Selective catalytic reduction of NO\textsubscript{x} with NH\textsubscript{3} over short-range ordered W-O-Fe structures with high thermal stability

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Abstract

The selective catalytic reduction (SCR) of NO\textsubscript{x} with NH\textsubscript{3} was studied over poorly-crystalline W-Fe composite oxides (W\textsubscript{a}FeO\textsubscript{x}). The short-range order present within the W-O-Fe structure was found to be responsible for the excellent SCR activity, in which the strong atomic-level interaction between Fe and W atoms promoted the formation of both Lewis and Brønsted acidity. The W-O-Fe structure existed as amorphous overlayers, approximately 2 nm thick over the surface of crystalline particles after high-temperature aging as shown by high-angle annular dark field scanning transmission electron microscopy (HAADF-STEM). After treatment at 800\degree C for 5 h, the W\textsubscript{a}FeO\textsubscript{x} catalysts still showed almost 100\% NO conversion in the range 300-450\degree C with 100\% N\textsubscript{2} selectivity, despite the loss in surface area. This resistance to the impacts of high temperature ageing guarantees high activity of SCR catalysts which often suffer during high-temperature excursions as in the case of diesel exhaust due to diesel particulate filter (DPF) regeneration.

Keywords: Nitrogen oxides; Selective catalytic reduction; Ammonia; Short-range order; High thermal stability
1. Introduction

Nitrogen oxides (NO\textsubscript{x}, referring to NO and NO\textsubscript{2}) are major air pollutants, which contribute to environmental issues such as acid rain, photochemical smog, atmospheric oxidant ozone increase and haze and harm human health \cite{1, 2}. To reduce these effects, the removal of NO\textsubscript{x} from anthropogenic sources including stationary (coal-fired power plants, etc.) and mobile sources (motor vehicles) is crucial. Selective catalytic reduction (SCR) of NO\textsubscript{x} with NH\textsubscript{3} has proved to be an efficient means of reducing NO\textsubscript{x} emission (deNO\textsubscript{x}) \cite{3-5}. V\textsubscript{2}O\textsubscript{5}-WO\textsubscript{3}/TiO\textsubscript{2} is the most widely used NH\textsubscript{3}-SCR catalyst, which has been commercialized for deNO\textsubscript{x}. However, the disadvantages including the toxicity of vanadium, the narrow operational temperature window, and the deterioration of the structure and constituents after high-temperature aging, restricts its wider application \cite{6, 7}. Development of new catalysts with improved NH\textsubscript{3}-SCR performance and research on active site identification continues. Amorphous active catalysts/active species have attracted considerable attention due to their high activity.

As early as 1990s, the amorphous Cr\textsubscript{2}O\textsubscript{3} catalyst was reported to exhibit superior SCR activity and N\textsubscript{2} selectivity compared to its crystalline counterpart \cite{8, 9}. In 2007, Tang \textit{et al.} found that the amorphous phase of MnO\textsubscript{x} was much more active than its crystalline counterpart at low temperatures \cite{10}. Similar phenomena were also found for composite oxides, for example, amorphous Mn and Ce species were thought to be responsible for SCR activity in Mn-supported TiO\textsubscript{2} \cite{11, 12}, and Ce-Ti mixed oxides \cite{13-15}, respectively. Significantly, the consensus for composite oxides is that short-range ordered structure is the location of as active sites, as in Fe-O-Ti \cite{16-18}, Ce-O-Ti \cite{19}, and Ce-O-W \cite{20} systems, thereby highlighting the pivotal role of atomic-scale interaction.
It is well known that the amorphous structure is characterized by the absence of long-range order [21], which is metastable and readily transformed into the crystalline phase or is to phase separation after high-temperature treatment [22]. Both transformations generally lead to decreased SCR activity [10, 14]. For instance, during the diesel particulate filter (DPF) regeneration, the diesel exhaust gas temperature occasionally rises above 600°C, which may cause severe deactivation of V_2O_5-WO_3/TiO_2 catalysts [23]. Hence, the thermal stability of an SCR catalyst is crucial if it is to withstand such harsh environment. In this study, short-range ordered W-O-Fe active species in poorly-crystalline W-Fe composite oxides (W_aFeO_x) have been developed which exhibit excellent NH_3-SCR activity. Most importantly, the W-O-Fe structure was retained on the surface of a crystalline phase even after aging at 800°C for 5 h. Despite a significant loss in surface area, NO conversion in the range 300-450°C was close to 100% with 100% N_2 selectivity. These findings demonstrate the importance of fabrication of materials with short-range ordered W-O-Fe structure, which are highly dispersed at the outermost surface layer of crystallites after high-temperature and long-term operation.

