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Article

MoO_x-promoted Pt catalysts for the water gas shift reaction at low temperatures

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ABSTRACT

Pt-Mo/SiO₂ catalysts were prepared using impregnation-reduction methods. Mo-promoted Pt catalysts exhibit much higher water gas shift reaction activity at low temperatures than Pt/SiO₂ catalysts. Various characterization methods including inductive coupled plasma atomic emission spectrometry, X-ray diffraction, transmission electron microscopy, X-ray absorption near edge spectrum, and X-ray photoelectron spectroscopy were applied to investigate the composition, structure and chemical state of the Pt-Mo/SiO₂ catalysts. Our results indicate that the added Mo species effectively improves the dispersion of Pt nanoparticles and the synergistic effect between the Pt nanoparticles and surface MoO_x species enhances the catalytic performance for the water gas shift reaction. Pt nanoparticles decorated with highly dispersed MoO_x patches are found to be the active architecture.

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1. Introduction

Currently, the primary production method for H₂ is reforming fossil fuels. However, H₂ gas produced by this method contains more than 10% CO. It is well known that trace amounts of CO can severely poison Pt electrocatalysts in proton exchange membrane fuel cells (PEMFC). Therefore, there is a high demand for processes that selectively remove CO in excess H₂. Water gas shift (WGS) and preferential oxidation reactions in excess H₂ (PROX) have been regarded as two effective processes to eliminate CO in H₂. WGS is a moderately exothermic and equilibrium-limited reaction, and a lower concentration of outlet CO can be achieved at a lower reaction temperature. Thus, the WGS catalysts used for purification of H₂ for PEMFC should be highly active below 300 °C and also stable under the reformate streams. In the industrial process, Cu-ZnO/Al₂O₃ materi-

als are usually used as catalysts for low-temperature WGS processes. However, the Cu-ZnO/Al₂O₃ catalysts are pyrophoric and suffer from sintering during the operating process, which does not meet the criteria for fuel cell applications [1–3]. Oxide-supported noble metal catalysts have been considered as alternative catalysts. Among the catalysts investigated so far, supported Au catalysts exhibit remarkable activity at low temperatures, even better than Cu-ZnO/Al₂O₃ catalysts [4,5]. However, the supported Au catalysts deactivate quickly as a result of poisoning by carbonates and sintering of Au nanoparticles under the reaction conditions [6]. Supported Pt catalysts exhibit good stability in many reactions but are less active for low temperature WGS reactions [7,8]. Thus, the enhancement of catalytic activity at low temperatures is a critical issue for Pt-based catalysts.

Reducible oxide-supported Pt catalysts exhibit much higher

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activity than inert oxide-supported Pt catalysts in WGS reactions [9]. Many studies have illustrated that the WGS reaction proceeds via a bifunctional mechanism in which H₂O molecules are activated at the perimeter sites between Pt and reducible oxide supports, and then react with CO absorbed on the adjacent Pt nanoparticles [10]. Thus, an increase in the Pt-oxide interface density can enhance the WGS catalytic activity. Rodriguez et al. [11] found that when the inert Au(111) surface was decorated with CeO_x nanoislands it became highly active in the WGS reaction and optimal activity could be achieved with intermediate coverage of CeO_x islands. We found that highly dispersed FeO nanoislands confined on the surface of Pt(111) exhibited extraordinary activity for PROX [12]. Studies of model catalysts reveal strategies for increasing the interface density between transition metal oxide (TMO) and Pt nanoparticles, i.e. construction of highly dispersed TMO nanopatches on Pt nanoparticles.

In electrocatalytic systems, Mo has been widely used as a promoter for CO-tolerant Pt catalysts. It has been suggested that alloying Pt with Mo could alter the d-band center of Pt via a ligand effect and decrease CO adsorption strength [13]. In addition, the oxidative Mo species enriched on the PtMo alloy surface can catalyze H₂O dissociation at a low potential, which promotes CO oxidation via a bifunctional mechanism [14–16]. Both CO adsorption and activation of H₂O are key steps in the WGS reaction. Thus, Mo and MoO_x could have a role in improving the catalytic performance of Pt-based catalysts for the WGS reaction. Dorazio et al. [17,18] found that Mo-promoted Pt catalysts were highly active in the WGS reaction and the formation of the PtMo alloy was essential to the high activity. Williams et al. [19] studied the effect of Mo addition on supported Pt catalysts in the WGS reaction and found that reducible Mo oxide in close proximity to Pt enhanced the reaction rate. Despite many studies of Pt-Mo catalysts, the promotion effect of the Mo species on the Pt catalysts is still not well understood.

