Synthesis of CrO$_x$/C catalysts for low temperature NH$_3$-SCR with enhanced regeneration ability in the presence of SO$_2$†

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Chromium oxide nano-particles with an average diameter of 3 nm covered by amorphous carbon (CrO$_x$/C) were successfully synthesized. The synthesized CrO$_x$/C materials were used for the selective catalytic reduction of NO$_x$ by NH$_3$ (NH$_3$-SCR), which shows superb NH$_3$-SCR activity and in particular, satisfactory regeneration ability in the presence of SO$_2$ compared with Mn-based catalysts. The as-prepared catalysts were characterized by XRD, HRTEM, Raman, FTIR, BET, TPD, TPR, XPS and in situ FTIR techniques. The results indicated presence of certain amounts of unstable lattice oxygen exposed on the surface of CrO$_x$ nano-particles with an average size of 3 nm in the CrO$_x$/C samples, which led to NO being conveniently oxidized to NO$_2$. The formed NO$_2$ participated in NH$_3$-SCR activity, reacting with catalysts via a “fast NH$_3$-SCR” pathway, which enhanced the NH$_3$-SCR performance of the CrO$_x$/C catalysts. Furthermore, the stable lattice of the CrO$_x$ species made the catalyst immune to the sulfation process, which was inferred to be the cause of its superior regeneration ability in the presence of SO$_2$. This study provides a simple way to synthesize stable CrO$_x$ nano-particles with active oxygen, and sheds light on designing NH$_3$-SCR catalysts with highly efficient low temperature activity, SO$_2$ tolerance, and regeneration ability.

1. Introduction

Low-temperature NH$_3$-SCR (<200 °C), which can be located downstream of electrostatic precipitators and even desulfurizers, where most of SO$_2$ and dust have been removed, has been paid increasing attention in the past few decades. Various transition metal oxides exhibit satisfactory activity for low-temperature NH$_3$-SCR, such as Mn, Fe, Cu, and Co. Among them, Mn-based catalysts have become a focus for their excellent low-temperature activity and inherent environment-friendly nature. According to literature, Mn-based catalysts have a unique advantage for low-temperature SCR (<200 °C) in contrast with other competitors. For example, Hu et al. reported a Co–Mn/TiO$_2$ catalyst with superior NH$_3$-SCR activity at 200 °C. Mn–Ce–Ti mix-oxide catalysts were recorded to exhibit an operating temperature window from 150 °C to 200 °C. We also reported Mn–Fe–Ti mix-oxide catalysts with satisfactory NH$_3$-SCR activity from 100 °C to 350 °C. However, the poor SO$_2$ resistance performance of Mn-based catalysts limits their practical application.

According to the previous reports, the tolerance of metal oxide based catalysts to SO$_2$ depends on the type and oxidation state of the deposited metal, the nature of the support, and the type of reducing agent. In general, the rapid deactivation of NH$_3$-SCR catalysts involves two main mechanisms. One is the formation of ammonium salts. The SO$_2$ in the feed gas can be oxidized to SO$_3$ on the surface of the catalysts, and the formed SO$_3$ would respond to NH$_3$ and water in feed gas transforming to NH$_4$HSO$_4$. The formed NH$_4$HSO$_4$ would deposit on the surface of the catalysts, cover active sites, block pores of the catalysts, and result in the deactivation of the catalysts. The other fact is the irreversible sulfation of the active phase. For most transition metal oxides usually reported as NH$_3$-SCR catalysts, such as Mn, Fe, Cu, and Co, all sulfating processes are spontaneous according to their Gibbs free energy values (Table S1†). In the sulfation process, formation of a metal sulfate requires breaking the metal oxide lattice. It is reasonable to predict that the more stable the metal oxides, the more difficult it is to break the metal oxide lattice and thus, harder is the sulfation of metal oxide. In general, the metal oxide with a high melting point has...
a stable crystal lattice. Thus, the melting point can be an indicator of the stability of the crystal lattice of metal oxides.\textsuperscript{34} In the case of Mn-based catalysts, MnO\textsubscript{2} has a low melting point (Table S1\textsuperscript{†}), indicating its unstable structure, which is the cause of the severe irreversible sulfation of MnO\textsubscript{2} in the NH\textsubscript{3}-SCR process, particularly in the low temperature range (<200 °C).\textsuperscript{13,14,25–28} Cr\textsubscript{2}O\textsubscript{3}, which has the highest melting point among the transition metal oxides with NH\textsubscript{3}-SCR activity (listed in Table S1\textsuperscript{†}), was expected to have resistance to the sulfation process. Although the low NH\textsubscript{3}-SCR activity of crystalline Cr\textsubscript{2}O\textsubscript{3} is unsatisfactory, amorphous Cr\textsubscript{2}O\textsubscript{3} exhibits superb low temperature NH\textsubscript{3}-SCR activity, according to literature.\textsuperscript{29–31} Thus, it appears to be a promising strategy to design a SCR catalyst with both low temperature activity and SO\textsubscript{2} tolerance via enhancing the catalytic activity of crystalline Cr\textsubscript{2}O\textsubscript{3}.

