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The Enhanced CO Tolerance of Platinum Supported on FeP Nanosheet for Superior Catalytic Activity Toward Methanol Oxidation

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Abstract: The inferior CO-like intermediates tolerance of Pt nanoparticle greatly hampered the MOR activity and durability. To alleviate this issue, tremendous efforts have been made to create oxygen-containing groups on neighbouring Pt site for oxidizing the poisonous carbonaceous species. Given this, two-dimensional FeP nanosheet with excellent HER activity was utilized as support and cocatalyst. FeP nanosheet with special Fe^{δ^+} and P^{δ^-} active sites was conductive to mass transfer, fast charge transfer and facilitating water dissociation for generating OH species to removal CO-like intermediates on Pt sites. The XRD, XPS, SEM and TEM analysis demonstrated that the Pt nanoparticle with an average size of 3.68 nm was successfully deposited on the FeP nanosheet surface. The methanol oxidation experiments in acidic medium revealed that the as-prepared binary Pt/FeP nanosheet hybrid exhibited superior MOR activity with enhanced anodic peak current density of 0.994 mA/cm², which was 2.74-fold greater than that of commercial Pt/C, and the intensive CO oxidation peak potential was negatively shifted about 100 mV with respect to that of Pt/C. The better CO tolerance of Pt/FeP nanosheet hybrid might be attributed to cooperative effect from down-shifted d-band center of Pt, abundant hydroxyls on the Pt/FeP and special activity of Fe^{δ^+} and P^{δ^-} . In addition, this hybrid

electrocatalyst also showed relatively higher HER activity compared with that of Pt/C. This study provides a promising application of metal phosphide in methanol oxidation for enhancing CO resistance capability of Pt-based catalyst.

Keywords: Methanol oxidation, Pt/FeP nanosheet, CO tolerance, hydrogen evolution reaction

1. Introduction

The growing energy crisis and severe environmental pollution have urged the researchers all over the world to develop alternative green energy ^[1-3]. Direct methanol fuel cells (DMFCs) have great prospect due to their great energy density, easy handling and environmental friendliness ^[4-6]. Pt-based catalysts with high catalytic activity for methanol oxidation are generally used in DMFCs ^[7-9]. However, the skyscraping cost, scarce Pt reserves, the poor durability because of low tolerance to CO-like poisoning intermediates during methanol oxidation and electrochemical corrosion of carbon support accompanying with agglomeration of Pt nanoparticle on the carbon material, greatly hampered its commercial application ^[10, 11]. To further increase catalytic activity, improve the durability and reduce the cost, tremendous efforts have been made.

Recently, metal oxides such as TiO₂, SnO₂ and CeO₂ et al., have been utilized as support to load Pt nanoparticle for enhancing catalytic performance, lowering cost and strengthening the resistance to CO poisoning ^[12-18]. However, because of the inferior conductivity of metal oxides, the element doping such as Nb ^[19, 20], Sn ^[13], Mo ^[21], N ^[22, 23] et al., was dedicated to improve electrical conductivity. What's more, carbon-based materials such as graphene, carbon nanotube et al., were often utilized to boost charge transfer rate ^[24-28]. Although ternary hybrid materials could improve the methanol oxidation activity, the risk of electrochemical corrosion of carbon during the operation still existed. Hence, development of carbon-free support material with high conductivity and cocatalytic activity was desirable and meaningful.

Transition metal phosphides (TMPs) as the interstitial alloys exhibited unexceptionable conductivity and have been used in the field of hydrogen evolution (HER), methanol oxidation and Li-ion batteries (LIBs), etc. ^[29-33]. According to the reported literatures ^[29, 34-36], metal M could be served as hydride-acceptor center and P was regarded as proton-acceptor center among TMPs due to the reason that P atoms with a lower electronegativity can contributed to the deviation of electron cloud of metal M. This special nature made TMPs endow superior HER performance and also facilitated water adsorption and dissociation. It was ever reported that WP-C, MoP-C, Cu₃P-C, Ni₂P-C and CoP-C hybrid could enhance MOR activity due to the acceleration of water adsorption and activation on the metal M of TMPs, leading to M-OH formation, which could enhance the tolerance to the CO-like poisoning intermediates during MOR ^[34, 35, 37-39]. However, FeP was seldom applied to methanol oxidation. Recently, iron phosphide with outstanding HER catalytic activity and stability has gained great attention ^[40-44]. Hence, FeP as Pt support for methanol oxidation might also have cocatalytic effect and then increases MOR activity, CO-like intermediates tolerance and durability.