In the present paper, SiO₂-supported Pt-Mo catalysts with different Mo/Pt atomic ratios were prepared and their activities for the WGS reaction were studied. The results illustrate that highly dispersed MoO_x patches confined on Pt nanoparticles are oxygen-deficient, which significantly enhances the catalytic performance of Pt-based catalysts for the WGS reaction.

2. Experimental

2.1. Catalyst preparation

SiO₂ surface functionalization: The isoelectric point of SiO₂ is very low (2.0) and its surface cannot effectively adsorb negative ions in aqueous solution. To enhance the adsorption of PtCl₆⁴⁻ and Mo₇O₂₄⁶⁻ anions onto the support surface, SiO₂ particles were functionalized with amine groups. SiO₂ powder with a surface area of 348 m²/g (Qingdao Ocean Chemical Company) was calcined at 550 °C for 4 h. The calcined SiO₂ (5 g) was transferred to a flask containing 150 mL toluene and 6 mL APTES (H₂N-(CH₂)₃Si(OEt)₃). The mixture was heated in an oil bath and refluxed by stirring at 95 °C for 24 h. The solution was filtrated and washed with ethanol and then dried at 60 °C for

12 h. The collected powder was marked as SiO₂-NH₂.

Pt/SiO₂ catalyst preparation: SiO₂-NH₂ powder (1.0 g) was transferred to a flask containing 10.6 mL H₂PtCl₆ solution (1.93 × 10⁻² mol/L). The liquid was evaporated using a rotary evaporator. The collected powder was reduced in H₂ at 300 °C for 2 h to obtain the Pt/SiO₂ catalyst.

Pt-Mo/SiO₂ catalyst preparation: SiO₂-NH₂ powder (1.0 g) was transferred to a flask containing 10.6 mL H₂PtCl₆ solution (1.93 × 10⁻² mol/L) and 1.02 mL (NH₄)₆Mo₇O₂₄ solution (7.14 × 10⁻³ mol/L). The liquid was evaporated using a rotary evaporator. The collected powder was reduced in H₂ at 300 °C for 2 h to obtain the Pt₄Mo₁/SiO₂ catalyst with a Pt/Mo atomic ratio equal to 4/1. The catalysts with higher Mo/Pt atomic ratios, including Pt₁Mo₁/SiO₂ and Pt₁Mo₄/SiO₂, were prepared by following the same procedure and changing the amount of (NH₄)₆Mo₇O₂₄ precursor. In all of the Pt-based catalysts, the nominal loading of Pt was around 4.0 wt% and the nominal loadings of Mo in the Pt₄Mo₁/SiO₂, Pt₁Mo₁/SiO₂ and Pt₁Mo₄/SiO₂ catalysts were 0.5 wt%, 2.0 wt%, and 8.0 wt%, respectively.

Mo/SiO₂ catalyst preparation: SiO₂-NH₂ powder (1.0 g) was transferred to a flask containing 16.32 mL (NH₄)₆Mo₇O₂₄ solution (7.14 × 10⁻³ mol/L). The liquid was evaporated using a rotary evaporator. The collected powder was reduced at 300 °C for 2 h to obtain the Mo/SiO₂ catalysts.

2.2. Catalyst characterization

CO pulse absorption was carried out using a Micromeritics Chemisorption Analyzer. The actual loadings in all samples were determined by washing the samples in an aqua regia solution and ion concentrations of the leached solutions were measured by inductively coupled plasma atom emission spectrometry (ICP-AES, ICPS-8100, Shimadzu). X-ray diffraction (XRD) patterns were collected using a Rigaku D/Max 2500 diffractometer with a Cu K_α (λ = 0.1541 nm) radiation source. Transmission electron microscopy (TEM) images were recorded on a FEI Tecnai G2 microscope operated at an acceleration voltage of 120 kV. X-ray absorption near edge spectrum (XANES) was performed on the BL14W beamline of the Shanghai Synchrotron Radiation Facility. Pt L₃-edge XANES spectra of the Pt-Mo/SiO₂ catalysts were collected in transmission mode. Data from a standard Pt foil were recorded as a reference. X-ray photoelectron spectroscopy (XPS) measurements were performed using a Thermo Scientific ESCALAB 250Xi spectrometer. The XPS spectra were obtained using an Al K_α X-ray source, and the passing energy was fixed at 20 eV. The Si 2p peak, located at 103.5 eV, from the SiO₂ support was used for the calibration of binding energies.