2. Experimental

2.1 Sample preparation

The W_aFeO_x catalysts (with a W/Fe atomic ratio of a, ICP data) was prepared by a co-precipitation method using an aqueous solution of sodium tungstate (Na_2WO_4·2H_2O, 200 mL) and ferrous sulfate (FeSO_4·7H_2O, 100 mL) with ammonium hydroxide (NH_3·H_2O, 25-28 wt.%) at 35°C, with the pH of the precipitation process maintained above 6.0 and that of the resulting solution maintained at 9.0. The total amount of the metallic salt precursor was 0.03 mol. Ascorbic acid (C_6H_8O_6, 100 mg) was added to the initial iron precursor solution to mol.
ascorbic acid (C₆H₈O₆, 100 mg) was added to the initial iron precursor solution to enhance the reducibility of the Fe²⁺. The obtained slurry was aged at 35°C with stirring for 3 h and subsequently filtrated and washed. The resulting solid was dried overnight at 70°C and calcined at 500°C (or 800°C) for 5 h. For comparison purposes, Fe₂WO₆ was prepared by calcination of a stoichiometric mixture of iron oxide and tungsten oxide [24]. The mechanically mixed catalyst (Fe₂O₃-800+Fe₂WO₆) is thought to simulate the ideal W₀.13FeOₓ catalyst with complete crystallization.

2.2 Sample characterization

X-ray diffraction (XRD) patterns were recorded on a Rigaku D/max-2500/PC diffractometer employing Cu Kα radiation (λ = 1.5418 Å) operating at 50 kV and 200 mA. The Brunauer-Emmet-Teller (BET) surface area and pore structure were measured by N₂ adsorption/desorption using a Micromeritics 2020 M instrument. Before N₂ physisorption, the sample was outgassed at 300°C for 5 h. Inductively coupled plasma-atomic emission spectrometer (ICP-AES) experiments were carried out on the IRIS Intrepid II XSP instrument from Thermo elemental. Field emission scanning electron microscope (FESEM) was performed on a Hitachi SU-70 microscope. High-resolution transmission electron microscopy (HRTEM) equipped with selected area electron diffraction (SAED) and energy dispersive X-ray analysis (EDX) was conducted on a JEOL JEM-2010 microscope at an accelerating voltage of 200 kV. High-angle annular dark field scanning transmission electron microscopy (HAADF-STEM) images were recorded in a Tecnai F20. X-ray photoelectron spectroscopy (XPS) data were obtained on an AXIS-Ultra instrument from Kratos Analytical using monochromatic Al Kα radiation (225 W, 15 mA, 15 kV) and low-energy electron flooding for charge compensation. To compensate for surface charge effects, the binding energies were calibrated using the C 1s
hydrocarbon peak at 284.80 eV. X-ray absorption fine structure (XAFS) measurements at the W L_{III}-edge and Fe K-edge were performed in the transmission mode and fluorescence mode at room temperature on the XAFS station of the 1W1B beamline of Beijing synchrotron radiation facility (BSRF, Beijing, China), respectively. XAFS data were analyzed using IFEFFIT software package [25]. In the least-squares-fitting procedure, the possible scattering paths were also calculated using this software package.

Temperature-programmed reduction in H\textsubscript{2} (H\textsubscript{2}-TPR) was performed in a quartz reactor with a thermal conductivity detector (TCD) to monitor the H\textsubscript{2} consumed. A 50 mg sample was pretreated \textit{in situ} at 500\textdegree C for 1 h in a flow of O\textsubscript{2} and cooled to room temperature in the same gas. TPR was conducted at 10\textdegree C/min to 900\textdegree C in a 30 mL/min flow of 5 vol.% H\textsubscript{2} in N\textsubscript{2}. CuO was used as a calibration reference.