Ultrathin two-dimensional (2D) nanomaterial with marvelous physical, electronic and chemical property due to electron confinement in 2D plane has achieved considerable researches ^[45-49]. The unique 2D structure is beneficial to Pt nanoparticle dispersion, increasing special surface area and active sites amount for enhancement of MOR performance. Wang et al. ^[49] ever successfully prepared noble metal (Au, Ag, Pd, Pt) nanocrystal grown on MoS₂ nanosheets and the results suggested that 1T metallic phase of MoS₂ could significantly increase the charge transfer ability and guaranteed the homogeneously dispersion of Pt nanoparticle which contributed to the high MOR activity. However, to the best of our knowledge, FeP nanosheet supported Pt nanoparticle as MOR catalyst was never reported so far.

Herein, FeOOH two-dimensional nanosheet was prepared according to the published literature ^[50] and then FeP was successfully fabricated by phosphorization at 300 °C for 2 h using NaH₂PO₂·H₂O as P source under Ar flow. Finally, Pt nanoparticle was deposited onto the carbon-free support of FeP nanosheet through the

reduction of H₂PtCl₆ by NaBH₄. The schematic diagram of preparation process of Pt/FeP nanosheet (Scheme 1) was shown as follows. The methanol oxidation test revealed that Pt/FeP nanosheet hybrid exhibited better MOR activity and durability due to the unique 2D structure and convenient water dissociation leading to the enhancement of CO-like intermediates tolerance ability of Pt-based catalyst. Furthermore, this hybrid electrocatalyst also owned higher HER activity due to the synergistic effect between Pt and FeP.

2. Experimental

2.1 Chemicals and materials

Hexachloroplatinic acid (H₂PtCl₆·6H₂O) was purchased from Shanghai Jiuyue Chemical Co., Ltd. Sodium hydroxide (NaOH), absolute ethanol and NaBH₄ were derived from Sinopharm Chem. Reagent Co., Ltd. Commercial Pt/C (20 wt. % Pt) was from Johnson Matthey Corp. All the aqueous solutions used were prepared with ultrapure water (18.2 M Ω cm, Milli-Q Corp.).

2.2. Synthesis of FeP nanosheet

Firstly, FeOOH nanosheet was prepared according to the published literature ^[50]. And then, the as-prepared FeOOH was phosphided by using NaH₂PO₂·H₂O as P source at 300 °C for 2 h in Ar flow. It was noteworthy that NaH₂PO₂·H₂O and FeOOH were located at different positions in the tube furnace, in which NaH₂PO₂·H₂O was at the upstream and FeOOH was placed at the downstream. After the reaction, the prepared sample was cooled to room temperature naturally under Ar flow and then taken out from the tube furnace.

2.3 Synthesis of Pt/FeP nanosheet hybrid material

Preparation of FeP suspension: 20 mg FeP nanosheet was dispersed into 20 mL ultrapure water under ultrasound for 60 min for forming a homogeneous suspension.

Preparation of H_2PtCl_6 solution: 24.5 mg sodium citrate was dissolved into 5 mL ultrapure water by magnetic stirring for 10 min, and then 0.66 mL 38.5 mM $H_2PtCl_6 \cdot 6H_2O$ was added into the above solution under magnetic stirring.

Preparaton of NaBH₄ solution: 2.5 mg NaBH₄ was dissolved into 4.3 mL ultrapure water homogeneously.

H₂PtCl₆ solution was dropped into the FeP suspension under magnetic stirring for 20 min, and then NaBH₄ solution was mixed together with the above solution under stirring for 24 h. After that, the as-prepared sample was centrifugated and then washed repeatedly by using ethanol and water with the volume ratio of 3:1, then dried at 60 °C under vacuum. Finally, a norminal 20 wt. % Pt was successfully supported on the FeP nanosheet.

