Influence of crystal structure of Y-doped ZrO$_2$ as support oxide on the three-way catalytic performance of supported Rh catalyst

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The effect of crystal structure of Y-doped ZrO$_2$ as support on the three-way catalytic performance of Rh catalyst was investigated. Rh catalyst supported on 3Y-ZrO$_2$ with tetragonal phase showed higher activity than that on 3Y/ZrO$_2$ with monoclinic phase. The difference in the Rh-supported oxide interaction was suspected from the measurements of temperature-programmed reduction by CO (CO-TPR). The use of Y-doped ZrO$_2$ as support was found to contribute to the formation of easily reducible Rh species, resulting in high catalytic activity. Rh species can more strongly interact with 3Y/ZrO$_2$ than with 3Y-ZrO$_2$, resulting in the formation of catalytically active reducible Rh species in Rh/3Y-ZrO$_2$, which showed the highest activity. From Fourier transform infrared (FT-IR) spectroscopy following CO adsorption, no qualitative difference in the surface valence state of Rh particles irrespective of crystallite structure of Y-doped ZrO$_2$ was observed. On the other hand, a large fraction of the surface of Rh particles in Rh/3Y-ZrO$_2$ was found to be Rh$^0$ sites rather than Rh$^+$ sites. This is related to the interaction of Rh particles with Y species in tetragonal 3Y-ZrO$_2$. We concluded that the tetragonal structure of 3Y-ZrO$_2$ with which Rh can interact via Y species is a key-factor to obtain highly active Rh catalysts.

Key-words : Three-way catalyst, Yttria-stabilized zirconia, Rhodium, Tetragonal phase, Monoclinic phase, CO-TPR, FT-IR spectroscopy

1. Introduction

In recent years, one of the major environmental concerns that were paid a lot of attention is the air pollution caused by the exhausts of vehicles. Three-way catalysts (TWCs) represent the most innovative technologies for automotive emission control. TWCs can work simultaneously and efficiently to reduce NO and to oxidize CO and hydrocarbons (HCs) in a narrow window of air-to-fuel ratio, close to the stoichiometric point. Although more than 99% of emissions are purified by using TWCs, further improvement of the performance of TWCs is highly required to achieve strict emission regulations, which are constantly becoming more stringent worldwide. Especially, the efficient removal of pollutants emitted during cold-start operation before warming up the catalytic converter must be an important issue.

Among the catalytic components employed for TWCs, platinum group metals (PGMs) such as Pt, Pd and Rh are regarded as promising active component. Therefore, an increase in the loading of PGMs would be one of the strategies to improve the performance of TWCs. However, PGMs have been determined as critical raw materials, which were defined to the materials combining a high economic importance with a high risk associated with their supply. The development of highly active TWCs with less PGMs loading has to be achieved for “Sustainable Development Goals”.

Producing the optimum interaction between PGM and support oxide may be another strategy for the achievement of high catalytic performance. Nagai et al. reported that the use of CeO$_2$ and CeO$_2$–ZrO$_2$, which possess surface basicity, can improve the dispersion state of Pt and Rh. This was explained by the formation of PGM–Ce bonds, which act as anchor for PGM particles on CeO$_2$-based oxides. The interaction of Rh with basic oxide was also pointed out to cause the formation of reducible RhO$_x$ species, resulting in low catalytic performance. On the other hand, Kawabata et al. investigated the TWC performance of Rh catalyst supported on La-containing ZrO$_2$ (Rh/Zr–La–O), and found that Rh/Zr–La–O was highly active for the removal of NO and HCs from a synthetic auto exhaust. They explained its high performance of Rh/Zr–La–O by the stabilized Rh species in low oxidation state.

The catalytic performance of noble metals is known to be affected by the crystal structure of support oxide. For example, Li et al. reported that Au catalyst supported on ZrO$_2$ with monoclinic phase showed higher activity...
for water-gas shift reaction than that on ZrO2 with tetragonal phase. The hydroxyl groups on the surface of ZrO2 with monoclinic phase seem to play an important role in the water-gas shift reaction. Murata et al. investigated the catalytic activity of Pd supported on Al2O3 with different crystal phase for CH4 oxidation, and reported that Pd/α-Al2O3 and Pd/γ-Al2O3 showed a volcano-shaped dependence of the catalytic activity on the size of Pd particles, while the catalytic activity of Pd/γ-Al2O3 increased with the particle size. The Pd-Al2O3 interaction is strongly dependent on the crystal phase of Al2O3, resulting in the different distribution of catalytically active sites on Pd particle surface.

