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# Behavior of $Ti^{3+}$ Centers in the Low- and High-Temperature Reduction of $Pt/TiO_2$ , Studied by ESR

T. Hulzinga\* and R. Prins

Laboratory for Inorganic Chemistry, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands

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Reduction of  $Pt/TiO_2$  at 573 K leads to the formation of a  $Ti^{3+}$  ESR signal, which disappears after a subsequent evacuation at 573 K. Readmission of hydrogen at room temperature makes the signal reappear. Such a reversibility is not observed when reduction takes place at 773 K. These observations are explained by a spillover of hydrogen atoms under the formation of  $Ti^{3+}$  and  $OH^-$  ions. During the high-temperature reduction the hydrogenated  $TiO_2$  surface around the platinum is dehydrated and a  $Ti_4O_7$  layer is formed, thereby inhibiting the reversibility.

## Introduction

Recently interest in titanium dioxide as a support in heterogeneous catalysis has grown appreciably. Especially the findings of Tauster et al.,<sup>1</sup> that the chemisorption capabilities of platinum for hydrogen disappeared when  $Pt/TiO_2$  systems were reduced at relatively high temperatures (773 K), created great interest. Transmission electron microscopy showed that the reduced chemisorption capabilities were not due to trivial effects such as sintering of the metal. The reason for the change in behavior of the metal on titanium dioxide after a high temperature reduction has been ascribed to a special metal-support interaction. Baker, who showed with electron diffraction that in  $Pt/TiO_2$  catalysts after a high-temperature reduction layers of  $Ti_4O_7$  are formed,<sup>2</sup> has suggested that reducibility plays an important role in this so-called strong metal-support interaction (SMSI).<sup>3</sup> That the SMSI properties are indeed related to the reducibility of the support is proved by the fact that noble metals on  $V_2O_5$ ,  $Nb_2O_5$ , and (weakly)  $Ta_2O_5$  also exhibit SMSI properties.<sup>4</sup> Until now the nature of this strong metal-support interaction has not been explained, although proposals have been put forward.<sup>4</sup>

Not only the chemisorption properties but also activities and selectivities of metals on titanium dioxide may be different from metals on conventional supports. Thus it was found that  $Ni/TiO_2$  is a much better catalyst for the hydrogenation of carbon monoxide.<sup>5</sup> Both activity and selectivity toward higher hydrocarbons are increased compared to conventional  $Ni/Al_2O_3$  systems.<sup>6</sup>

In this Letter we present the results of an ESR study of platinum on  $TiO_2$ . Our results demonstrate that, at temperatures as low as 573 K,  $Ti^{3+}$  ions are formed presumably in the neighborhood of the platinum particles. The  $Ti^{3+}$  ions, when formed by a low-temperature reduction, can easily be retransformed into  $Ti^{4+}$  ions, but this is not the case for  $Ti^{3+}$  ions formed at 773 K. It will be shown that this can be explained by the formation of  $Ti_4O_7$  by dehydration of the  $TiO_2$  support in the neighborhood of the metal particles.

## Experimental Section

The titanium dioxide used (anatase, Tioxide Ltd., CLDD 1367) had a surface area of  $50 \text{ m}^2 \text{ g}^{-1}$  and a pore volume of  $0.9 \text{ cm}^3 \text{ g}^{-1}$ . Platinum was put on the support in the form of  $Pt(NH_3)_4(OH)_2$  (Johnson Matthey Chemicals Ltd.) by using a combined ion-exchange and wet impregnation method; a known amount of  $Pt(NH_3)_4(OH)_2$  was added to a well-stirred aqueous slurry of titanium dioxide at pH 9 and stirring was continued for 6 h. Subsequently, the water was evaporated by slowly heating to 363 K at reduced pressure. The platinum content was 2 wt %.

To determine the metal particle size of the reduced samples X-ray diffraction, transmission electron microscopy, and hydrogen chemisorption were applied. The electron micrographs were taken on a Philips 400 electron microscope and hydrogen chemisorption measurements were carried out in a conventional volumetric glass system. ESR spectra (X-band) were recorded with a Varian E-15 spectrometer equipped with a TE-104 dual sample cavity and a liquid helium flow cryostat. An in-situ cell was used<sup>7</sup> and the temperature of the sample was kept constant between 20 and 293 K with a Cryoson CE 5348 temperature controller. Signal intensity and position were calibrated with the aid of the Varian strong pitch ( $g = 2.0028$ ,  $3.01 \times 10^{15} \text{ spins cm}^{-1}$ ). Quantitative measurements of signal intensities were performed at 20 K.