2.4 Structural Characterization

X' Pert Pro MPD X-ray diffractometer (Philips, Holland) using Cu K α radiation (λ = 1.5406 Å) was carried out to determine the crystal structure. Scanning electron microscopy (SEM, Helios Nanolab 600i) was utilized to confirm the surface morphology. High resolution transmission electron microscopy (HRTEM, FEI Tecnai G² F20, America) was employed to analyze the structure and morphology of the as-prepared samples. X-ray photoelectron spectra (XPS, PHI 5700 ESCA System with a monochromatic Al K α X-ray source) was performed to study the chemical valence of the surface elements and further confirm the sample's chemical composition. Inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7700 instrument) was used to determine the element content of the as-prepared samples.

2.5 Electrochemical measurements

The measurement of electrocatalytic activity was conducted in a standard three-electrode system by using a CHI 660E electrochemical station at 298 K. Pt foil and Hg/Hg₂SO₄ were respectively utilized as counter and reference electrodes. A glassy carbon electrode (GC, 4 mm diameter) coated with catalyst was as working electrode and the detailed preparation procedure of working electrode was shown as follows: 5.0 mg catalyst powder was dispersed into 5 mL absolute ethanol and then sonicated for 15 min. After that, 15 μ L catalyst ink was pipetted onto GC surface and dried naturally. Finally, 5 μ L 0.05 wt.% Nafion solution (DuPont, USA) was dropped onto the catalyst layer and dried for electrochemical test. But for HER, 5 mm rotating disk electrode (RDE) coated with catalyst was as working electrode, and 40 μ L catalyst ink and 10 μ L 0.05 wt.% Nafion solution were pipetted onto the RDE surface.

Before formal cyclic voltammogram (CV) test, the pre-activation in 0.5 M

N₂-purged H₂SO₄ solution was performed by CV sweep between 0.05 V and 1.2 V until a stable CV curve was achieved. Afterwards, the MOR activity was conducted by CV test (50 mV s⁻¹) in N₂-saturated 0.5 M H₂SO₄ + 0.5 M CH₃OH solution. *i-t* measurement was carried out at a fixed potential of 0.6 V. The CO stripping voltammogram was obtained in 0.5 M H₂SO₄ solution with the scan rate of 10 mV s⁻¹. It was noteworthy that before CO stripping test, the H₂SO₄ solution was purged with CO for 15 min at the constant potential of 90 mV and then bubbled with N₂ for 30 min in order to remove the residual CO. The long-term durability was evaluated through continuous potential cycling in 0.5 M H₂SO₄ at 50 mV s⁻¹. As for HER test, linear sweep voltammetry was conducted in 0.5 M H₂SO₄ with a scan rate of 10 mV/s and rotating speed of 1600 rpm. Note that all of the potentials in this work were versus the reversible hydrogen electrode (RHE).

3. Results and discussion

3.1 Characterizations of Pt/FeP nanosheet hybrids

The chemical composition and surface morphology were investigated by XRD, XPS, SEM and TEM techniques. From Fig. S1 and S2, it could be confirmed that the δ -FeOOH (JCPDS 77-0247) with nanosheet structure was successfully prepared. After phosphidation, the XRD patterns shown in Fig. 1 revealed that three weak diffraction peaks were observed for the phosphorized sample which matched with the standard peaks of FeP, meaning that as-prepared phosphorized sample was FeP with poor crystallinity. In addition, from EDS in Fig. S3, it was found that the atomic ratio of Fe and P was 1:1, verifying that FeP was achieved after high temperature phosphidation. As for XRD pattern of Pt/FeP also shown in Fig. 1, the typical diffraction peaks at 39.9°, 46.4°, 67.7° and 81.6° of Pt were distinctly observed corresponding to (111), (200), (220) and (311) planes separately, signifying that the well crystalized Pt nanoparticle was successfully obtained through NaBH₄ reduction. In addition, Pt loading amount was determined to be 20.0 wt. % through ICP measurement. However, the diffraction peak for FeP in Pt/FeP hybrid was insignificant which was masked by the strong characteristic peak of Pt.