2.3. Catalytic activity test

The reduced catalysts (0.1 g) were loaded into a fixed-bed micro-reactor and activated at 150 °C in H₂ for 2 h. Subsequently, the gas stream was switched to the reaction atmosphere (3% CO, 10% H₂O, balanced with He) with a flow rate of 30 mL/min. The corresponding gas hourly space velocity

(GHSV) was 18000 mL/(g·h) unless otherwise specified. Water vapor was introduced using a bubbling method. The catalytic performance was investigated from 150 to 300 °C with the heating rate of 1 °C/min. Gas products were analyzed using a gas chromatograph 6890 equipped with a TDX-01 column and a thermal conductivity detector.

3. Results and discussion

The Pt/SiO₂ and Mo/SiO₂ catalysts have low WGS activity below 300 °C, as shown in Fig. 1(a). At 250 °C, CO conversion for both catalysts is less than 1%. In contrast, the Pt-Mo/SiO₂ catalysts exhibit remarkable reaction activities, even at low temperatures. The CO conversions at 250 °C for the Pt₄Mo₁/SiO₂ and Pt₁Mo₁/SiO₂ catalysts are 58% and 67%, respectively. The CO conversion decreases significantly when the Mo content is further increased. For the Pt₁Mo₄/SiO₂ catalyst, the CO conversion at 250 °C is only 4%. We suggest that the excess Mo species may result in covering of the Pt nanoparticles and reduce the number of surface active sites, as discussed below. Furthermore, a lifetime test indicates that deactivation of the Pt₁Mo₁/SiO₂ catalyst is not significant; the CO conversion maintains around 40% after running for 20 h at 250 °C (Fig. 1(b)).

To investigate the intrinsic activities and activation energies (E_a) of the Pt/SiO₂ and Mo-promoted catalysts, the WGS reaction was carried out at a specific GHSV with the CO conversion below 10%. CO chemisorption was used to measure the surface site density of Pt. The CO pulse chemisorption uptake for the

Pt/SiO₂ catalyst was 0.90 mmol/g_{Pt} (Table 1). For the Pt₄Mo₁/SiO₂, Pt₁Mo₁/SiO₂, and Pt₁Mo₄/SiO₂ catalysts, the CO chemisorption uptakes were 0.72, 0.70, and 0.04 mmol/g_{Pt}, respectively. The turnover frequency (TOF) is calculated on the base of the density of the surface-exposed Pt atoms at 250 °C. The TOF was $1.6 \times 10^{-3} \text{ s}^{-1}$ for the Pt/SiO₂ catalyst and $4.1 \times 10^{-1} \text{ s}^{-1}$ for the Pt₁Mo₁/SiO₂ catalyst. The calculated E_a for the Pt/SiO₂ catalyst was 67 kJ/mol, while it decreased to 44 kJ/mol for the Pt₁Mo₁/SiO₂ catalyst. The addition of the Mo species significantly enhances the reaction activity and lowers the E_a by about 20 kJ/mol [19,20].

According to ICP-AES data, the loadings of Pt in the Pt/SiO₂, Pt₄Mo₁/SiO₂, Pt₁Mo₁/SiO₂, and Pt₁Mo₄/SiO₂ catalysts are 3.5 wt%, 3.8 wt%, 3.7 wt%, and 3.3 wt%, respectively, while the loadings of Mo are 0 wt%, 0.4 wt%, 1.7 wt%, and 5.8 wt%, respectively (Table 1). The actual loadings of Pt and Mo were lower than the nominal values, which could be caused by: (1) the loss of metal species due to adsorption on the walls of the flask or beaker; (2) the evaporation of precursors during the drying process. XRD patterns of the Pt/SiO₂ and Pt-Mo/SiO₂ catalysts are shown in Fig. 2. For the Pt/SiO₂ catalyst, the diffraction peak from the Pt(111) plane is sharp and located at 39.8°, which indicates that the SiO₂-supported Pt nanoparticles are relatively large. Using Scherrer's formula, the average diameter of Pt nanoparticles was calculated to be approximately 4.5 nm. The diffraction peak from the Pt(111) plane in the Pt-Mo/SiO₂ catalysts became much broader, which suggests that the addition of Mo can effectively increase the dispersion of Pt nanoparticles. The calculated diameter of Pt nanoparticles

Fig. 1. CO conversion light-off curves of the Pt/SiO₂ catalyst and Pt-Mo/SiO₂ catalysts (a) and the lifetime test of the Pt₁Mo₁/SiO₂ catalyst at the reaction temperature of 250 °C (b).