Compared with traditional metal oxide catalysts with a large particle size, nano-sized catalysts often have significant amounts of unsaturated-coordinated atoms exposed on their surfaces. Unsaturated-coordinated atoms are usually active; thus, nano-sized catalysts exhibit unique redox ability and enhanced catalytic activity.\textsuperscript{34–36} Therefore, decreasing the size of catalysts appears to be a promising strategy to enhance low temperature NH\textsubscript{3}-SCR performance of crystalline Cr\textsubscript{2}O\textsubscript{3}. However, nano-particle materials have the disadvantage of instability and tend to aggregate due to their high surface energy and their abundant surface unsaturated atoms. Recently, metal oxide nano-particles catalysts derived from MOFs material were reported.\textsuperscript{37–39} Through a thermal decomposition process under controlled atmosphere, MOFs built from metal ions or nodes and polyfunctional organic ligands can transform into nano-materials, including nano-particles, single atoms, and metal oxide clusters. Wu \textit{et al.}\textsuperscript{40} synthesized Co nano-particles and single atoms from Co MOF and Co/Zn bimetallic MOF. Similar results were also reported by Li \textit{et al.}\textsuperscript{7} and Sun’s group.\textsuperscript{41} The carbon from the organic ligands of MOFs remains in materials and can protect metal oxide nano-particles from aggregation.

Herein, novel CrO\textsubscript{2} nano-particles covered by amorphous carbon (CrO\textsubscript{2}/C) have been synthesized by a MOFs assisted process for low temperature NH\textsubscript{3}-SCR. MIL-101, with a metal node of 3 Cr atoms,\textsuperscript{42,43} was employed as a precursor. The results of the catalytic tests for NH\textsubscript{3}-SCR showed that the prepared CrO\textsubscript{2}/C catalyst exhibited satisfactory activity and superior regeneration ability. According to a series of characterizations, the CrO\textsubscript{2}/C catalyst was observed to be composed of CrO\textsubscript{2} nano-particles with an eskolaite phase and activated lattice oxygen. It was deduced that the activated lattice oxygen was closely related to the enhanced NH\textsubscript{3}-SCR activity of the CrO\textsubscript{2}/C catalyst. The stable lattice of the eskolaite phase-CrO\textsubscript{2} inhibited the sulfating process, thus causing the SO\textsubscript{2} tolerance and regeneration ability. To the best of our knowledge, it is the first time that a non-Mn catalyst with excellent low temperature NH\textsubscript{3}-SCR activity and remarkable regeneration ability has been reported. This study provides a simple route to synthesize stable CrO\textsubscript{2} nano-particles with active oxygen and shed light on designing low temperature NH\textsubscript{3}-SCR catalysts with SO\textsubscript{2} tolerance and regeneration ability.

## 2. Experimental details

### 2.1. Preparation of catalysts

Typically, MIL-101(Cr) was prepared by reacting terephthalic acid (332 mg, 2.0 mmol) with Cr(NO\textsubscript{3})\textsubscript{3}·9H\textsubscript{2}O (800 mg, 2.0 mmol) and de-ionized water (9.5 mL) at 220 °C for 8 h. Microcrystalline green powders of MIL-101(Cr) were produced during the reaction. The obtained powders were washed by ammonium hydroxide, water, and ethanol, in sequence, 3 times each. The powders were dried and calcined at a certain temperature for 4 h under N\textsubscript{2} flow, and the heating rate was set at 1 °C min\textsuperscript{−1}. Finally, the cooled sample was exposed to air and denoted as Cr\textsubscript{2}O\textsubscript{3}/C-X, in which X represents the calcining temperature.