In order to gain insight into the surface elemental information of Pt/FeP nanosheet, XPS was employed to analyze the surface chemical composition and elemental valent state of Pt/FeP. The surface composition of Pt/FeP was comprised of Fe, P, O, C and Pt (Fig. S4a) among which carbon was derived from the exterior contaminant and O might be ascribed to the surface oxidation due to the exposure to air. Fe 2p XPS spectrum shown in Fig. S4b could be fitted into five characteristic peaks among which 710.6 eV and 723.7 eV were the binding energy (BE) of Fe^{2+} 2p3/2 and 2p1/2 separately, and the peaks at 714.0 eV and 727.4 eV reflected the BE of Fe^{3+ [51-53]}; In addition, a weak peak at 719.0 eV was the satellite peak of Fe 2p. The results acquired from Fig. S4b indicated that Fe²⁺ and Fe³⁺ coexisted on the FeP surface, and no distinct FeP characteristic peak around 707 eV was observed due to the severe oxidation of FeP leading to the overlapping of Fe^{δ^+} peak in FeP with the XPS peak of $Fe^{2+/3+}$ 2p3/2. Compared with that of Fe 2p3/2 of FeP alone, the Fe 2p3/2 peak of Pt/FeP nanosheet shifted toward lower energy direction due to the electron interaction between Pt and FeP nanosheet shown in Fig. 2a. P 2p XPS spectrum in Fig. 2b was convoluted into two peaks at 133.3 eV and 128.8 eV. The small peak at 128.8 eV was close to the P^{δ} in FeP while the intense peak at 133.3 eV was assigned to the oxidized P⁵⁺ species due to drastic oxidation ^[44, 54]. Fig. 2c presented the convoluted Pt 4f XPS spectra of both Pt/FeP nanosheet and Pt/C, from which two chemical states of Pt were detected. As for Pt/FeP nanosheet, the peaks at around 71.9 eV and 75.4 eV belonged to metallic Pt, while the high energy doublet at 72.9 eV and 76.2 eV were indexed to the bivalent Pt ion (Pt²⁺) ^[55, 56]. Compared with Pt/C, the Pt 4f7/2 peak of Pt/FeP nanosheet shifted toward higher binding energy, which is different from the cases of Pt-Ni₂P/C and Pt-CoP/C^[38, 39]. The reason for this difference should be ascribed to the composition and structure of our FeP nanosheet. On the one hand, the electronegativity of Fe is lower than that of Ni, Co, so Fe is more susceptible to oxidation than Ni and Co^[57]. On the other hand, our FeP was in the form of nanosheet, whose surface area was rather high. Therefore, the oxidation of our FeP nanosheet was more serious, which has been verified by the XPS results in Fig. 2a, 2c and S4(c). The oxidation of FeP caused the positive shift of Pt 4f binding energy. This shift will

result in the down-shifted d-band center and consequently weaken the adsorption of CO-like intermediates, leading to enhanced MOR activity ^[58-60]. Meanwhile, the oxidation of FeP facilitated the formation of Fe-O and P-O bonds, which were good for MOR by the so-called bifunctional mechanism. In addition, the metallic Pt content on Pt/FeP nanosheet increased from 57.0 % to 66.4 % relative to Pt/C, providing more available Pt active sites for methanol oxidation. Fig. 2d exhibited the O 1s XPS spectra of FeP and Pt/FeP indicating that three peaks located at 530.4 eV, 531.7 eV and 533.4 eV could be observed among which the largest peak at 531.7 eV was assigned to the oxygen in hydroxide and the peak at 533.4 eV was due to the H₂O adsorbed to the sample surface ^[61, 62]. The small peak centered at 530.4 eV resulted from the P-O or Pt-O bond due to the surface oxidation. It was noteworthy that the area of peak corresponding to hydroxyl in O1s XPS patterns was largest for both FeP and Pt/FeP, suggesting that the abundant hydroxyls were mainly derived from FeP surface. The existing hydroxyls on catalyst surface could react with the poisoning CO species during MOR and then improve the CO tolerance ability.

After phosphidation, the microstructure of as-prepared FeP was acquired through electron microscopy shown in Fig. 3. SEM image in Fig. 3a showed that FeP presented representative nanosheet structure with interconnection forming porous structure. TEM images in Fig. 3b and 3c further demonstrated the sheet-like morphology and the nanosheet was extraordinarily thin. The high resolution TEM image in Fig. 3d indicated that some crystal fringes were observed but insignificant suggesting that the crystallinity of as-prepared sample was poor, further verifying the weak diffraction peaks of FeP in XRD pattern; In addition, the crystalline interplanar spacing was 1.88 Å corresponding to FeP (211) lattice plane.