The temperature-programmed desorption of NH\textsubscript{3} (NH\textsubscript{3}-TPD) experiments were performed in a quartz reactor using 50 mg catalyst. NH\textsubscript{3} was monitored using a quadrupole mass spectrometer (MS; OmniStar 200, Balzers) with m/z=16. Prior to the experiments, the samples were pretreated at 500\textdegree C for 30 min in 10 vol% O\textsubscript{2}/He (50 mL/min) and cooled to 100\textdegree C. Sample was exposed to 0.4 % NH\textsubscript{3} (50 mL/min) until the outlet NH\textsubscript{3} concentration was stable. The samples were then purged with He to remove any weakly absorbed NH\textsubscript{3} and then the heated to 800\textdegree C at 10\textdegree C/min.

The \textit{in situ} FTIR spectra of reaction were recorded using a Bruker Tensor 27 spectrometer over the range 4000-400 cm\textsuperscript{-1}, with 16 scans, at a resolution of 4 cm\textsuperscript{-1}. Self-supporting wafers were pretreated in the IR cell at 500\textdegree C in a flow of He for 30 min to remove adsorbed species. After cooling to room temperature (RT) or 100\textdegree C, the background spectrum was recorded. The IR spectra were recorded at RT or 100\textdegree C in a flow of 500 ppm NH\textsubscript{3} + He (150 mL/min)
or 500 ppm NO + 500 ppm NH₃ + 5.3 % O₂ + He (300 mL/min). Samples were then heated to 450°C at 10°C/min.

2.3 Catalytic testing

The steady state SCR and NO oxidation activity over WₓFeOₓ catalysts was tested in a fixed-bed quartz tube reactor (6.0 mm i.d.) with a thermocouple placed inside catalysts in the temperature range of 150-500°C. In the SCR reaction, the model flue gas consisting of 500 ppm NO, 500 ppm NH₃, 5.3 vol.% O₂, 10 vol.%, and balanced with He. The total flow rate maintained at 300 mL/min, corresponding to a gas hourly space velocity (GHSV) of 50000 h⁻¹. In the case of NO oxidation, the feed consisted of 500 ppm NO, and 5 vol.% O₂ with He as balance. The total flow rate kept at 100 mL/min and the same GHSV (50000 h⁻¹) was used. Concentrations of NO and NO₂ were monitored by chemiluminiscence analyzer (42i-HL, Thermo). N₂O and NH₃ were detected by a quadrupole mass spectrometer (MS, OmniStar 200, Balzers) using the m/z signals of 44 for N₂O, and 17 for NH₃. The data for steady-state activities of catalysts were collected after ca. 1 h on stream. The durability tests of the catalysts were performed in the SCR reaction feed at 300°C for 12 h.

The reaction rate was measured using the same conditions as for steady-state reaction. However, in this case, the powder samples were pressed, crushed and sieved (100-200 mesh) prior to use. The GHSV was estimated as 200,000 h⁻¹. Isothermal reactions at 180°C were conducted at a stable and low NOₓ conversion (≤15%) ensuring operation within the kinetic regime.

3. Results and discussion
XRD patterns of $W_aFeO_x$ show the presence of few $Fe_2O_3$ microcrystals in the large-scale amorphous phase [26]. Strong interaction between W and Fe in the $W_aFeO_x$ inhibits crystallization of the individual components during the precipitation process, and results in much higher surface areas [19, 26, 27] and gives rise to the geometry and morphology changes observed (Figure 1). The 3D flower-type structure of $W_aFeO_x$ is composed of numerous irregular nanosheets which randomly stack together. The HAADF-STEM image and corresponding elemental mapping confirmed that the W atoms are incorporated into the rhombohedral matrix of $Fe_2O_3$ [26].

**Figure 1.** SEM images of $W_aFeO_x$ catalysts: (a) $Fe_2O_3$, (b) $WO_3$, (c) $W_{0.09}FeO_x$, (d, e) $W_{0.13}FeO_x$, and (f) $W_{0.17}FeO_x$.