As reported in ref. 44, a Cr\textsubscript{2}O\textsubscript{3} sample was obtained by calcining Cr(NO\textsubscript{3})\textsubscript{3}·9H\textsubscript{2}O at 450 °C for 4 h. MnO\textsubscript{2} was purchased from Aladdin and was used without further purification. An active carbon supported Cr\textsubscript{2}O\textsubscript{3} catalyst was synthesized through a wetness impregnation process. Active carbon (1.00 g) was dispersed into de-ionized water (50 mL) containing Cr(NO\textsubscript{3})\textsubscript{3}·9H\textsubscript{2}O (9.92 g). The turbid solution was oil-bath heated at 110 °C until the water was totally evaporated. The dried powders were calcined at 450 °C for 4 h under a N\textsubscript{2} flow and the obtained sample was noted as Cr\textsubscript{2}O\textsubscript{3}/C-WI.

### 2.2. Characterizations

The X-ray diffraction (XRD) patterns of the catalysts were studied using an XRD-6000 X-ray diffractometer (Shimadzu). X-ray fluorescence (XRF) analysis was performed on an ARL-900 X-ray fluorescence analyzer. FTIR analysis was carried out using a NEXUS670 spectrometer (NICOLET, America). Raman spectra were measured at a resolution of <1 cm\textsuperscript{−1} using a JY Labram HR 800 spectrophotometer equipped with an argon-ion laser source and an air-cooled CCD detector. N\textsubscript{2} adsorption/desorption isotherms of the catalysts were obtained at −196 °C using an ASAP2020 physical adsorption instrument (Micromeritics) to calculate the BET surface area of the catalysts. TEM analysis was performed on a double-aberration corrected Titan™ cubed G2 60-300 S/TEM equipped with Super-X™ technology. X-ray energy dispersive spectroscopy (EDS) mappings were acquired using the Super-X EDS system, which is composed of four silicon drift detectors covering 0.7 s rad collection.

NH\textsubscript{3}-temperature programmed desorption (NH\textsubscript{3}-TPD) experiments were performed using a multifunction chemisorption analyzer, equipped with a thermal conductivity detector (TCD). Samples were pretreated under a NH\textsubscript{3}–N\textsubscript{2} flow (NH\textsubscript{3} 1%) at 150 °C for 1 h and were heated under N\textsubscript{2} flow; the heating rate was set at 10 °C min\textsuperscript{−1}.

O\textsubscript{2}-temperature programmed desorption (O\textsubscript{2}-TPD) experiments were performed using a multifunction chemisorption analyzer, equipped with a thermal conductivity detector (TCD). Samples were pretreated under O\textsubscript{2}–He flow (O\textsubscript{2} 25%) at 25 °C for 1 h and were heated under a He flow; the heating rate was set at 10 °C min\textsuperscript{−1}.

H\textsubscript{2}-temperature programmed reduction (H\textsubscript{2}-TPR) of the catalysts was recorded using a chemisorption analyzer. Samples were pretreated under a N\textsubscript{2} flow at 200 °C for 1 h, and were
heated under a H₂−Ar flow (H₂, 7%); the heating rate was set at 10 °C min⁻¹.

X-ray photoelectron spectroscopy (XPS) measurements were performed using a PHI 5000 VersaProbe spectrophotometer. The contents of the metal ions were measured via an inductive coupled plasma emission spectrometer (Optima 5300DV, PE). Energy referencing was accomplished by setting the adventitious carbon peak to 284.6 eV. The ex situ XPS details are described below. The sample was treated under a certain atmosphere for a certain time in a reaction chamber connected with the intro chamber of the XPS instrument. Following this, the reaction chamber was vacuumized and the treated sample was transferred to the XPS instrument without exposure to air.

The in situ DRIFT experiments were performed on a Nicolet Nexus 5700 FTIR spectrometer using a diffuse reflectance attachment (HARRICK) equipped with a reaction cell (ZnSe windows). The number of scans was 32 at a resolution of 4 cm⁻¹ and the spectra were presented as Kubelka–Munk function, referred to the background spectra of the recorded catalyst in N₂.

2.3. NO oxidation tests

The NO oxidation tests were performed in a fixed-bed reactor with 0.2 g catalyst. The feed gas contained 500 ppm NO and 5 vol% O₂ with N₂ as the balance gas. The total flow rate of the feed gas was 100 mL min⁻¹, corresponding to a space velocity of approximately 30 000 h⁻¹. Including NO and NO₂, the effluent gases were continuously analyzed at 150 °C by an online Thermo Fisher IS10 FTIR spectrometer equipped with a 2 m path-length gas cell (250 mL volume).

