One-step synthesis of Pt based electrocatalysts encapsulated by polyoxometalate oxidation†

Shan Gao,¹ Xiaoxuan Yang,¹ Mei-Jie Wei,¹ Song Liang,² Hong-Ying Zang,³* ⁴ Hua-Qiao Tan, ⁴ Mei-Jie Wei,¹ and Yang-Guang Li ⁴* ⁴

Methanol oxidation is a very important reaction in direct methanol fuel cells. Developing stable and efficient Pt-based catalysts with a convenient method has been the stage recently. Herein, we employed a convenient one-pot method to synthesize Pt nanoparticles encapsulated by polyoxometalates (POMs) spreading on a few layers of graphene oxide with a nickel foam as a conductive substrate. Four kinds of samples with different Pt loadings were finally obtained by adjusting the H₂PtCl₆ concentration, named as PPGN-ₙ (ₙ = 1, 2, 3, 4). The microscopic structure of the sample was characterized using scanning electron microscopy (SEM), transmission electron microscopy (TEM), X-ray photoelectron spectroscopy (XPS) and Raman spectroscopy. It was proved that small-sized Pt nanoparticles with a diameter of ca. 2.47 nm spread on graphene oxide (GO) with the nickel foam support were successfully synthesized. The synthesized electrocatalysts exhibited higher electrocatalytic activities than commercial Pt/C for methanol oxidation in electrocatalytic tests. The mass activity of PPGN-1 of 250.6 mA mg⁻¹ can be achieved. During the synthesis, POM was used as a bifunctional reagent; as a reductant for reducing chloroplatinic acid and a stabilizer for the regulation of the Pt nanoparticle size simultaneously. POM cooperated rapid synthesis of Pt nanoparticles can offer a new route for designing and synthesizing electrocatalysts.

1. Introduction

Nowadays, fossil fuels are declining, and research as well as invention to replace fossil fuels with renewable clean energy has become important. Development of new clean energy is a necessary choice against the energy crisis all over the world.¹,² Consequently, the discovery of fuel cells which can directly convert chemical energy into electrical energy has attracted great interest from scientists. Mobile phones, laptops and cars with fuel cells as power generators are already available. Among them, direct methanol fuel cells (DMFCs) are very promising energy storage and conversion devices due to their high efficiency, low operation temperature, cleanliness and safety.³,⁴ However, low kinetic constants for the methanol oxidation reaction (MOR), scarcity of noble metals and noble catalysts being poisoned by intermediate products have hampered the large-scale commercial application of DMFCs.⁵,⁶ The invention of a new electrocatalyst is an effective strategy to solve this issue. Besides, Pt-based catalysts are widely used as MOR electrocatalysts. In the design of catalysts, more and more nanoscale carbon materials are introduced into the catalyst system for immobilization of Pt nanoparticles due to their excellent physical and chemical properties, especially graphene. The development of a convenient and green preparation methodology for the synthesis of Pt-modified carbon-based nanomaterials is the current focus.

Carbonaceous species such as Vulcan XC-72,⁷ carbon nanotubes,⁸ graphene⁹ and carbon cloth¹⁰ as the catalyst carriers have become the focus in recent years, because of their excellent stability in acidic or alkaline solutions, low-cost, and good electronic conductivity. Graphene is a new type of two-dimensional material discovered by Geim et al in 2004,¹¹ and carbon atoms are interconnected by an sp² hybrid orbital. Graphene oxide (GO) is a precursor of graphene prepared by chemical oxidation with a great quantity of oxygen-containing groups attached to the surface and the edge as well as some defects.¹²,¹³ Moreover, the oxygenous functional groups on the GO surface provide modified active sites that can anchor metal particles. Although GO is inferior to graphene in electrical...
conductivity, GO has unique characteristics, such as hydrophilicity, more reactive sites, high chemical controllability and easy functionalization, which are more suitable for preparing functional nanomaterials. The choice of an appropriate carrier can improve the dispersion of noble metal nanoparticles, promote the transmission of electrons, and improve the electrochemical performance. Accordingly, GO having a high specific surface area is selected as a catalyst carrier. The surface oxygen group contributes to the dispersion of noble metal nanoparticles and improves the electrochemical activity of the catalyst.