## Results and Discussion

The combined ion-exchange and impregnation technique leads to a rather well-dispersed platinum phase on the titanium dioxide support, as is indicated by the absence of any metallic platinum X-ray diffraction line after reduction at 573 K and passivation of the  $Pt/TiO_2$  sample. Electron micrographs showed the presence of raftlike metallic structures on the support, the mean particle diameter of which was found to be 3.1 nm. This particle diameter is in reasonable agreement with the H/Pt ratio of 0.7 found in hydrogen chemisorption, determined after subtraction of reversibly adsorbed hydrogen.

The influence of oxidation and reduction treatments on the  $Pt/TiO_2$  sample was followed with electron spin resonance measurements, which yielded information on the state of the platinum, as will be discussed elsewhere.<sup>8</sup> Here we will be mainly concerned with the titanium ESR signal found after reduction of the  $Pt/TiO_2$  sample.

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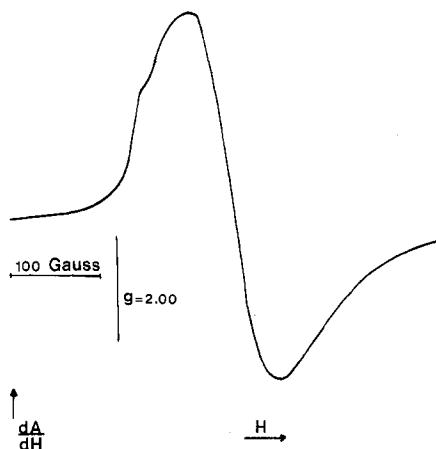


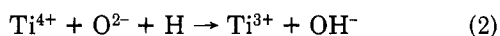
Figure 1. X-band ESR spectrum for a  $\text{Ti}^{3+}$  species, recorded at 20 K after reduction at 573 K and evacuation at 293 K.

TABLE I: Intensity of the  $\text{Ti}^{3+}$  Signal

sample	pretreatment <sup>a</sup>	no. of $\text{Ti}^{3+}$ / no. of $\text{Ti}^{4+}$ ions
$\text{TiO}_2$	R 375, E 293	$1 \times 10^{-4}$
Pt/ $\text{TiO}_2$	R 573	$2.8 \times 10^{-3}$
	R 573, E 293	$3.0 \times 10^{-3}$
	R 573, E 293, E 573	$3.4 \times 10^{-5}$
	R 573, E 573	$3.3 \times 10^{-5}$
	R 573, E 573, H 293, E 293	$2.2 \times 10^{-3}$
	R 773, E 293	$3.5 \times 10^{-3}$
	R 773, E 573	$1.8 \times 10^{-3}$
	R 773, E 573, H 293, E 293	$1.9 \times 10^{-3}$

<sup>a</sup> R denoted reduction, E, evacuation, and H, hydrogen admission. Numbers indicate temperatures (K). The heating rate was 4 K/min. Time of the pretreatments at elevated temperatures 1 h, at 293 K 5 min. ESR spectra were recorded at 20 K.

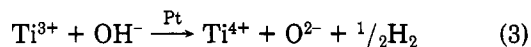
This signal at  $g = 1.92$  with  $\Delta H = 100$  G (cf. Figure 1) is assigned to a  $\text{Ti}^{3+}$  species in an octahedral environment. The  $g$  value is in accordance with expectations from second-order perturbation theory for a  $\text{Ti}^{3+} 3d^1$  system. This signal has been observed before in pure  $\text{TiO}_2$  systems.<sup>9</sup> The  $\text{Ti}^{3+}$  ESR signal observed after reduction of a Pt/ $\text{TiO}_2$  sample at 573 K for 1 h is about 30 times larger than that observed after reduction of pure  $\text{TiO}_2$  under the same conditions (cf. Table I). This demonstrates that the reduction of the  $\text{TiO}_2$  by hydrogen is catalyzed by the platinum. Apparently hydrogen chemisorbs dissociatively on platinum, after which the hydrogen atoms diffuse to the support and reduce  $\text{Ti}^{4+}$  ions to  $\text{Ti}^{3+}$ :



A similar reduction mechanism has been proposed for the uncatalyzed reduction of pure  $\text{TiO}_2$ .<sup>10</sup> In that case defect structures at the surface function as centers for the dissociative adsorption of the hydrogen.