We have recently investigated the additive effect of various rare earths on the TWC performance of Rh/ZrO2 to gain the knowledge on Rh–support interaction, and found that Rh–support interaction can control the dispersion state and the surface oxidation state of Rh. We have also reported the advantages to use Y-stabilized ZrO2 as support oxide for Pt and Rh in HCs oxidation and TWC reactions. The use of Y-stabilized ZrO2 caused an enhancement of the reducibility of Rh species, resulting in the stabilization of Rh in active metallic state during the reaction. On the other hand, the crystal structure of Y-stabilized ZrO2 is known to be systematically controlled by changing the thermal treatment conditions and the Y2O3 content. This suggests that Rh catalysts possessing different interaction with support can be obtained by using Y-stabilized ZrO2 with different crystal structure, leading us to consider the effect of crystal structure on the TWC performance. In the present study, we have employed Y-doped ZrO2 with monoclinic and tetragonal phases as support oxide for Rh catalyst, and then evaluated the catalytic performance for TWC reactions. The effect of crystal structure of Y-doped ZrO2 on the TWC performance of Rh catalyst was investigated.

2. Experimental procedure

Two kinds of Y-doped ZrO2 were employed. One is a commercial sample purchased from Tosoh denoted as 3Y-ZrO2 (TZ-3Y; 16 m² g⁻¹), where the loading of Y2O3 was 3 mol %. Another Y-doped ZrO2 with 3 mol % Y2O3 loading, denoted as 3Y/ZrO2, was prepared by impregnation of ZrO2 (Tosoh, TZ-0; 14 m² g⁻¹) with an aqueous solution of yttrium(III) nitrate (Fujifilm Wako Pure Chemical Corporation), followed by drying and calcination at 600 °C for 5 h in air. Rh was deposited on ZrO2, 3Y-ZrO2 and 3Y/ZrO2 by immersing a solution of Rh(NO3)3 (Tanaka Kikinzoku Kogyo), followed by drying and calcination at 900 °C for 5 h in air.

The catalytic activity test was carried out using a flow reactor system by passing a stoichiometric reaction gas mixture containing NO (0.1 %), CO (0.3 %), C3H6 (0.04 %), O2 (0.28 %) and H2O (2 %) diluted in N2 at a rate of 500 cm³ min⁻¹ over 0.1 g of catalyst (SV = ca. 450,000 h⁻¹), which had been pretreated in situ in a flow of the reaction gas at 800 °C for 1 h. The activity was measured while raising the temperature from 40 to 800 °C at a rate of 10 °C min⁻¹. The concentrations of NOx, O2, CO and CO2 and the total HCs in the effluent gas were continuously monitored using an on-line gas analyzer, Horiba, PG-240 and Shimadzu, VMS-1000F, respectively.

X-ray diffraction (XRD) patterns were recorded using a Rigaku MiniFlex diffractometer with CuKα radiation at 30 kV and 15 mA. Raman spectra were measured with a Micor-RAM300/NK (Lambda Vision) equipped with a TE-cooled charge coupled device detector and a green laser (λ = 532 nm) under the ambient atmosphere. Electron probe microanalysis (JEOL, JXA-8230) was used to evaluate the distribution of Y species in the Y-doped ZrO2 samples.

The dispersion of Rh was calculated from CO chemisorption measured by the pulse method at room temperature. The sample was first reduced with H2 at 400 °C for 1 h and then cooled to room temperature in flowing He. Several pulses of CO were introduced into the sample until no more adsorption was observed. As for the stoichiometric ratio of CO/Rh, Belton and Schmieg determined the stoichiometric ratio of 1.0 from the comparison of the particle size of Rh and the amount of CO desorption for Rh/Al2O3 model catalyst. The use of 1.0 CO/Rh adsorption stoichiometry was also reported to reasonable for the evaluation of Rh dispersion. Therefore, the Rh dispersion was calculated from the amount of CO chemisorption by assuming a stoichiometric ratio of 1.0 CO/Rh. Temperature-programmed reduction by CO (CO-TPR) was performed to investigate the reducibility of the catalysts. Prior to each experiment, the sample (0.1 g) was pretreated in situ in a flow of 5 % O2/He at 500 °C for 1 h and then cooled to room temperature. After purging with He, the TPR profiles were obtained from room temperature to 600 °C in a 20 cm³ min⁻¹ flow of 0.5 % CO/He at a heating rate of 10 °C min⁻¹. The effluent gas was analyzed with an on-line quadrupole mass spectrometer (PFEFFER Omnistar).