Table 1

The chemical composition, particle sizes and catalytic activities of the Pt-Mo/SiO₂ catalysts with various Mo/Pt atomic ratios.

Catalyst	Particle size by TEM (nm)	Loading of Pt (wt%)	Loading of Mo (wt%)	CO uptakes (mmol/g _{Pt})	TOF* (s ⁻¹)	E_a (kJ/mol)
Pt-SiO ₂	3.2	3.5	—	0.90	1.6×10^{-3}	67
Pt ₄ Mo ₁ -SiO ₂	2.8	3.8	0.4	0.72	—	—
Pt ₁ Mo ₁ -SiO ₂	2.1	3.7	1.7	0.70	4.1×10^{-1}	44
Pt ₁ Mo ₄ -SiO ₂	1.7	3.3	5.8	0.04	—	—

*TOF is calculated based on the density of the surface-exposed Pt atoms. CO chemical adsorption with CO/Pt stoichiometry of 1 was used to estimate the Pt dispersion.

Fig. 2. XRD patterns from the Pt/SiO₂ catalyst and the Pt-Mo/SiO₂ catalysts.

in the Pt₄Mo₁/SiO₂, Pt₁Mo₁/SiO₂, and Pt₁Mo₄/SiO₂ catalysts was 3.4, 2.9, and 2.6 nm, respectively. The Pt(111) diffraction peak measured from all three Pt-Mo/SiO₂ catalysts was located at 39.8°, which is the same as that of the Pt/SiO₂ catalyst. This suggests that Mo and Pt in the Pt-Mo/SiO₂ catalysts cannot form PtMo alloys upon reduction at 300 °C. TEM image of the Pt/SiO₂ catalyst shows that the average diameter of Pt nanoparticles supported on SiO₂ was 3.2 nm with a broad size distribution. The nanoparticles in the Pt-Mo/SiO₂ catalysts are much smaller. The particle diameter decreases with an increase in the Mo/Pt atomic ratios (Fig. 3). The measured particle diameters in the Pt₄Mo₁/SiO₂, Pt₁Mo₁/SiO₂, and Pt₁Mo₄/SiO₂ catalysts are 2.8, 2.1, and 1.7 nm, respectively. These results indicate that the addition of the Mo species increased the dispersion of Pt nanoparticles.

The white line of XANES L₃-edge has been attributed to the

Fig. 4. XANES Pt L₃-edge spectra from Pt foil, Pt/SiO₂ catalyst and Pt-Mo/SiO₂ catalysts.

electronic transition from the core-level $2p_{3/2}$ to the 5d state, which is sensitive to the unoccupied electronic states of the 5d orbital of the Pt nanoparticles. As shown in Fig. 4, the XANES Pt L₃-edge was recorded from the Pt/SiO₂ and Pt-Mo/SiO₂ catalysts. For the Pt foil, the L₃-edge energy is located at 11566.0 eV and a strong white line peak is observed. The Pt/SiO₂ catalyst L₃-edge energy remains the same while the intensity of the white line increases. The L₃-edge energy shifts to 11566.5 eV for the Pt₄Mo₁/SiO₂ catalyst. For the Pt₁Mo₁/SiO₂ and Pt₁Mo₄/SiO₂ catalysts, the L₃-edge energies shift to a higher energy of 11567.0 eV and the white line intensity also increases. The increase in the white line intensity may be attributed to increased dispersion of Pt nanoparticles as a result of the Mo, since there is a strong correlation between the white line intensity and the nanoparticle size and the smaller Pt nanoparticles have stronger white line intensity [21,22]. In addition, the in-

Fig. 3. TEM images and corresponding Pt nanoparticle size distributions from the Pt/SiO₂ and Pt-Mo/SiO₂ catalysts. (a) Pt/SiO₂; (b) Pt₄Mo₁/SiO₂; (c) Pt₁Mo₁/SiO₂; (d) Pt₁Mo₄/SiO₂.

teraction between Pt and MoO_x would lead to charge transfer from Pt to MoO_x moieties. The Pt species in immediate contact with MoO_x is positively charged, which shifts the L_3 -edge energy to a higher energy and enhances the white line intensity [23,24].