At present, many groups have successfully synthesized platinum-loaded graphene nanocatalysts. Duan et al. used sodium borohydride to synthesize platinum-loaded graphene aerogels (Pt/GOA). Wang et al. prepared three dimensional network graphene using the chemical vapor deposition (CVD) method, followed by loading Pt with graphene (Pt/G3DN). Shi et al. used an ionic liquid to functionalize the graphene and then used it as a carrier to support Pt (Pt/IL1–IL2/GN). However, the preparation of the above electrocatalysts often requires cumbersome experimental steps and the introduction of reducing agents. Moreover, experimental equipment is also complex and expensive. As a consequence, a convenient synthetic way is urgently required to prepare a highly efficient MOR electrocatalyst.

Polyoxometalates (POMs) are nanoscale metal oxygen anionic clusters with high electronegativity, an oxygen-rich surface, a special redox potential and exhibit electron transfer capability, and are widely used in electrical devices, electrodes and electrochemical capacitors, and other fields. According to the previous literature, POMs can be used as reducing agents to restore noble metal nanoparticles and can be coated on the surface of the nanoparticles to form a wrapping structure. At the same time, POM can be used as a connecting agent, through hydrogen bonding, to connect the carbon-based carrier and noble metal nanoparticles.

In general, the preparation of electrodes by the drop coating method needs the use of an adhesive to immobilize the catalyst on the surface, but only the surface layer participates in the reaction. The nickel foam has 3D porous structures which can improve the utilization of platinum and the catalytic performance of MOR directly as a working electrode. Herein, we used the Keggin type H₃PMo₁₂O₴₀ as a reducing agent and a stabilizing agent, selecting the 3D nickel foam as the conductive substrate, preparing Pt/POM/GO/NF multiple hybrid nanomaterials at room temperature in one step. In this work, POM acts as a reducing reagent to reduce Pt nanoparticles, also as a stabilizer to limit the agglomeration of nanoparticles and control the particle size. Electrochemical tests showed that the nanocatalysts all showed good electrocatalytic activity and durability.

2. Experimental part

2.1 Reagents and materials

All reagents were of analytical grade and were not further purified. H₂PtCl₆·6H₂O was purchased from Third Party Pharmaceutical Technology Co. Ltd. H₃PMo₁₂O₴₀, natural flake graphite and commercial Pt/C catalysts were purchased from Johnson Matthey. Ultrapure water was used throughout the experiment.

2.2 Preparation of graphene oxide

Graphene oxide (GO) is obtained by the oxidation of natural flake graphite with an improved method. The preparation process is briefly described below: first, natural flake graphite (3 g) was added to a mixture of sulfuric acid (360 mL) and phosphoric acid (40 mL) and then KMnO₄ (18 g) was added. The temperature was raised to 50 °C for 12 h. After that ice water (400 mL) was added, followed by dropping an appropriate amount of hydrogen peroxide into the solution and the color of the solution became golden yellow. The product was washed with hydrochloric acid and ultrapure water. Finally the sample was freeze-dried to collect the solids.