Fourier transform infrared (FT-IR) spectra of adsorbed CO as a probe molecule were taken with a Nicolet 6700 FT-IR spectrometer (Thermo Scientific) at a resolution of 4 cm⁻¹. Prior to each experiment, a self-supporting sample disk of about 20 mg cm⁻² placed in an IR cell with CaF2 windows was first pretreated at 400 °C in a flow of the reaction gas containing NO (0.1 %), CO (0.3 %), C3H6 (0.04 %) and O2 (0.25 %) diluted in He at a stoichiometry and then cooled to 50 °C in flowing He. Observation of adsorbed CO species was carried out in a flow of 0.35 % CO/He at 50 °C for 10 min, followed by purging with He for 10 min.

3. Results and discussion

Figure 1(A) shows the XRD patterns of ZrO2, 3Y-ZrO2 and 3Y/ZrO2 as support. Distinct XRD peaks indexed to a monoclinic phase were detected for ZrO2. The same XRD pattern was observed for 3Y-ZrO2, indicating that Y³⁺ ions impregnated onto ZrO2 did not change the crystal structure of ZrO2. On the other hand, 3Y-ZrO2 was found to possess a mixture of monoclinic and tetragonal phases, suggesting the coexistence of thermodynamically metastable
and stable phases. To confirm the crystal structure of ZrO$_2$-based materials, Raman spectra were measured, because Raman spectroscopy is sensitive technique to the crystal symmetry.\textsuperscript{28) As seen in Fig. 1(B), ZrO$_2$ and 3Y/ZrO$_2$ showed the same Raman spectrum. All the peaks detected at 176, 188, 219, 305, 330, 345, 379, 472, 499, 534, 554, 611 and 632 cm$^{-1}$ are well consistent with those observed for ZrO$_2$ with monoclinic phase (m-ZrO$_2$).\textsuperscript{29),30) In case of 3Y-ZrO$_2$, the intensity of the peaks due to m-ZrO$_2$ was clearly decreased compared with that for ZrO$_2$. Besides, an appearance of characteristic peaks at 144 and 260 cm$^{-1}$, which can be ascribed to tetragonal phase of ZrO$_2$ (t-ZrO$_2$),\textsuperscript{29),30) was observed. These results indicate the coexistence of t-ZrO$_2$ and m-ZrO$_2$ in 3Y-ZrO$_2$. The results obtained from Raman spectroscopy are well consistent with those from XRD measurements.

Considering the preparation method of 3Y/ZrO$_2$, Y species are suspected to be deposited on the surface of ZrO$_2$. In fact, as show the elemental distribution of Y in Fig. 2(B), an aggregation of Y species was observed for 3Y/ZrO$_2$. Aggregated Y species do not affect the crystal structure of ZrO$_2$. On the other hand, the presence of relatively well dispersed Y species was observed for 3Y-ZrO$_2$ [Fig. 2(A)]. In accordance with the results of XRD and Raman, Y species are incorporated in the lattice of ZrO$_2$, resulting in the formation of tetragonal phase.

In order to confirm the influence of Rh deposition on the crystal structure, XRD patterns and Raman spectra of Rh/ZrO$_2$, Rh/3Y-ZrO$_2$ and Rh/3Y/ZrO$_2$ were measured. Figures 3(A) and 3(B) show the XRD patterns and the Raman spectra, respectively. From the comparison of Fig. 3(A) with Fig. 1(A), no difference in the XRD patterns were observed for Rh/ZrO$_2$ and Rh/3Y/ZrO$_2$. However, as seen in Fig. 3(B), the Raman peaks were broadened by the presence of Rh. In Figs. S1(A) and S1(B) (see in “Supplementary File”) are compared the Raman spectra of ZrO$_2$ and 3Y/ZrO$_2$ before and after calcination at 900 °C for 5 h in air. It appears that no significant difference in the position and intensity of Raman peaks was observed, suggesting that heat-treatment at 900 °C does not cause structural change of ZrO$_2$. Therefore, the broadened Raman peaks of Rh/ZrO$_2$ and Rh/3Y/ZrO$_2$ would be due to the formation of structural disordered ZrO$_2$ with monoclinic phase caused by the interaction with Rh.\textsuperscript{31) On the other hand, in case of Rh/3Y-ZrO$_2$, XRD peaks due to monoclinic phase of ZrO$_2$ were significantly