2.4. NH₃-SCR activity, SO₂ poisoning, and regeneration tests

The NH₃-SCR activity tests were performed in a fixed-bed reactor with 0.2 g catalyst. The feed gas contained 500 ppm NO, 500 ppm NH₃, 5 vol% O₂, 50 ppm SO₂ (when used), 5 vol% H₂O (when used) and N₂ as the balance gas. The total flow rate of the feed gas was 100 mL min⁻¹, corresponding to a space velocity of approximately 30 000 h⁻¹. SO₂ poisoning and regeneration tests of catalysts were carried out at 150 °C. Including NO, NH₃, NO₂, and N₂O, the effluent gases were continuously analyzed at 150 °C using an online Thermo Fisher IS10 FTIR spectrometer equipped with a 2 m path-length gas cell (250 mL volume).

2.5. Regeneration of SO₂ poisoned catalysts

SO₂ poisoned catalysts were regenerated at 300 °C for 30 min, and then were cooled down to room temperature. All the heat treatments were carried out under N₂ atmosphere.

The sulfination of metal oxide catalysts during SO₂ poisoning was investigated by inductively coupled plasma-emission spectroscopy (ICP).

The SO₂-poisoned catalyst (0.2 g) was washed with deionized water for 5 times. The eluate was collected and diluted to 50 mL. The diluted eluate was investigated by ICP analysis. The contents of metal sulfate \( m_{\text{MSO}_4} \) were calculated using the equation below.

\[
m_{\text{MSO}_4} = \frac{m_{\text{Me}^{x+}} \times 0.05L \times M_{\text{MSO}_4}}{M_{\text{M}}}
\]

where, \( m_{\text{Me}^{x+}} \) is the content of the metal ion, \( M_{\text{MSO}_4} \) was obtained via ICP analysis and \( M_{\text{M}} \) is the molar mass of metal sulfate, which also corresponds to the molar mass of the metal ion.

For Cr oxide, \( m_{\text{Cr}_{x}(\text{SO}_4)_{y}} = m_{\text{Me}^{x+}} \times 0.188 \)

For Mn oxide, \( m_{\text{MnSO}_4} = m_{\text{Me}^{x+}} \times 0.137 \)