As shown in Fig. 5 and Table 2, the intensities of the XPS Pt 4f peaks measured from the Pt-Mo/SiO₂ catalysts are all larger than those measured from the Pt/SiO₂ catalyst. The area ratio of Pt 4f/Si 2p increases from 0.07 in the Pt/SiO₂ catalyst to 0.18 in the Pt₁Mo₄/SiO₂ catalyst. The XPS results indicate that the addition of the Mo species onto the Pt/SiO₂ catalyst can increase the dispersion of Pt. The main Pt species in the Pt/SiO₂ catalyst are metallic with the Pt 4f_{7/2} peak located at 71.4 eV. The residual Pt species are Pt²⁺ located at 72.8 eV. The ratio of Pt²⁺/Pt⁰ species in the Pt/SiO₂ catalyst is 0.26. For the Pt₄Mo₁/SiO₂ and Pt₁Mo₁/SiO₂ catalysts, the ratios of Pt²⁺/Pt⁰ species are 0.29 and 0.30, respectively. The binding energy positions of the Pt⁰ and Pt²⁺ species in the Pt₁Mo₄/SiO₂ catalyst shift to 71.5 and 72.9 eV, and the ratio of Pt²⁺/Pt⁰ species in the Pt₁Mo₄/SiO₂ catalyst is 0.31. Consistent with the XANES results, the Pt nanoparticles have a stronger positive charge in the

Pt-Mo/SiO₂ catalysts with higher Mo/Pt atomic ratios [25].

The intensity of the Mo 3d signal is very weak in the Pt₄Mo₁/SiO₂ catalyst. The area ratio of Mo 3d/Si 2p is only 0.03. The area ratios of Mo 3d/Si 2p for the Pt₁Mo₁/SiO₂ and Pt₁Mo₄/SiO₂ catalysts are 0.10 and 0.23, respectively. From XPS data, the atomic ratio of Pt/Mo on the surfaces of the Pt₄Mo₁/SiO₂ and Pt₁Mo₁/SiO₂ catalysts are 2.12 and 0.77, respectively. They are much lower than the bulk value measured by ICP-AES, which indicates that the Pt nanoparticles are partially covered by the surface Mo species.

In the Mo/SiO₂ catalysts, the Mo 3d_{5/2} contains two components of Mo⁵⁺ and Mo⁶⁺, which are located at 231.6 and 232.8 eV (not shown in Fig. 5) [26–28]. The deposited Mo species on the Pt-Mo/SiO₂ catalysts contains both Mo⁵⁺ and Mo⁶⁺ species but not metallic Mo, which indicates that a PtMo alloy was not formed after the reduction at 300 °C (Fig. 5 and Table 2). The ratio of Mo⁵⁺/Mo⁶⁺ species in the Pt₄Mo₁/SiO₂ catalyst is 0.22, decreasing to 0.06 for the Pt₁Mo₄/SiO₂ catalyst. Most of the Mo species in the Pt₄Mo₁/SiO₂ catalyst are in contact with Pt, while the excess of Mo in the Pt₁Mo₄/SiO₂ catalyst leads to the formation of MoO_x species free from the interaction with Pt. We

Fig. 5. XPS Pt 4f (a) and Mo 3d (b) spectra from the Pt/SiO₂ and Pt-Mo/SiO₂ catalysts.

Table 2

The atomic ratios of Pt/Mo, Pt²⁺/Pt⁰, and Mo⁵⁺/Mo⁶⁺ in the Pt/SiO₂ and Pt-Mo/SiO₂ catalysts measured with XPS and ICP-AES.

Catalyst	Intensity ratio		Atomic ratio		Chemical state	
	Pt 4f/Si 2p	Mo 3d/Si 2p	Pt/Mo (XPS)	Pt/Mo (ICP)	Pt ²⁺ /Pt ⁰	Mo ⁵⁺ /Mo ⁶⁺
Pt-SiO ₂	0.07	—			0.26	—
Pt ₄ Mo ₁ -SiO ₂	0.09	0.03	2.12	4.5	0.29	0.22
Pt ₁ Mo ₁ -SiO ₂	0.11	0.10	0.77	1.1	0.30	0.16
Pt ₁ Mo ₄ -SiO ₂	0.18	0.23	0.53	0.3	0.31	0.06

suggest that the strong interaction between Pt and MoO_x patches confined on Pt nanoparticles produces a lower valence state Mo species [29–31].

