic performance than CpPy-NS, CpPy-NS@300 and CpPy-NS@700, mainly owing to its ultrasmall size of well-crystallized metallic Pt NPs on the surface. While surprisingly, the CpPy-NS containing amorphous Pt NPs shows much lower overpotential of 160 mV than 250 mV of CpPy-NS@300. To elucidate the result, the morphology of CpPy-NS and CpPy-NS@300 after activation by CV scanning for 50 cycles was analyzed by TEM. From Fig. S3, it is clear that the morphology of activated CpPy-NS is remarkably different from that without activation. The activation with CV scanning endowed the sample with fiber-like morphology. Moreover, clear lattice fringes corresponding to metallic Pt can be found on the fiber-like architecture from the HR-TEM image. While fiber-like morphology was only partially generated at the edges of nanosheets for CpPy-NS@300 (Fig. S4). The observed difference toward HER electro-catalysis between CpPy-NS and CpPy-NS@300 can be speculated as follows: the CpPy-NS without thermal treatment is much more flexible and transformable than CpPy-NS@300, and then transformed into fiber-like architecture and the Pt NPs crystallize during the CV scanning activation. The CpPy-NS demonstrates much higher performance than CpPy-NS@300, attributed to the crystallized fiber-like nanostructure. The C_{dl} , linearly proportional to ECSA, can be determined *via* CV measurement [35]. As illustrated in Fig. 5b and Fig. S5, CpPy-NS@500 shows a much larger C_{dl} of 14.60 mF cm^{-2} than those of CpPy-NS (0.15 mF

Figure 4 XPS survey spectrum of CpPy-NS@500 (a); high-resolution deconvoluted spectra of Pt 4f (b), C 1s (c) and N 1s (d) of CpPy-NS@500.

Figure 5 (a) LSV curves of CpPy-NS, CpPy-NS@X (X= 300, 500 and 700) and 20% Pt/C in 0.5 mol L⁻¹ H₂SO₄ under a N₂ flow at a scan rate of 1,600 rpm; (b) Fitting plot of ΔJ ($J_a - J_c$) as a function of scan rate for CpPy-NS, CpPy-NS@X (X= 300, 500 and 700) and 20% Pt/C in 0.5 mol L⁻¹ H₂SO₄.

cm⁻²), CpPy-NS@300 (1.01 mF cm⁻²), CpPy-NS@700 (12.73 mF cm⁻²) and even 20% Pt/C (8.61 mF cm⁻²). The ECSA can be assessed by the C_{dl} value of the catalyst. Higher C_{dl} suggests a larger density of catalytically active sites, and CpPy-NS@500 possesses higher density of

electrochemically active sites than CpPy-NS, CpPy-NS@300, CpPy-NS@700 and even 20% Pt/C for HER.

The HER kinetics of CpPy-NS@500 and 20% Pt/C were evaluated by Tafel slope. As depicted in Fig. S6a,

CpPy-NS@500 holds a Tafel slope of 33 mV dec^{-1} close to that of 20% Pt/C (32 mV dec^{-1}), indicating a comparable charge transfer kinetics of HER *via* a Volmer-Tafel route [36]. EIS of CpPy-NS, CpPy-NS@300, CpPy-NS@500 and CpPy-NS@700 were measured as illustrated in Fig. S6d. Among them, CpPy-NS@500 exhibits the smallest diameter of the semicircle, implying the lowest charge transfer resistance. Presumably, the extraordinarily high electron conductivity of CpPy-NS@500 should be attributed to the N-doped carbon nanosheet by carbonization and the crystallized Pt NPs embedded in it after high temperature annealing. Therefore, the CpPy-NS@500 shows a more favorable HER kinetics compared to CpPy-NS and CpPy-NS@300. Furthermore, the ADT was carried out for CpPy-NS@500 and 20% Pt/C using CV method. In Fig. 6a, it can be seen that CpPy-NS@500 shows negligible increment of overpotential at 10 mA cm^{-2} after 5,000 cycles of CV scanning, which is comparable to that of benchmark Pt/C.