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Fig. 1. (A) XRD patterns and (B) Raman spectra of ZrO$_2$, 3Y-ZrO$_2$ and 3Y/ZrO$_2$.

Fig. 2. Scanning electron microscope (SEM) image and elemental distribution of Zr and Y for (A) 3Y-ZrO$_2$ and (B) 3Y/ZrO$_2$.
weakened [Fig. 3(A)]. In addition, no Raman peaks due to m-ZrO2 were observed in the Raman spectrum [Fig. 3(B)]. Therefore, Rh/ZrO2 seems to mainly consist of tetragonal phase of ZrO2. The XRD patterns of 3Y-ZrO2 before and after calcination at 900 °C for 5 h in air were compared in Fig. S2 (see in "Supplementary File"). Although a slight decrease in the intensity of the peaks due to monoclinic phase was observed, no significant change in the crystal structure of 3Y-ZrO2 was observed. The same result was obtained in Raman spectra given in Fig. S1(B). Therefore, the disappearance of monoclinic phase in Rh/3Y-ZrO2 would be ascribed to the interaction with 3Y-ZrO2.

Machida et al.32) reported that Rh2O3 with hexagonal phase can strongly interact with AlPO4 with monoclinic phase leading to the formation of Rh–O–P bonding. Tanabe et al.9),33) also reported the strong interaction of Rh species with Nd2O3 surface-enriched tetragonal ZrO2, resulting in the formation of Rh–O–Nd bonding. In the present study, Rh/3Y-ZrO2 was calcined at 900 °C in air, so that thermodynamically stable Rh oxide (Rh2O3) would be formed. Considering the report of Machida et al.32) and Tanabe et al.,33),34) Rh2O3 is suspected to strongly interact with not only monoclinic phase but also tetragonal phase of 3Y-ZrO2, resulting in the distortion of monoclinic and tetragonal ZrO2 phase, which causes the disappearance of XRD peaks due to monoclinic phase and the broadened Raman peaks.

No peaks ascribed to Rh were detected in XRD patterns and Raman spectra for all the samples, suggesting high dispersion state of Rh species. In fact, as summarized in Table 1, Rh dispersion as high as 10% was achieved for Rh/ZrO2 and Rh/3Y-ZrO2. It is also noteworthy that the highest Rh dispersion was obtained for Rh/3Y/ZrO2.

Figure 4 shows the temperature dependence of conversion efficiencies of NO, CO and C3H6 as a function of temperature for three-way catalytic reactions over Rh/ZrO2, Rh/3Y-ZrO2 and Rh/3Y/ZrO2.

Rh/3Y-ZrO2 and Rh/3Y/ZrO2 were shifted to low temperature region compared with that of Rh/ZrO2. From the comparison of the activity of Rh/3Y-ZrO2 and Rh/3Y/ZrO2, the former catalyst showed higher activity for NO reduction and CO/C3H6 oxidation than the latter one in the temperature range of 200–250 °C. Since Y-doped ZrO2 without Rh does not effectively catalyze the TWC reactions,34) Rh must be the catalytically active component. Therefore, the dispersion state of Rh species is considered to be an important factor affecting the catalytic activity, because catalytic reactions take place on catalyst surfaces. As given in Table 1, the highest Rh dispersion was obtained for Rh/3Y/ZrO2, which showed lower activity.

Table 1. Physico-chemical properties of supported Rh catalyst

|              | BET surface area/m² g⁻¹ | Rh dispersion (CO/Rh) |
|--------------|-------------------------|-----------------------|
| Rh/ZrO2      | 10.0                    | 0.12                  |
| Rh/3Y-ZrO2   | 10.0                    | 0.15                  |
| Rh/3Y/ZrO2   | 12.8                    | 0.53                  |
Therefore, the high catalytic activity of Rh/3Y-ZrO₂ can not by explained by the dispersion state of Rh. From the results of XRD and Raman measurements (Fig. 3), the use of Y-doped ZrO₂ with tetragonal phase seems to be effective to obtain highly active Rh catalyst.