XRD and TEM results indicate that the Pt nanoparticles are smaller in the Pt-Mo/SiO₂ catalysts than the Pt/SiO₂ catalyst. This suggests that added Mo species onto the Pt/SiO₂ catalyst has increased the Pt dispersion, which has been observed by other groups [26,32]. During the reduction process, the decoration of MoO_x on Pt nanoparticles can enhance the interaction between the Pt nanoparticles and the SiO₂ support via formation of a Pt-MoO_x-SiO₂ interface, which results in the significant enhancement of Pt dispersion for the Pt-Mo/SiO₂ catalysts. In the Pt₄Mo₁/SiO₂ and Pt₁Mo₁/SiO₂ catalysts, XPS results show that the atomic ratios of Pt/Mo at the sample surfaces are much lower than the bulk ratio obtained via ICP analysis. This demonstrates that the added MoO_x species decorate the Pt nanoparticles [33,34]. We can infer that there is a strong interaction between surface MoO_x patches and the area underneath Pt nanoparticles. Therefore, the highly dispersed MoO_x patches confined on Pt nanoparticles in the Pt₄Mo₁/SiO₂ and Pt₁Mo₁/SiO₂ catalysts have a lower valence state and may present more oxygen vacancies. Park et al. [26] have shown that MoO_x in close contact with Pt nanoparticles has more Mo^{5+} species. The Pt/SiO₂ and Mo/SiO₂ catalysts are less active in the WGS reaction. The Pt₄Mo₁/SiO₂ and Pt₁Mo₁/SiO₂ catalysts, which include Pt nanoparticles decorated with highly dispersed MoO_x patches, exhibit remarkable catalytic activities and a lower barrier at low temperatures compared with the Pt/SiO₂ catalyst. The most probable explanation for this is that the interface sites between MoO_x patches and Pt nanoparticles are the active sites for the WGS reaction and maximum activity can be achieved with the optimum coverage of MoO_x patches on the

Pt nanoparticles. Therefore, H₂O can be activated at the interface sites between MoO_x patches and Pt nanoparticles and then react with CO adsorbed on the adjacent Pt nanoparticles through a bifunctional mechanism similar to that of the Au/MoO₂ model catalyst [35]. A similar promotion effect of MoO_x on Pt-based catalysts has been found in other reactions [25,26,36–40].

4. Conclusions

Pt/SiO₂ and MoO_x/SiO₂ catalysts are less active for the WGS reaction below 300 °C. However, MoO_x -promoted Pt nanoparticles exhibit remarkable activities under similar conditions. The activity enhancement depends on Mo/Pt atomic ratios and the maximum activity can be achieved with the optimum coverage of MoO_x patches on Pt nanoparticles. Pt nanoparticles decorated with highly dispersed MoO_x patches are the active architecture for the WGS reaction. The highly dispersed MoO_x patches confined on Pt nanoparticles have a low valence state and facilitate the dissociation of H₂O.

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Graphical Abstract

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MoO_x-promoted Pt catalysts for the water gas shift reaction at low temperatures

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MoO_x-promoted Pt nanoparticles exhibit remarkable activity for the WGS reaction at low temperatures and highly dispersed MoO_x nanoparticles on Pt nanoparticles are the active architecture.

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MoO_x促进的Pt基催化剂用于低温水汽变换反应

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摘要: 通过浸渍还原法制备了不同比例的Pt-Mo/SiO₂催化剂, 采用X射线衍射、透射电镜、X射线近边吸收谱和X射线光电子能谱表征了Pt-Mo/SiO₂催化剂的组成、结构及价态。研究结果表明, 少量MoO_x修饰Pt-Mo/SiO₂催化剂在低温水汽变换反应中表现出比Pt/SiO₂催化剂更高的催化活性, 过量MoO_x包覆的Pt-Mo/SiO₂催化剂活性较低。低温水汽变换反应活性来自于Pt与表面MoO_x的界面协同作用, 限域在Pt纳米颗粒表面的MoO_x表现出较低价态, 高分散MoO_x纳米岛修饰的Pt纳米颗粒是低温水汽变换反应的活性结构。

关键词: 水汽变换反应; 铂; 钼氧化物; 协同作用; 界面催化

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