3. Results and discussion

3.1. NH₃-SCR performance, SO₂ tolerance, and regeneration

The NH₃-SCR activities of the CrO₃ samples derived from various precursors and MnO₂ are shown in Fig. 1 and S1†. As it was anticipated, all the catalysts derived from MIL-101 exhibited superior activities than pure Cr₂O₃. Remarkably, CrO₃/C-450, parallel to MnO₂, exhibited a wide operation temperature window from 125 °C to 200 °C. The activity of CrO₃/C-WI was enhanced compared with pure Cr₂O₃, while it was much lower than CrO₃/C-450. This extraordinarily low temperature NH₃-SCR performance makes CrO₃/C-450 the best catalyst among all the samples derived from MIL-101. To evaluate the NH₃-SCR performances on the catalysts more precisely, the normalized rates per mole transition metal were calculated and the results are displayed in Fig. 2a. The catalytic activity order is CrO₃/C-450 > MnO₂ > CrO₃/C-WI > Cr₂O₃. In addition, the apparent active energies of CrO₃/C-450 and Cr₂O₃ based catalysts were obtained when NO conversions were limited to low conversion (Fig. 2b and Table S2†). The apparent active energy of NH₃-SCR on the CrO₃/C-450 catalyst was lower than those of SCR on CrO₃/C-WI and Cr₂O₃, which further confirms the superb catalytic activity of the CrO₃/C-450 sample. Based on the kinetics data listed in Tables S3 and S4† apparent kinetics equations of NH₃-SCR on CrO₃/C-450 and CrO₃/C-WI catalysts were obtained (Fig. S2†). For CrO₃/C-450, \( r = \frac{[\text{NH}_3]^{0.586}[\text{NO}]^{0.964}}{M_{\text{M}}} \) at 150 °C, while for Cr₂O₃/C-WI, \( r = \frac{[\text{NH}_3]^{0.433}[\text{NO}]^{0.092}}{M_{\text{M}}} \). The different reaction rate equations of NH₃-SCR on CrO₃/C-450 and CrO₃/C-WI catalysts indicated their different reaction mechanisms, which may result in different NH₃-SCR performance of CrO₃/C-450 and Cr₂O₃/C-WI catalysts. The N₂ selectivity of CrO₃/C-450 remained at a high level (over 90%) in its operation temperature window, while those of Cr₂O₃ and MnO₂ were very poor. This indicated that side reactions such as the formation of N₂O hardly occurred on the CrO₃/C-450 catalyst. SO₂- and H₂O-tolerance of CrO₃/C-450 was further tested and the results are presented in Fig. 1c and S1c†. CrO₃/C-450 exhibited over 80% NO conversion within 24 h in the presence of H₂O₂, indicating its satisfactory water tolerance. When SO₂ was introduced into the feed gas, the activity of CrO₃/C-450 gradually dropped to 60% within 20 h, while it dropped to 50% in 20 h when SO₂ and H₂O co-existed in the feed gas. The activity of CrO₃/C-450 could be recovered after a heat treatment at a temperature as low as 300 °C. This indicated that the poisoning effect of SO₂ on CrO₃/C-450 could be accelerated by H₂O, while H₂O hardly influenced the regeneration ability of CrO₃/C-450. In contrast, the MnO₂ catalyst...
deactivated rapidly upon SO_{2} introduction in 6 h, and this process was irreversible. It was demonstrated that the CrO_{x}/C-450 catalyst has satisfactory SO_{2}-tolerance. The regeneration ability of CrO_{x}/C-450 was further studied. As shown in Fig. 1d, over 90% of the catalytic activity of CrO_{x}/C-450 could be recovered as compared to that of the fresh catalyst after 3 poisoning–regeneration cycles irrespective of whether H_{2}O was introduced by regeneration at 300 °C in flowing N_{2}, while that of MnO_{2} catalyst dropped dramatically through only 1 poisoning–regeneration cycle, which indicated the remarkable regeneration ability of the CrO_{x}/C-450 sample.

3.2. Structural information
To investigate the NH_{3}-SCR on the catalysts, the structural information of catalysts was necessary. XRD, XRF, FTIR, Raman, and TEM analyses were carried out to investigate the structural properties of the catalysts synthesized from MIL-101(Cr). The XRD patterns of all samples are shown in Fig. S3.\(^\dagger\) In the XRD pattern of the precursor, sharp and distinct peaks attributed to the MIL-101 phase were detected, which is in agreement with the data reported by Jhung \textit{et al.}\(^\text{43}\) When MIL-101 was heated in N_{2}-flow, the XRD peaks of MIL-101 became weak and gradually disappeared with an increase in
temperature. When the calcining temperature reached 450 °C, the peaks of the MIL-101 phase disappeared completely and replaced with wide and weak peaks at 24.5°, 33.5°, and 36.1°, which belonged to the (012), (104), and (110) plane, respectively, of the eskolaite phase (PDF#38-1479) as well as Cr2O3/C-WI. This indicated that the MIL-101 structure could be destroyed through the calcining process, accompanied with the formation of the eskolaite phase. Furthermore, the CrOx/C-450 sample was found to have a small particle size based on its broad XRD peaks.

FTIR and Raman analyses were carried out to study the carbon species in the catalysts. As shown in Fig. S4a, the bands at 3300 cm\(^{-1}\), 1600 cm\(^{-1}\), and 1400 cm\(^{-1}\) were identified in the FTIR spectra of MIL-101. The broad band at 3300 cm\(^{-1}\) arises due to the stretching vibration of the surface –OH groups. The two bands at 1600 and 1400 cm\(^{-1}\) could be attributed to the stretching vibration of the –COO group of the organic linkers of MIL-101. However, the intensity of bands at 1600 cm\(^{-1}\) and 1400 cm\(^{-1}\) decreased on increasing the calcination temperature. This indicates that the organic linker begins to decompose and carbonize when the calcining temperature increases. The carbonization process was further investigated by Raman analysis (Fig. S4b). Wide bands at 1360 and 1590 cm\(^{-1}\), corresponding to the D-band and G-band of MIL-101, were detected in the samples calcined at low temperatures, such as 350 and 400 °C. When the calcining temperature increased, the G-band gradually disappeared and the D-band still remained, which indicated the loss of the ordered structure of MOFs and the formation of amorphous carbon. In the spectrum of Cr-550, the G-band disappeared absolutely and only a wide D-band was observed. This illustrates that the organic linker carbonized and transformed to amorphous carbon during the calcining process, which accompanied with the destruction of the MOFs structure.