XAFS spectra were measured in order to obtain information about the local environment around the specific atoms in poorly-crystalline $W_aFeO_x$ [19, 28]. The Fe K-edge XANES
spectra and RSF curves for Fe$_2$O$_3$ and W$_a$FeO$_x$ are similar, indicating that the Fe atoms in W$_a$FeO$_x$ are trivalent and exhibit octahedral ($O_h$) coordination, similar to Fe$_2$O$_3$ (Figure S1a) [26]. In the case of the W L$_{III}$-edge, the peak position and shape of the normalized XANES and RSF curves for W$_a$FeO$_x$ correspond with those of Fe$_2$WO$_6$, which implies that most of the hexavalent W atoms in W$_a$FeO$_x$ exist in the same $O_h$ coordination environment as that of Fe$_2$WO$_6$ anions (Figure S1b and c), namely forming W-O-Fe short-range ordered structure [29]. The lower intensity of the RSF curves can be attributed to the higher local disorder level for W$_a$FeO$_x$ [30]. Notably, the disordered structure is strongly reflected in the Debye-Waller factor (DWF, $\sigma^2$), a term appearing in the EXAFS equation that accounts for the level of disorder of a given sample [31, 32]. DWFs for W$_a$FeO$_x$ were obtained by quantitative curve fitting in R-space of the W L$_{III}$-edge EXAFS spectra (Figure 2, Figure S1c and Table S1).
Figure 2. Reaction rates normalized by W contents ($r_W$), Debye-Waller factor (DWF), NH$_3$ adsorption amount for W$_a$FeO$_x$ catalysts; reaction rates ($r_h$) and amount of non-crystalline W species for W$_a$FeO$_x$-800 catalysts.

In our previous studies [26], W$_a$FeO$_x$ promoted NO conversion at low temperature compared with Fe$_2$O$_3$ and WO$_3$ due to the higher surface area and surface W/Fe atomic ratios (Table S2). In the present work, the reaction rates of W$_a$FeO$_x$ normalized by W content ($r_W$) were measured to provide a reliable correlation between the intrinsic activity and the amount of W-containing species. As shown in Figure 2, the $r_W$ at 180°C shows a clear positive correlation with the DWF for W$_a$FeO$_x$, suggesting that the W-O-Fe structure acts as the active sites for W$_a$FeO$_x$ catalysts, as all W atoms participate in the formation of the W-O-Fe structure.
Figure 3. (a) NH$_3$-TPD profiles for Fe$_2$O$_3$, WO$_3$, and W$_x$FeO$_{x-c}$ catalysts; *in situ* FTIR spectra of NH$_3$ exposed to (b) Fe$_2$O$_3$ and (c) W$_{0.13}$FeO$_x$ at room temperature and subsequently heated to 350°C in a flow of He.

To further clarify how the chemical properties of W$_x$FeO$_x$ were improved by the presence of short-range ordered W-O-Fe structures, the redox properties and acidity were assessed, as these are key characteristics associated with the SCR activity [7, 33-35]. As shown in the H$_2$-TPR (Figure S2), the reduction of the Fe species was delayed for W$_x$FeO$_x$ in comparison with Fe$_2$O$_3$, suggestive of interactions between W and Fe [36]. On the other hand, NH$_3$-TPD spectra show a greater amount of ammonia desorption in the range 100-500°C (NH$_3$ adsorption on WO$_3$ is negligible) (Figure 3a), indicating numbers of acid sites in W$_x$FeO$_x$. By using the integrated NH$_3$-TPD peak areas, the relative amounts of adsorbed NH$_3$ show a clear correlation with the reaction rates of W$_x$FeO$_x$ (Figure 2), suggesting that the enhanced activity is primarily related to the enhanced acidity derived from the strong interactions in the W-O-Fe structure.

To study the nature of species adsorbed on sites within the short-range ordered W-O-Fe structure during NH$_3$ exposure, *in situ* FTIR spectra were collected (Figure 3b and c). Fe$_2$O$_3$ does not show evidence for Lewis acidity although Brønsted acid sites are detected (~1437 cm$^{-1}$, Figure 3b). The coordinated NH$_3$ (~1202 and 1600 cm$^{-1}$) suggests the presence of Lewis acidity on W$_{0.13}$FeO$_x$ (Figure 3c) [12]. As for Brønsted acidity, a greater intensity peak ~1440 cm$^{-1}$ was observed for W$_{0.13}$FeO$_x$ than Fe$_2$O$_3$. The increase in amounts of both the Lewis and Brønsted acidity promotes catalytic activity [37-42]. With increasing temperature, both the peak intensities due to adsorption at Lewis and Brønsted acid sites decreased, with the later exhibiting lower thermal stability compared with ammonia on Lewis acid sites. The band at ~1417 cm$^{-1}$ nearly
disappeared at 350°C, whereas the band at 1238 cm\(^{-1}\) is still clearly observed. An additional band at \(\sim 1361\) cm\(^{-1}\) was observed which could be ascribed to an oxidised product of adsorbed ammonia [38, 43, 44]. These results provide persuasive evidence that the atomic-scale interaction in the short-range ordered W-O-Fe structure enhances both Lewis and Brønsted acidity of the catalysts and these are favorable for catalytic activity.