In order to understand the intrinsic role of crystal structure of Y-doped ZrO₂, various characterizations were carried out. CO-TPR measurements were first performed to gain insights on the Rh–support interaction. In CO-TPR measurements, CO is formed via the reaction of CO with oxygen species present either on the surface or in the bulk of a sample. Therefore, CO₂ formation temperature is dependent on, for example, dispersion state of supported metals,35) metal–support interaction35) and so on. Figure 5 shows the temperature dependence of CO₂ formation as CO-TPR profile of supported Rh catalysts. Distinct CO₂ formation was observed in the temperature range of 100–500 °C. Since ZrO₂ and Y-doped ZrO₂ do not possess oxygen species which can react with CO, the CO₂ formation is related to the reaction of CO with oxygen attributed to Rh and/or Rh–support oxide interface. Therefore, the finding that different CO-TPR profile was observed for each Rh catalyst suggests that the reducibility of Rh species is different depending on the support oxide. As seen in Fig. 5, Rh/ZrO₂ gave the CO₂ formation peaks at 188 and 240 °C along with broad peaks in 300–450 °C range. Tanabe et al.9,33) observed three reduction peaks at around 90, 130 and 180 °C in the H₂–TPR profile of Rh/Nd₁₋₃ₓZrO₂ and then ascribed the peaks to the reduction of three-dimensional, two-dimensional Rh₂O₃ and Rh species interacting strongly with Nd₂O₃, respectively. Burch and Loader8) also reported that Rh species, which had little interaction with support, are easily reduced at lower temperature, while those with strong support interaction are reduced at higher temperature. Taking into account the lower reduction ability of CO compared with H₂, the CO₂ formation peaks detected in the CO-TPR profile of Rh/ZrO₂ are ascribed to the reduction of Rh₂O₃ surface, Rh–ZrO₂ interface, and Rh species interacting strongly with ZrO₂, respectively, from low temperature.

As seen in Fig. 5, CO-TPR profile of Rh catalysts supported on Y-doped ZrO₂ is also basically composed of three peaks at 188, ca. 220 and ca. 300 °C. It appears that the CO₂ formation peak at 240 °C observed for Rh/ZrO₂ was clearly shifted to lower temperature, when Y-doped ZrO₂ was employed as support. The use of Y-doped ZrO₂ seems to weaken the interaction of Rh with ZrO₂. In other words, the reducibility of Rh species supported on Y-doped ZrO₂ was improved. Metallic state of Rh is known to act as catalytically active sites for TWC reactions.30) In fact, Rh/3Y-ZrO₂ and Rh/3Y/ZrO₂ showed higher catalytic activity that Rh/ZrO₂ (Fig. 4). Therefore, one of the roles of Y-doped ZrO₂ would be to form easily reducible Rh species.

On the other hand, the interaction of Rh species with Y-doped ZrO₂ seems to be different depending on the dispersion state of Y species. As seen in Fig. 5, Rh/3Y-ZrO₂ showed a peak at 218 °C, which can be ascribed to the reduction of the interface between Rh and Y species in t-ZrO₂, while Rh/3Y/ZrO₂ gave the peak at higher temperature (224 °C). This suggests that Rh supported on the surface of 3Y/ZrO₂ possesses stronger interaction than Rh on 3Y-ZrO₂, in which Y dissolved in ZrO₂ lattice. Since the strong interaction of Rh with support oxide leads to the difficulty of the formation of catalytically active reducible Rh species, Rh/3Y-ZrO₂ showed higher catalytic activity than Rh/3Y/ZrO₂ (Fig. 4).

As seen in Fig. 5, an additional peak was observed at 260 °C in the CO-TPR profile of Rh/3Y-ZrO₂. Considering that the CO₂ formation peak at 240 °C in the CO-TPR profile of Rh/ZrO₂ is ascribed to the reduction of Rh–m-ZrO₂ interface, the peak at 260 °C would be due to the reduction of Rh–t-ZrO₂ interface. Rh species seems to more strongly interact with t-ZrO₂ than with m-ZrO₂. Our results are well consistent with the report of Heo et al.14) They investigated the interaction of Rh and ZrO₂ with different crystallite phases, and then reported that Rh had a stronger interaction with tetragonal ZrO₂ than with the monoclinic form. The interaction of Rh with Y species in tetragonal 3Y-ZrO₂ is also suspected by the disappearance of XRD peaks due to monoclinic phase and the broadened Raman peaks as described before (Fig. 3).