The elemental contents of catalysts were studied via XRF analysis. Since the organic species in MIL-101 completely transformed to amorphous carbon in CrOx/C-450, as mentioned before, the ignition loss in XRF analysis of CrOx/C-450 was believed to be the result of carbon species burning. Thus, the elemental contents of the catalysts could be calculated from the XRF data and the results are shown in Table 1. The CrOx/C-450 catalyst consisted of 19.2% Cr, 28.7% O, and 52.0% C. As it was designed, the elemental contents of CrOx/C-WI were similar to those of CrOx/C-450.

**Table 1** Element contents and surface areas of catalysts

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cr2O3 (wt%)</th>
<th>Ignition loss</th>
<th>Cr (at%)</th>
<th>O (at%)</th>
<th>C (at%)</th>
<th>Sample</th>
<th>Carbon support (m² g⁻¹ catalyst)</th>
<th>Active material</th>
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<tbody>
<tr>
<td>CrOx/C-450</td>
<td>70.2</td>
<td>29.8</td>
<td>19.2</td>
<td>28.7</td>
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<tr>
<td>Cr2Ox/C-WI</td>
<td>69.5</td>
<td>30.5</td>
<td>18.9</td>
<td>28.4</td>
<td>52.7</td>
<td>279</td>
<td>897</td>
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</tr>
<tr>
<td>Cr2Ox</td>
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<td>0.1</td>
<td>40.0</td>
<td>60.0</td>
<td>—</td>
<td>28</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

\(^a\) Contents of catalysts were obtained from XRF analyses. \(^b\) Surface areas of catalysts were obtained from N\(_2\) adsorption/desorption analyses. \(^c\) Carbon support of CrOx/C-450 catalyst was obtained by washing CrOx/C-450 using hydrochloric acid. Carbon support of CrOx/C-WI is active carbon.
designed in this study. The CrO$_2$/C-450 sample after 3 poisoning–regeneration cycles was also imaged to investigate the stability of the catalyst (Fig. S5b†). The used sample was primarily composed of CrO$_x$ nano-particles, similar to the fresh sample, and no major difference in the particle size of Cr$_2$O$_3$ could be observed after 5 deactivation–regeneration cycles, which evidently proved the stability of the sample CrO$_x$/C-450. Cr$_2$O$_3$ and Cr$_2$O$_3$/C-WI, however, had a bulk-like shape (Fig. S5c and d†) with average particle sizes of over 100 nm. In the structure of the MIL-101 precursor, metal nodes containing 3 Cr atoms were covered by organic linkers. Therefore, it is reasonable to suggest that Cr$_2$O$_3$ nano-particles in the CrO$_x$/C-450 catalyst stabilized by covering carbon species transformed from organic linkers of MIL-101 after the calcining process.

The feasible mechanism of catalyst synthesis is displayed in Fig. 4. During the calcination process, organic linkers covering Cr nodes carbonized and the structure of MIL-101 gradually destroyed. The amorphous carbon from organic linkers limited the growth of Cr nodes. Finally, when the calcined sample was exposed to air, the remaining Cr nano-particles were oxidized to CrO$_x$ nano-particles with eskolaite phase, forming the structure of amorphous carbon covered Cr$_2$O$_3$ nano-particles (CrO$_x$/C).

### 3.3. Textural properties of catalysts

As mentioned before, the CrO$_x$/C-450 catalyst was primarily formed by CrO$_x$ nano-particles with eskolaite phase and exhibited enhanced NH$_3$-SCR activity and satisfying regeneration ability. To explore the relationship between the structure of CrO$_x$/C-450 and the NH$_3$-SCR performance, the properties of the catalysts were characterized by BET, XPS, H$_2$-TPR, O$_2$-TPD, and NH$_3$-TPD analyses.