Figure 4. XRD patterns of Fe\(_2\)O\(_3\)-800, Fe\(_2\)WO\(_6\), and W\(_x\)FeO\(_x\)-800 catalysts.

Table 1. Textural properties, XRD and ICP data of Fe\(_2\)O\(_3\)-800 and W\(_x\)FeO\(_x\)-800 catalysts.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Surface area (m(^2)/g)</th>
<th>Pore volume (cm(^3)/g)</th>
<th>Pore size (nm)</th>
<th>Fe(_2)WO(_6) concentration from XRD (wt.%)</th>
<th>W mass concentration from ICP[26] (wt.%)</th>
<th>W contents in Fe(_2)WO(_6) phase (wt.%)</th>
<th>Non-crystallized W contents (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W(_{0.09})FeO(_x)-800</td>
<td>23.7</td>
<td>0.0843</td>
<td>16.4</td>
<td>4.42</td>
<td>16.4</td>
<td>2.1</td>
<td>14.3</td>
</tr>
<tr>
<td>W(_{0.13})FeO(_x)-800</td>
<td>20.0</td>
<td>0.0573</td>
<td>14.1</td>
<td>12.82</td>
<td>23.2</td>
<td>6.0</td>
<td>17.2</td>
</tr>
</tbody>
</table>
To determine the stability of the short-range ordered W-O-Fe structure at higher temperature, the $W_aFeO_x$ samples were calcined at high temperature (800°C, 5 h) (denoted as $W_aFeO_x$-800). An increase in calcination temperature (Figure 4), results in the emergence of a new phase, Fe$_2$WO$_6$ (JCPDS 70-0495) in addition to Fe$_2$O$_3$, indicating a transformation from amorphous to crystalline. This confirmed the XAFS results that W in $W_aFeO_x$ exists in the $O_h$ coordination environment as in Fe$_2$WO$_6$. From quantitative analysis of W concentrations (wt.%) in Fe$_2$WO$_6$ phase over different samples on the basis of XRD data, it is interesting to note that the concentrations are lower than those obtained by ICP, suggesting that only a part of the amorphous W-containing species in $W_aFeO_x$ are transformed into Fe$_2$WO$_6$ crystallites, while the other remains in an amorphous state (Table 1). As shown in Table 1, $W_{0.13}FeO_x$-800 possesses the highest non-crystallized W content. As expected, the BET surface area was significantly decreased on increasing the calcination temperature.

SCR performances of $W_aFeO_x$-800 catalysts show that the increasing calcination temperature resulted only in the decrease of low-temperature activity due to the decreased BET surface area, but had no clear influence on the high-temperature activity (Figure 5). Furthermore, NO$_x$ conversion for $W_{0.13}FeO_x$-800, as an example, was stable over a 12 h test period (Figure S3). The high activity at 300-450°C compared with the low activity of Fe$_2$O$_3$-800 might be ascribed to Fe$_2$WO$_6$ microcrystals or the synergistic effect of Fe$_2$O$_3$ and Fe$_2$WO$_6$ microcrystals. However, this proposal is rejected based on the poor SCR activity of pure Fe$_2$WO$_6$ and Fe$_2$O$_3$-800+Fe$_2$WO$_6$ samples (Figure 5). The latter is thought to simulate the ideal $W_{0.13}FeO_x$ catalyst with complete
crystallization. It remains unanswered as to whether the retained activity is related with the residual amorphous phase and where these are located.

Figure 5. (a) NO<sub>x</sub> conversion and (b) N<sub>2</sub> selectivity of W<sub>x</sub>FeO<sub>x</sub>-800 catalysts and reference samples.
Figure 6 shows TEM images for $W_{0.13}FeO_x$-800. The well-crystallized Fe$_2$O$_3$ and Fe$_2$WO$_6$ microcrystals are randomly aggregated for $W_{0.13}FeO_x$-800 (Figure 6a). Based on the extensive characterization, the Fe$_2$WO$_6$ phase consists of long-range ordered W-O-Fe structures, which are derived from the sintering of the coordinated W, O, and Fe atoms in amorphous phase (Figure S4). HRTEM was used to provide directly interpretable images of $W_{a}FeO_x$-800 to search for the remaining amorphous phases (Figure 6b-d). Surprisingly, an amorphous phase layer of ~2 nm thickness was detected on the surfaces of Fe$_2$WO$_6$ and Fe$_2$O$_3$ microcrystals for $W_{0.13}FeO_x$-800. According to the semi-quantitative analysis of surface atomic concentrations (% as molar ratio) over $W_{0.13}FeO_x$-800 from XPS data, the surface W/Fe atomic ratio was 0.48, which is much higher than the surface and bulk ratios for $W_{0.13}FeO_x$ (XPS and ICP data [26], respectively, Table S2), suggesting an enrichment of amorphous W-containing species on the surface.
Figure 6. (a) TEM images with SAED patterns (insets), (b-d) HRTEM images for W_{0.13}FeO_x-800.