ORR performance evaluation of as-synthesized catalysts in $0.1 \text{ mol L}^{-1} \text{ KOH}$

From the CV curves in Fig. 7a, it can be observed that

CpPy-NS@500 exhibits a much larger integral area than those of CpPy-NS and CpPy-NS@300, which is indicative of higher ECSA. Furthermore, CpPy-NS@500 shows a much higher peak current density than the others. In polarized LSV curves (Fig. 7b), CpPy-NS@500 demonstrates a more positive half-wave potential (0.81 V) than CpPy-NS, CpPy-NS@300 and CpPy-NS@700, but slightly lower than that of benchmark Pt/C (0.88 V). As shown in Fig. S6b, CpPy-NS@500 gives a Tafel slope of 83 mV dec^{-1} , also a little higher than that of 20% Pt/C (72 mV dec^{-1}). In Fig. S6e, the CpPy-NS@500 owns a much smaller diameter of the semicircle in high frequency region than CpPy-NS@300 and CpPy-NS@700. Lower Tafel slope and EIS indicate faster electron transfer kinetics of CpPy-NS@500 for ORR in $0.1 \text{ mol L}^{-1} \text{ KOH}$. The stability test was conducted by CV method. As shown in Fig. 6b, a large negative shift of half-wave potential (38 mV) was produced after 5,000 cycles in comparison to that of 20% Pt/C. While CpPy-NS@500 actually shows a slightly positive shift of half-wave potential, ascribed to the unique architecture with ultrasmall and extremely uniform Pt nanocrystallites embedded in the N-doped carbon nanosheets.

Figure 6 Operational stabilities of CpPy-NS@500 and 20% Pt/C after 5,000 cycles of CV scanning. (a) LSV curves of HER in $0.5 \text{ mol L}^{-1} \text{ H}_2\text{SO}_4$; (b) LSV curves of ORR in $0.1 \text{ mol L}^{-1} \text{ KOH}$, inset is the enlarged view of half-wave potential for CpPy-NS@500; (c) CV curves of ORR in $0.1 \text{ mol L}^{-1} \text{ HClO}_4$; (d) LSV curves of ORR in $0.1 \text{ mol L}^{-1} \text{ HClO}_4$.

Figure 7 CV curves of CpPy-NS, CpPy-NS@X (X = 300, 500 and 700) in 0.1 mol L⁻¹ KOH (a) and 0.1 mol L⁻¹ HClO₄ (c) saturated with O₂; LSV curves of CpPy-NS, CpPy-NS@X (X = 300, 500 and 700) and 20% Pt/C in 0.1 mol L⁻¹ KOH (b) and 0.1 mol L⁻¹ HClO₄ (d) saturated with O₂.

ORR performance evaluation of as-synthesized catalysts in 0.1 mol L⁻¹ HClO₄

The ORR catalytic properties of the as-prepared materials were also evaluated in O₂-saturated 0.1 mol L⁻¹ HClO₄. As revealed in Fig. 7c, the CpPy-NS@500 shows much larger potential-current integral area than CpPy-NS and CpPy-NS@300, even Pt/C, suggesting that the CpPy-NS@500 possesses higher ECSA. From the polarized LSV curves in Fig. 7d, we can see that CpPy-NS@500 has a half-wave potential of 0.833 V (vs. RHE), which is close to that of 20% Pt/C (0.834 V). Moreover, the CpPy-NS@500 shows a larger limit current density than that of Pt/C. Based on the hydrogen adsorption/desorption peak area from 0.05 to 0.4 V (vs. RHE) in Fig. S7, the ECSA of CpPy-NS@500 was determined to be 633.8 cm² g_{Pt}⁻¹, much higher than that of 20% Pt/C (447.4 cm² g_{Pt}⁻¹), which can be attributed to high-density distribution of ultrasmall Pt nanocrystallites and the large surface area of the N-doped carbon nanosheets. The ORR kinetics in 0.1 mol L⁻¹ O₂-saturated HClO₄ is characterized by Tafel slope and EIS measurements. From Fig. S6c, CpPy-NS@500 shows a rather low Tafel slope of 86 mV dec⁻¹, close to that of Pt/C. Meanwhile,