The surface morphology and structure of Pt/FeP nanosheet hybrid were also studied by TEM and HRTEM. As shown in Fig. 4a, 4b and 4c, Pt nanoparticles was smoothly anchored to the FeP nanosheet surface and FeP nanosheet directed by the red arrow and Pt nanoparticle indicated by the white arrow could be obviously observed. Fig. 4c suggested that the lattice spacing of 2.26 Å and 1.88 Å could be assigned to (111) and (211) plane of Pt nanoparticle and FeP nanosheet, respectively. From the size

distribution of Pt nanoparticle in Fig. 4d, it could be concluded that the average size of Pt nanoparticle was 3.68 nm. The electronic conductivity of Pt/FeP and Pt/C was measured by the four-point probe technique. It was found that the electronic conductivity of Pt/FeP was 1.01 S/cm, which was slightly lower than that of Pt/C (1.20 S/cm), probably due to the fact that FeP is somewhat lower conductive than carbon materials.

On the basis of the above analyses, it could be deduced that this hybrid material consisted of FeP nanosheet and Pt nanoparticle, and Pt nanoparticle with average size of 3.68 nm was resoundingly adhered on the FeP nanosheet surface.

3.2 The electrocatalytic performance for methanol oxidation reaction

The electrocatalytic behavior of Pt/FeP nanosheet was investigated by cyclic voltammetry test at the scan rate of 50 mV/s in the N₂-saturated 0.5 M H₂SO₄ solution as shown in Fig. 5a, accompanying with that of commercial Pt/C for comparison. It could be known that the distinct hydrogen adsorption/desorption region was presented in the potential range from 0.05 V to 0.35 V. According to the reported literature ^[63], the electrochemically active surface area (ECSA) could be calculated and the result suggested that ECSA of Pt/FeP nanosheet was 30 m²/g which was 50 % of that of Pt/C catalyst (60 m²/g) which might be due to the reason that the size of Pt nanoparticle was larger than that of Pt/C leading to the phenomenon that the accessible active sites of Pt were relatively low. However, although the ECSA of Pt/FeP nanosheet was smaller, its specific activity of methanol oxidation was better.

The methanol oxidation experiments of Pt/FeP nanosheet and Pt/C were evaluated by CV in the 0.5 M H₂SO₄ + 0.5 M CH₃OH solution and the results were exhibited in Fig. 5b. The CV curves in Fig. 5b indicated that two significant anodic peaks in the potential range of 0.5 ~ 1.1 V could be observed in the forward and backward scan due to the electrooxidation of methanol and intermediates respectively, and the forward peak current density of Pt/FeP nanosheet was 0.994 mA/cm², which was 2.74-fold greater than that of Pt/C (0.363 mA/cm²), suggesting that the MOR activity of Pt/FeP nanosheet was higher than that of Pt/C catalyst.

The durability of the as-prepared hybrid nanomaterial was evaluated by the *i*-t test

in the 0.5 M H₂SO₄ + 0.5 M CH₃OH. The result in Fig. 5c suggested that at the initial stage both Pt/FeP nanosheet and Pt/C underwent a rapid decay of current density, after that the degradation was sluggish. After running for 2 h, 0.02 and 0.01 mA/cm² were retained for Pt/FeP nanosheet and Pt/C respectively, and the former was two times larger than that of the latter which meant that the Pt/FeP nanosheet hybrid presented better durability for methanol oxidation.

To verify the CO tolerance of Pt/FeP nanosheet hybrid, the CO stripping experiments were fulfilled shown in Fig. 5d. From this figure, the onset potential of CO oxidation at around 0.60 V and two obvious oxidative peak potentials at approximate 0.70 V and 0.77 V on the Pt/FeP nanosheet were observed. For Pt/C, the onset potential was shifted positively to 0.68 V and two oxidative peaks at about 0.72 V and 0.80 V also exhibited, but the former peak was extremely weak and insignificant. The lower onset potential and peak potential of Pt/FeP nanosheet suggested that CO adsorbed on the Pt active sites could be effectively removed due to the favorable oxidation of carbonaceous poisons by FeP nanosheet which was adjacent to Pt nanoparticle. From the electrochemical impedance spectra (EIS) in Fig. S5, the charge transfer resistance (diameter of the semicircle in the medium frequency region) of Pt/FeP nanosheet was smaller than that of Pt/C, which meant that the reaction kinetics on methanol oxidation of Pt/FeP nanosheet was faster than that on Pt/C.