Figure 7. HRTEM images and EDX analysis of Fe_2O_3 and Fe_2WO_6 nanoparticles in W_{0.13}FeO_x-800 catalyst: (a) HRTEM bright-field image, (b) HAADF image, and (c) EDX mapping results of the region in the yellow dashed box for a Fe_2O_3 nanoparticle; (d) HRTEM bright-field image (e) HAADF image, and (f) EDX mapping results of the region in the yellow dashed box for a Fe_2WO_6 nanoparticle.

The chemical composition of the amorphous overlayer was determined by HAADF-STEM in conjunction with the corresponding EDX mappings (Figure 7). The latter was acquired from both the overlayer and the inside of Fe_2O_3 and Fe_2WO_6 nanoparticles. HAADF-STEM clearly
shows that the Fe atoms are homogeneously distributed over the Fe2O3 nanoparticle, while the W atoms are detected primarily on the surface of the amorphous overlayers of the Fe2O3 nanoparticles (Figure 7a-c). EDX gives a W/Fe molar ratio of about 0.08 for the amorphous overlayer on the Fe2O3 nanoparticle, which is much higher than that in the Fe2O3 nanoparticle (0.01), suggesting that W atoms are primarily doped in the amorphous Fe-O overlayer of the Fe2O3 nanoparticle (Figure 7a-c), with similar short-range ordered W-O-Fe structure as in W₉FeOₓ. Comparatively, HAADF-STEM images of the Fe₂WO₆ nanoparticle show Fe and W atoms throughout the whole section (Figure 7d-f). EDX indicates that the W/Fe molar ratio of the overlayer on the Fe₂WO₆ nanoparticle is 1.00, consistent with that of the short-range ordered W-O-Fe structure. On extending to the inside of the Fe₂WO₆ nanoparticle, the W/Fe molar ratio decreases to 0.60, which is very close to that of the bulk Fe₂WO₆. The above analysis confirms that the non-crystallized W species as derived from XRD are mainly located in the amorphous overlayers of the Fe₂O₃ and Fe₂WO₆ nanoparticles, which agrees well with the XPS. Consequently, the retained high-temperature activity of W₉FeOₓ-800 is a consequence of the amorphous phase on the surface of microcrystals.

Following the same strategy as applied to W₉FeOₓ, the reaction rates (rₑ) of W₉FeOₓ-800 were also measured (Figure 2). Apparently, the variation of rₑ correlates well with the amount of amorphous W-containing species (Figure 2 and Table 1), providing proof that the intrinsic activity was derived from the W-O-Fe structure on the surface amorphous overlayer. In other words, the short-range ordered W-O-Fe active sites in W₉FeOₓ were retained in the W₉FeOₓ-800 in the form of the surface amorphous overlayer, which ensures retained the high-temperature activity at 300-450°C after aging at 800°C for 5 h.
4. Conclusions

Poorly-crystalline W-Fe composite oxides ($W_{a}FeO_{x}$), consisting of short-range ordered W-O-Fe structures were prepared. A direct correlation between the level of disorder and the intrinsic activity indicated that the short-range ordered W-O-Fe structure hosts the active catalytic sites. Strong atomic-level interactions between Fe and W atoms within the disordered W-O-Fe structure was shown and this enhanced the amounts of Lewis and Brønsted acidity, leading to improved deNO$_x$ activity. Of significance, the short-range ordered W-O-Fe structure was retained as amorphous overlayers over the surface of crystalline particles after aging at 800°C for 5 h, leading to the retention of activity. This finding may open up new pathways in the fabrication of the active deNO$_x$ catalysts with high thermal stability by rationally enhancing atomic-scale interactions between heteroatoms in composite oxides.

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