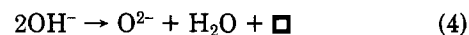
Evacuation of the reduced Pt/ $\text{TiO}_2$  sample at room temperature did not change the intensity of the ESR signal. However, evacuation at 573 K after reduction at the same temperature decreased the intensity by approximately two orders of magnitude. On the other hand, evacuation at 573 K of a Pt/ $\text{TiO}_2$  sample reduced at 773 K made the ESR intensity decrease by only a factor of two.

At first glance these results seem inconsistent but one can find a natural explanation if closer attention is paid to the properties of the hydrogen atoms on the  $\text{TiO}_2$  surface. After reduction of the  $\text{Ti}^{4+}$  cation by a hydrogen atom the resulting proton combines with an oxygen anion to form a hydroxyl anion. To compensate the decreased charge of the reduced titanium cation this hydroxyl anion will be in the immediate surroundings of this cation. As long as this hydroxyl anion does not diffuse too far away from its place of birth reactions 1 and 2 may be reversed upon evacuation:



The removal of  $\text{H}^+$  in the form of  $\text{H}_2$  brings about the oxidation of the  $\text{Ti}^{3+}$  ion to a  $\text{Ti}^{4+}$  ion and the decrease of the ESR signal. Also in this reverse process the platinum metal functions as a catalyst by aiding the formation of molecular hydrogen gas.

That no decrease in the ESR intensity is observed after reduction at 773 K followed by evacuation at 573 K must be due to the fact that in this case the reverse reaction cannot take place because the hydroxyl anions have disappeared at high reduction temperatures by dehydration of the  $\text{TiO}_2$  surface:



From the work of Iwaki et al.<sup>11</sup> on pure  $\text{TiO}_2$  it is indeed known that an appreciable loss in weight takes place when  $\text{TiO}_2$  is reduced at temperatures above 673 K. An alternative explanation for the fact that after reduction at 773 K the ESR signal intensity is but weakly influenced by evacuation could be that the platinum is no longer capable of catalyzing the association reaction of hydrogen atoms, or is incapable of transferring protons into hydrogen atoms. This would be in line with observations reported in the literature that Rh/ $\text{TiO}_2$  and Pt/ $\text{TiO}_2$  were incapable of adsorbing hydrogen and of catalyzing the reduction of benzene after a high-temperature reduction.<sup>12</sup> This alternative explanation cannot be excluded completely, but the fact that the protons have left the surface in the form of water molecules<sup>11</sup> means that the reoxidation of the  $\text{Ti}^{3+}$  ions cannot take place, even if the platinum metal was still active.

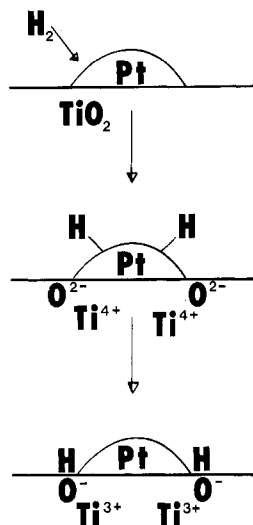
The above explanation of our ESR observation means that in the Pt/ $\text{TiO}_2$  system not only reduction of the support plays an important role but also the intermediary presence of hydroxyl ions. The diffusion of hydrogen atoms from the platinum particles to the surrounding support surface during the formation of protons and reduced titanium ions is related to the so-called spillover phenomenon. In view of the observed catalytic effect of platinum (and of metals such as rhodium and iridium as well, to be published elsewhere<sup>8</sup>) on the formation of  $\text{Ti}^{3+}$  ions it is logical to assume that these  $\text{Ti}^{3+}$  ions are formed around (and beneath) platinum particles in the first place. This is confirmed by an experiment in which hydrogen is admitted at room temperature to a Pt/ $\text{TiO}_2$  sample which had been reduced and evacuated at 573 K. This sample therefore showed a small ESR intensity. After contacting the sample again with hydrogen at room temperature almost 70% of the ESR signal intensity that had been observed after reduction at 573 K was regained. This proves also the reversibility of reactions 1 and 2. The fact that not all the intensity was regained must be due to the

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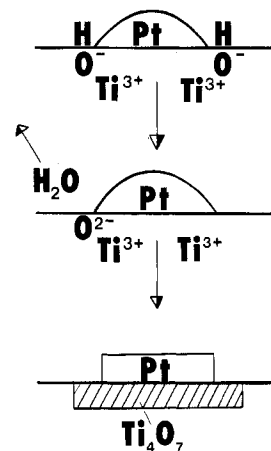


**Figure 2.** Formation of  $\text{Ti}^{3+}$  ions at low reduction temperatures.

smaller diffusivity at room temperature.