In addition, this electrocatalyst also exhibited superior HER activity in 0.5 M H_2SO_4 which was shown in Fig. S6. The HER performance of Pt/FeP nanosheet was slightly higher than that of Pt/C on the whole which might be imputed to the synergistic effect between FeP nanosheet and Pt nanoparticle.

The intriguing MOR activity of Pt/FeP nanosheet hybrid material could benefit from the following aspects. Firstly, the fascinating 2D structure of FeP nanosheet was conducive to accessing more methanol and water molecules by enhancing mass transfer, and shorten the diffusion length of ions and electrons; Secondly, according to the reported literatures ^[36, 44], FeP as excellent HER catalyst owned proton-acceptor ($P^{\delta-}$ sites) and hydride-acceptor (Fe^{$\delta+$} sites) sites, among which $P^{\delta-}$ active sites could

facilitate the adsorption of proton in water molecule and $Fe^{\delta+}$ active sites could accept hydroxyl in water, then enhancing water dissolution. The existence of Fe-OH just like W-OH ^[34] with high activity could oxidize the poisoning carbonaceous species adsorbed on the neighboring Pt active sites generated during MOR reaction and then boosting the methanol oxidation and CO-like intermediates tolerance. Thirdly, the lowered d band center of Pt by Fe in FeP weakened the surface adsorption of the CO-like intermediates leading to more Pt active sites exposure to reactant, and then improved the MOR activity and stability. The schematic diagram of methanol electrooxidation mechanism was shown in Fig. 6. What's more, the promoted HER activity might be assigned to the synergistic activity between FeP nanosheet and Pt nanoparticle.

4. Conclusion

A novel carbon-free binary Pt/FeP nanosheet with outstanding and durable MOR activity was successfully fabricated. The as-prepared FeP nanosheet not only guaranteed higher degree of Pt dispersion, efficient access to the reactants and fast charge transfer, but also accelerated the decomposition of water molecules due to special activity of $Fe^{\delta+}$ and $P^{\delta-}$ in FeP which was beneficial to the removal of the poisonous CO-like intermediates adsorbed on the adjacent Pt active sites and then fortifying the CO-like intermediates tolerance of Pt-based electrocatalyst. The catalytic activity of Pt/FeP nanosheet hybrid toward methanol oxidation was 2.74 times higher than that of Pt/C. Meantime, the onset potential and peak potential of CO oxidation for Pt/FeP nanosheet were respectively lower than that of Pt/C, suggesting that the CO tolerance was incredible. The slightly better HER activity of Pt/FeP nanosheet was also exhibited in comparison with that of Pt/C.

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Fig. 1 XRD patterns of FeP nansheet and Pt/FeP nanosheet



Fig. 2 (a) Fe 2p XPS spectra for FeP and Pt/FeP nanosheet, (b) P 2p XPS spectra for Pt/FeP nanosheet, (c) Pt 4f XPS spectra for Pt/FeP nanosheet and Pt/C, (d) O 1s XPS spectra for FeP and Pt/FeP nanosheet



Fig. 3 SEM (a), TEM (b, c) and HRTEM (d) images of as-prepared FeP nanosheet. The inset in Fig. 3d is obtained by fast Fourier transform (FFT) on the area marked by square frame and smoothing edge by mask then inverse FFT



Fig. 4 TEM (a, b) and HRTEM (c) images of Pt/FeP nanosheet and size distribution of Pt nanoprticles (d). The inset in Fig. 4c is obtained by FFT on the area marked by square frame and smoothing edge by mask then inverse FFT



Fig. 5 Cyclic voltammetry curves of Pt/FeP nanosheet and Pt/C in N₂-saturated 0.5 M H_2SO_4 solution (a), cyclic voltammetry curves of Pt/FeP nanosheet and Pt/C in 0.5 M $H_2SO_4 + 0.5$ M CH₃OH solution at a scan rate of 50 mV/s (b), *i-t* curves of Pt/FeP nanosheet and Pt/C in 0.5 M $H_2SO_4 + 0.5$ M CH₃OH solution at 0.6 V (c), CO stripping voltammograms of Pt/FeP nanosheet and Pt/C in 0.5 M H_2SO_4 at a scan rate of 10 mV/s (d)



Fig. 6 The schematic diagram of methanol electrooxidation mechanism



Scheme 1. The schematic diagram of Pt/FeP nanosheet hybrid