2.3 Preparation of a Pt/POM/GO/NF hybrid catalyst

In order to remove impurities such as oil on the surface of the nickel foam, the untreated nickel foam was placed in 4 M hydrochloric acid, ethanol and ultrapure water successively for ultrasonic cleaning. A certain concentration of chloroplatinic acid solution was prepared (2.5, 5, 7.5 and 10 mM) using water and ethylene glycol with a volume ratio of 3:1 as a solvent. 4 mg mL⁻¹ GO solution (3 mL), 5 mM H₃PMo₁₂O₴₀ solution (3 mL) and the as-prepared chloroplatinic acid solution (3 mL) were mixed to form a homogeneous solution. The washed nickel foam was soaked in 3 mL mixed uniform solution for 2 min. The reaction system was rotated for 5 minutes using a vortex mixer (Qilinbeier Vortex-5), and then the nickel foam was washed with ultrapure water several times, finally drying at 50 °C. Pt/POM/GO/NF hybrid catalyst was successfully synthesized. The Pt/POM/GO/NF-n (n = 1, 2, 3, 4) composites were obtained by changing the concentration of chloroplatinic acid from low to high, referred to as PPGN-n (n = 1, 2, 3, 4). In order to further study the effect of POM and GO on the morphology and properties of the composites in the synthesis, the comparative samples were synthesized without adding POM or GO or both, while the other synthetic conditions were kept the same. These three comparative catalysts are referred to as PGN, PPN and PN, respectively. To obtain more information about the composite material, nickel foam was etched using HCl to facilitate subsequent characterization.

2.4 Electrochemical measurements

The Cyclic voltammetry (CV) or Chronoamperometry of the catalyst was tested using a Princeton Electrochemical Workstation (PMC CHS08A) at 25 °C. The as-prepared nickel foam has been used as the working electrode, Pt plate and saturated calomel electrode (SCE) as the counter electrode and reference electrode, respectively. Commercial Pt/C was used as a comparative working electrode, 2 mg of the Pt/C catalyst was dispersed in Nafion aqueous solution, 3 μL of the above Nafion solution was accurately added to the surface of the treated nickel foam to prepare a comparative electrode. Before electrochemical...
measurement, high purity nitrogen was bubbled through the electrolyte for 30 min to remove the dissolved oxygen in the solution. Since the nickel foam was unstable under acidic conditions, all electrochemical tests were carried out under alkaline conditions. Furthermore, Pt has higher resistance to CO poisoning in alkaline media than acidic media. For the methanol oxidation test, the performance of different catalysts was tested in 1 mol L⁻¹ CH₃OH + 0.1 mol L⁻¹ KOH solution and the electrochemical surface area (ECSA) of the catalyst was tested in 0.1 mol L⁻¹ KOH solution. Electrochemical tests were all carried out at 50 mV s⁻¹. The properties of commercial Pt/C or other contrast catalysts were also tested under the same conditions.

2.5 Characterization of catalysts

The samples were characterized using field emission scanning electron microscopy (FESEM; Hitachi SU-8010) and Transmission electron microscopy (TEM; JEOL-2100F). XPS was performed on a VG ESCALAB MKII spectrometer using a Mg Kα (1253.6 eV) achromatic X-ray source. The Raman spectra were recorded using the HR800 spectrometer.

3. Results and discussion

The typical synthesis of the nano-electrocatalyst PPGN is shown in Fig. 1. It can be proved that the experimental operation is convenient and the catalyst is obtained in one step. Moreover, the as-prepared catalyst has the structure that Pt nanoparticles encapsulated by POM are anchored to the GO layer. Fig. 2a shows the scanning electron microscope (SEM) image of PPGN-1 and it can be seen that a large number of particles are uniformly dispersed on the surface of the nickel foam. Fig. S1 (ESI†) is the SEM image of the nickel foam before (a) and after (b) the reaction. Observing these two graphs, we can find that bare nickel foam has a smooth surface,²⁷,²⁸ an irregular polygonal area covering the entire skeleton. Some of the surfaces also have a pit that may be caused by the production of nickel foam.