The picture that emerges from the ESR experiments is that when small particles of platinum on  $\text{TiO}_2$  are contacted with hydrogen at 573 K a surface layer on  $\text{Ti}^{3+}$  and  $\text{OH}^-$  ions is formed around the metal particles (cf. Figure 2). In a recent publication Gajardo et al. described  $^1\text{H-NMR}$  measurements on the  $\text{Rh}/\text{TiO}_2$  system.<sup>13</sup> After reduction in hydrogen at 573 K and cooling the sample to room temperature under hydrogen they observed a signal ascribed to hydrogen atoms adsorbed on the metal and another signal shifted 140 ppm to higher fields. Because of this large shift they assigned this signal to protons on the support in the proximity of paramagnetic  $\text{Ti}^{3+}$  ions. These findings seem to support our ESR results.

From the figures presented in Table I a semiquantitative estimate can be made of the size of the particle area surrounding the metal particles. After reduction at 573 K 0.3% of the total number of titanium ions is reduced to  $\text{Ti}^{3+}$ . Given a load of 2 wt % Pt on  $\text{TiO}_2$  and assuming the average platinum particle on the support to consist of 100 platinum atoms (dispersion = 0.7,  $\bar{d}$  = 3.1 nm, rafts) this means that on the average 37  $\text{Ti}^{3+}$  ions are present in the neighborhood of each platinum particle. In view of the dimensions of the  $\text{TiO}_2$  lattice cell one may conclude that the hydrogen atoms that are spilled over to the  $\text{TiO}_2$  support occupy an area that has about the size of a cross section through the average platinum particle. Depending on the shape of the metal particle the  $\text{Ti}^{3+}$  and  $\text{OH}^-$  ions may be under the particle if it is spherical- or droplet-like, or around the metal particle if its shape is half-spherical. The ESR results indicate that dehydration of the support



**Figure 3.** Dehydration of the  $\text{TiO}_2$  surface at high reduction temperatures.

takes place at 773 K in the neighborhood of the metal particles; as a result a reduced form of titanium dioxide is formed. In accordance herewith Baker<sup>2</sup> has inferred from electron diffraction measurements that reduction of  $\text{Pt}/\text{TiO}_2$  at 773 K leads to the formation of  $\text{Ti}_4\text{O}_7$  layers at the surface of  $\text{TiO}_2$  and that the noble metal particles spread as rafts over these  $\text{Ti}_4\text{O}_7$  layers. The combination of ESR and electron microscopy techniques suggests that the formation of the so-called SMSI state might be a consequence of the formation of the  $\text{Ti}_4\text{O}_7$  layer. In that case after reduction and dehydration of the support in the neighborhood of the metal particles  $\text{Ti}_4\text{O}_7$  layers are formed and the metal particles start spreading over these layers. We suggest that in this special configuration the properties of the metal undergo a change (Figure 3). The reason for this special interaction between noble metal atoms and the  $\text{Ti}_4\text{O}_7$  layer and thus for the special metal-support interaction has not become clear from the present investigation. If the above explanation for the formation of the SMSI state is correct it is especially the formation of the  $\text{Ti}_4\text{O}_7$  layer which is crucial. Several studies have shown that the SMSI state can be returned to a normal metal-on- $\text{TiO}_2$  state when oxygen or water vapor is admitted to the sample.<sup>14</sup> This is in accordance with the above explanation, since water destroys it by formation of  $\text{OH}^-$  groups, after which the  $\text{Ti}^{3+}$  ion can return to the  $\text{Ti}^{4+}$  state via reaction 3.

*Acknowledgment.* The present investigation has been supported by the Netherlands Foundation for Chemical Research (SON) with financial aid from the Netherlands Organization for the Advancement of Pure Research (ZWO).

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