Since catalytic reactions take place on catalyst surfaces, the Rh–support interaction is suspected to control the surface valence state of Rh species. In order to gain information on the surface valence state of Rh species, FT-IR spectra of CO species adsorbed on Rh catalysts pretreated with the TWC reaction gas were measured. Figure 6 shows a typical result obtained for Rh/3Y-ZrO₂, where IR spectra were continuously measured during CO/He flowing and subsequent He purge with an interval of 1 min. As seen in Fig. 6, three IR bands at 2089, 2056 and 2015 cm⁻¹ were observed immediately after the introduction of 0.35 % CO/He flow. These bands were increased with time on stream, and then slightly decreased by purging with He. After purging with He in 10 min, distinct three IR bands, which are due to CO species adsorbed on Rh sites, were still detected. The IR spectra obtained after purging
with He in 10 min were compared for supported Rh catalysts.

Figure 7 shows the FT-IR spectra of CO species adsorbed on Rh/ZrO$_2$, Rh/3Y-ZrO$_2$ and Rh/3Y/ZrO$_2$. IR spectra were recorded after purging with He in 10 min.

The activity of Rh catalysts supported on Y-doped ZrO$_2$ for three-way catalytic reactions is strongly dependent on the crystal structure of Y-doped ZrO$_2$. Rh/3Y-ZrO$_2$ with tetragonal phase showed higher activity than Rh/3Y/ZrO$_2$ with monoclinic phase. Since higher dispersion state of Rh was observed for the latter catalyst, the high catalytic activity of the former catalyst can not by explained by the dispersion state of Rh. CO-TPR measurements revealed the difference in the reducibility of Rh species dispersed on ZrO$_2$ and Y-doped ZrO$_2$ with either monoclinic or tetragonal phase. The reducibility of Rh species was improved when Y-doped ZrO$_2$ was employed, resulting in higher catalytic activity. Rh species can more strongly interact with Rh$^0$ state by the pretreatment with the reaction gas, is responsible for high TWC activity of Rh/3Y-ZrO$_2$. The tetragonal structure of 3Y-ZrO$_2$ with which Rh can strongly interact via Y species is a key-factor to obtain highly active Rh catalysts.

4. Conclusion

The activity of Rh catalysts supported on Y-doped ZrO$_2$ for three-way catalytic reactions is strongly dependent on the crystal structure of Y-doped ZrO$_2$. Rh/3Y-ZrO$_2$ with tetragonal phase showed higher activity than Rh/3Y/ZrO$_2$ with monoclinic phase. Since higher dispersion state of Rh was observed for the latter catalyst, the high catalytic activity of the former catalyst can not by explained by the dispersion state of Rh. CO-TPR measurements revealed the difference in the reducibility of Rh species dispersed on ZrO$_2$ and Y-doped ZrO$_2$ with either monoclinic or tetragonal phase. The reducibility of Rh species was improved when Y-doped ZrO$_2$ was employed, resulting in higher catalytic activity. Rh species can more strongly interact with Rh$^0$ than with 3Y-ZrO$_2$, resulting in the formation of catalytically active reducible Rh species in Rh/3Y-ZrO$_2$. In the IR spectra of CO species adsorbed on Rh, two kinds of IR bands due to a gem-dicarbonyl species on Rh$^+$ and a linear CO species on Rh$^0$ were observed for both Rh/3Y-ZrO$_2$ and Rh/3Y/ZrO$_2$, suggesting no qualitative difference in the surface valence state of Rh particles. However, a large fraction of the surface of Rh particles in Rh/3Y-ZrO$_2$ was found to be Rh$^0$ sites rather than Rh$^+$ sites. This was ascribed to the presence of two-
dimensional RhO₃ interacting with Y species in tetragonal 3Y-ZrO₂. We concluded that the tetragonal structure of 3Y-ZrO₂ with which Rh can interact via Y species is a key-factor to obtain highly active Rh catalysts.

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