After the reaction, the surface of the nickel foam becomes rough evidently, but the polygonal lines are still clearly visible, indicating that the hybrid material cladding the surface is thin. Fig. S2a, d, g (ESI†) are the SEM of the PPGN-2, 3, 4 catalysts. It is observed that nanoparticles are uniformly distributed on the nickel foam skeleton, which is similar to the morphology of PPGN-1. Furthermore, as the concentration of Pt in the reaction solution increases, the loading of Pt nanoparticles is increased and meanwhile, the boundaries between the particles become blurred and tend to form larger particles, which indicates the occurrence of agglomeration. The transmission electron microscopy (TEM) images of PPGN-1, 2, 3 and 4 samples are shown in Fig. 2b and Fig. S2b, e, h (ESI†), and their high-resolution transmission electron microscopy (HRTEM) image is shown in Fig. 2c and Fig. S2c, f, i (ESI†). The same conclusion can be obtained from these pictures. It can be seen in Fig. 2c and d that the average particle size of Pt nanoparticles in PPGN-1 is 2.47 nm and its lattice spacing is 0.23 nm, which is attributed to the face centered cubic (fcc) lattice structure of Pt, corresponding to the (111) plane.²⁹ The layered stripe is clearly visible in Fig. S2c, f, i (ESI†), demonstrating that the platinum-loaded GO is of few layers, which can preserve the structural stability of the catalyst. The EDX spectra of PPGN-1 capture the obvious C, O, P, Mo, Pt and Ni peaks as shown in Fig. S3 (ESI†), where the intensity of Ni elements is much larger than other elements, indicating that the content of the GO complex supported on nickel foam is low. Fig. 2e–h shows the elemental mapping of the PPGN-1 catalyst.

The micrographs of the three comparative samples (PGN, PPN, PN) are shown in Fig. S4 (ESI†). When H₃PMo₁₂O₄₀
is absent in PGN, the exposed Pt nanoparticles are formed on the surface and the slice structure is attributed to GO in Fig. S4a and b (ESI†). We did not find the microstructure of the noble metal nanoparticles loaded on GO. PPN was obtained without adding GO, and the surface of the nickel foam used on the substrate became uneven by analyzing its SEM in Fig. S4c and d (ESI†), due to the fact that POM was strongly acidic and corrosive. When GO and POM are not present in the reaction system, PN is obtained and its SEM is shown in Fig. S4e and f (ESI†). The exposed Pt nanoparticles with a larger diameter are formed on the surface of the nickel foam, while the surface becomes rough. From these three experiments, it can be confirmed that POM has the role of regulating the growth of Pt particles and effectively control the size of the particle. Simultaneously, the lack of GO for the samples makes nanoparticles larger in size and smaller in specific surface area. Therefore, the introduction of POM and GO into the reaction system is necessary.

The PPGN sample is characterized using XPS, which is a spectrum that can be used to obtain the composition of the sample surface, element valence, functional group and other relevant information of the surface composition of the sample. Fig. 3a is the survey XPS spectrum of PPGN-1, the emergence of the C 1s, O 1s, Pt 4f and Mo 3d peaks can prove the existence of C, O, Pt and Mo. This conclusion is in accordance with EDX. Compared with raw material GO in Fig. S5 (ESI†), there are also four different types of carbon present in PPGN-1 in Fig. 3b, which are C–C/C, C–O, C=O and O–C=O, corresponding to 284.6 eV, 286.6 eV, 288.0 eV and 288.9 eV. The Raman spectrum of GO and PPGN-1. 33 The D-band represents a disordered structure in graphene, characterizing defects or edges in graphene. 35 The G peak represents a graphitized carbon atom and is an ordered graphite structure with sp² bonds. The peak intensity ratio of the D peak to the G peak values indicates the reduction of partial O-containing groups, forming a small conjugated structure, which is consistent with the previous literature. 36

The electrochemical MOR performance of the PPGN-n sample is demonstrated by the MOR activity test and the durability test, as shown in Fig. 5. The performance data of the electrocatalysts are summarized in Table 1. The electrochemical surface area (ECSA) was estimated by calculating the area of H desorption (QH), on the basis of the following formula:

$$\text{ECSA} = \frac{Q_H}{0.21 \times [\text{Pt}]}$$

0.21 mC cm⁻² represents the monolayer adsorption charge of hydrogen on the Pt surface. [Pt] is the amount of Pt supported in the sample. From Fig. 5a, we can observe that PPGN-1 has a maximum ECSA value of 69.3 m² g⁻¹. The peak appearing at
densities were 61.9, 58.3, 44.8, 31.2 and 19.3 mA cm\(^{-2}\)/C\(_0\).