CpPy-NS@500 displays a lower electron transfer resistance with a smaller diameter of semicircle than those of CpPy-NS, CpPy-NS@500 and CpPy-NS@700 (Fig. S6f). Both of them manifest that CpPy-NS@500 exhibits favorable electron transfer kinetics, comparable to that of Pt/C. The operational stability of CpPy-NS@500 in 0.1 mol L⁻¹ O₂-saturated HClO₄ was tested *via* CV. As shown in Fig. 6c, d, the ECSAs for CpPy-NS@500 and 20% Pt/C decrease, while CpPy-NS@500 still maintains a higher ECSA than that of Pt/C after cycling test. From the LSV polarization curves, a negative shift of half-wave potential by 25 mV for CpPy-NS@500 is generated after stability test, which also outperforms that of 20% Pt/C. In all, CpPy-NS@500 possesses a better stability than 20% Pt/C.

The reaction mechanism during material synthesis is proposed as follows (Fig. 8): the pyrrole molecules self-assemble with each other in the presence of cisplatin which homogeneously attached to the formed two-dimensional nanosheets *via* coordinating N atom in pyrrole with Pt in cisplatin, accompanying the *in situ* reduction of Pt (II) to amorphous Pt NPs with a uniform distribution by the surrounding pyrrole molecules (CpPy-NS). When

Figure 8 Synthetic diagram of ultrasmall Pt NPs being homogeneously embedded in a two-dimensional N-doped carbon nanosheet.

annealed under N_2 flow at 500°C , the Pt NPs crystallized and still maintained partially-embedded and uniformly distributed with an ultrasmall size of ca. 2 nm in diameter on average (CpPy-NS@500). The excellent stability of CpPy-NS@500 would be attributed to the partially-embedding structure and the robust interaction between Pt NPs and N atoms in carbon nanosheet, in comparison with 20% Pt/C in which Pt NPs are weakly bound to the carbon support. According to the previous report [19,37], the Pt NPs of 20% Pt/C is susceptible to degradation due to the detachment and/or agglomeration after electrochemical durability tests. Comparatively, in this work, the CpPy-NS@500 possesses ultrasmall Pt NPs homogeneously embedded in N-doped carbon nanosheets via robust coordination of Pt and N, which not only prevents the Pt NPs growth and aggregation, but still favors the exposure of active sites, thereby leading to a comparative electro-catalytic activity to and better durability performance than that of 20% Pt/C under harsh operational conditions.

CONCLUSIONS

In this work, a facile strategy for synthesizing ultrasmall and uniform Pt NPs partially embedded in N-doped graphitic carbon nanosheet is established. The strong coordination between Pt atoms in cisplatin and N atoms in pyrrole is critical to forming such a partially-embedding structure. The CpPy-NS@500 shows comparative electrocatalytic activity and substantially improved electro-catalytic durability performance to that of commonly used 20% Pt/C, which is expected to be a potential alternative to commercial Pt/C. The partially-embedding structure, together with the strong coordination between Pt NPs and N atoms in carbon matrix, is responsible for the excellent structure stability and improved electro-catalytic durability. The synthesis strategy in this work can be further used to synthesize other types of metal-based 2D materials for a broad spectrum of applications.

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Supplementary information TEM characterization results, STEM-HAADF image and corresponding elemental mappings results, chemical composition derived from XPS analysis, cyclic voltammetry curves, Tafel plots and Nyquist plots are available in the online version of the paper.

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超细铂纳米晶部分嵌于氮掺杂碳纳米片复合结构的简易构筑及高效电催化性能研究

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摘要 本文报道了一种简易的超细铂纳米晶颗粒(~2 nm)部分均匀嵌于氮掺杂碳纳米片复合结构的构筑策略. 由于顺铂中铂原子与吡咯中氮原子之间的强配位相互作用, 在热处理后铂纳米颗粒仍均匀地分布于氮掺杂碳纳米片上. 该复合材料中部分嵌入的独特结构不仅有利于活性位点的暴露, 同时还有利于铂颗粒的固定和稳定, 从而产生可与商业铂碳催化剂(20 wt% Pt/C)相当的析氢、氧还原催化活性, 并具有优于Pt/C的电化学循环稳定性.