Looking at the data, PPGN-1 outperformed the other catalysts, exhibiting the highest catalytic activity. This is attributed to the optimized Pt nanoparticle size, which is crucial for efficient electrocatalysis. The size distribution in PPGN-1 is narrower, indicating better Pt nanoparticle utilization. The poisoning resistance of the catalysts was also evaluated. PPGN-1 showed the highest resistance to poisoning, which is crucial for practical applications in fuel cells.

The electrocatalytic activity of four catalysts for methanol oxidation is summarized in Table 1.

Table 1 Electrocatalytic activity of four catalysts for methanol oxidation

| Sample  | ECSA (m\(^2\)/g\(^{-1}\)) | \(I_1\) (mA mg\(^{-1}\)) | \(I_0\) (mA mg\(^{-1}\)) | \(I_f\) (mA cm\(^{-2}\)) |
|---------|------------------------|------------------------|------------------------|------------------------|
| PPGN-1  | 69.3                   | 250.6                  | 48.9                   | 101.4                  |
| PPGN-2  | 40.1                   | 129.4                  | 43.7                   | 98.9                   |
| PPGN-3  | 36.1                   | 67.6                   | 24.6                   | 86.5                   |
| PPGN-4  | 26.8                   | 39.3                   | 13.5                   | 75.1                   |

In Fig. 5a, the CV curves of PPGN-1 at 0.1 mol L\(^{-1}\) KOH solution (a) and 1 mol L\(^{-1}\) CH\(_3\)OH + 0.1 mol L\(^{-1}\) KOH solution (b and c) are shown. The Chronoamperometry of PPGN-1 in 1 mol L\(^{-1}\) CH\(_3\)OH + 0.1 mol L\(^{-1}\) KOH solution (d) is presented in Fig. 5b.

Fig. 5 CV curves of PPGN-\(n\) in 0.1 mol L\(^{-1}\) KOH solution (a) and in 1 mol L\(^{-1}\) CH\(_3\)OH + 0.1 mol L\(^{-1}\) KOH solution (b and c). The Chronoamperometry of PPGN-\(n\) in 1 mol L\(^{-1}\) CH\(_3\)OH + 0.1 mol L\(^{-1}\) KOH solution (d).

4. Conclusions

In this work, we report a convenient and rapid method for one-step synthesis of Pt/POM/GO/NF electrocatalysts. Through a series of characterizations, we found that POM played a significant role in controlling the particle size of Pt nanoparticles. Moreover, the defects in graphene oxide provide more active sites for supporting noble metal particles. The synthesized catalysts have a good effect on the direct electrocatalysis of methanol oxidation under alkaline conditions, and even higher than that of the commercial Pt/C catalyst. At last, since POM is not stable under alkaline conditions and may decompose into molybdenum oxide, the process still needs further study. However, the main role of POM is to control the particle size in the formation of nanoparticles, preventing excessive growth of Pt nanoparticles. Table S2 (ESI†) lists the MOR performance of the different electrocatalysts in the previous literature under alkaline conditions.

The electrochemical durability test of the PPGN-\(n\) electrocatalyst is shown in Fig. 5d. The current intensity of all the catalysts decreased rapidly at the beginning of the test and eventually reached a platform. The intermediate product of methanol oxidation continues to occupy the active site causing the rapid decline in current. The stability of the electrocatalyst can be determined by the current density of the platform region. It can be concluded that from Fig. 5d that PPGN-1 held the highest mass activity until 7200 s. Therefore the PPGN-1 catalyst has excellent durability for the electrocatalytic oxidation of methanol.

Conflicts of interest

There are no conflicts to declare.

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