The surface areas of the catalysts can influence the number of active sites on the catalyst surface, which is considered as an important factor affecting the catalytic activity of NH$_3$-SCR catalysts. The surface areas of CrO$_x$/C-450, Cr$_2$O$_3$, and Cr$_2$O$_3$/C-WI obtained from BET analysis are listed in Table 1. The BET surface areas of CrO$_x$/C-450 and Cr$_2$O$_3$/C-WI are similar and larger than that of Cr$_2$O$_3$. Due to the enhanced NH$_3$-SCR performances of CrO$_x$/C-450 and Cr$_2$O$_3$/C-WI (Fig. 1), it is believed that the enlarged surface area increased the activity of the Cr oxide catalyst. According to the reaction rates normalized by the surface areas of the active material of the catalysts, CrO$_x$/C-450 exhibited comparatively superior NO conversion than Cr$_2$O$_3$/C-WI at 125 °C and 150 °C. This infers that a large surface area is not the only reason for the excellent NH$_3$-SCR activity of CrO$_x$/C-450.

The acidity of the catalysts, which can influence the absorption of reaction agents, is an important factor affecting the NH$_3$-SCR performance of catalysts. This property of catalysts was investigated by NH$_3$-TPD analysis. As displayed in Fig. S6a† the NH$_3$ desorption behaviours of Cr$_2$O$_3$ and CrO$_x$/C-450 were similar. No distinct NH$_3$ desorption peak was observed from 150 to 400 °C in the profiles of both Cr$_2$O$_3$ and CrO$_x$/C-450 samples, which indicated the weak acidity of these two samples. Therefore, the giant NH$_3$-SCR performance difference between Cr$_2$O$_3$ and CrO$_x$/C is not the result of acidity.

The redox ability of materials is another significant factor influencing the catalytic activity of the NH$_3$-SCR catalyst. H$_2$-TPR method was utilized to discuss this property of the synthesized catalysts. As illustrated in Fig. 5b, Cr$_2$O$_3$ exhibited a single-peak profile. The H$_2$ consumption peak at 343 °C was a result of one-step reduction from Cr$^{6+}$ to Cr$^{3+}$, accompanied by the loss of lattice oxygen atoms connected with Cr$^{6+}$ ions.$^\text{46}$ For...
the CrO\textsubscript{x}/C-450 sample, the H\textsubscript{2} consumption peak shifted to a low temperature, which indicated that CrO\textsubscript{x}/C-450 exhibited stronger oxidation ability and a higher amount of active lattice oxygen than Cr\textsubscript{2}O\textsubscript{3}. In addition, O\textsubscript{2}-TPD analysis was carried out to investigate the stability of the oxygen atoms of the catalyst; the results are shown in Fig. S6b.\textsuperscript{†} In the profile of Cr\textsubscript{2}O\textsubscript{3}, no O\textsubscript{2} desorption peak was discovered in the temperature range from 50 °C to 450 °C, which indicates that the oxygen on the surface of Cr\textsubscript{2}O\textsubscript{3} is stable and inert. However, the curve of CrO\textsubscript{x}/C-450 exhibited an O\textsubscript{2} desorption peak from 200 to 350 °C, which was much higher than the desorption temperature of absorbed O\textsubscript{2} species recorded earlier.\textsuperscript{47} Hence, the desorption peak from 200 to 350 °C was believed to correspond to the dissociation of lattice oxygen from Cr\textsubscript{2}O\textsubscript{3}/C-450. This demonstrates that the lattice oxygen of CrO\textsubscript{x}/C becomes more active and unstable than that of Cr\textsubscript{2}O\textsubscript{3}. Remarkably, the CrO\textsubscript{x}/C catalyst has high surface atom/lattice atom rate for its ultrasmall size as mentioned before. It is reasonable to conclude that the unsaturated surface atoms of CrO\textsubscript{x}/C cause the unique redox ability exhibited in H\textsubscript{2}-TPR analysis and the instability of the lattice oxygen atom detected in O\textsubscript{2}-TPD analysis. Unstable and activated oxygen atoms are inferred to enhance the activity of CrO\textsubscript{x}/C catalyst.

In XPS analysis, Cr 2p spectra (Fig. 6a) of all the samples were comparable. The Cr 2P\textsubscript{3/2} peak could be divided into two peaks at 576.7 eV and 578.6 eV, belonging to Cr\textsuperscript{3+} and Cr\textsuperscript{6+}, respectively.\textsuperscript{48} The relative contents of Cr\textsuperscript{3+} and Cr\textsuperscript{6+} ions were analogous (Table 2), indicating their similar Cr state. The O 1s peak (Fig. 6b) could be separated into two peaks at 530.1 eV and 531.9 eV, attributed to the lattice oxygen and surface −OH groups, respectively.\textsuperscript{49,50} The relative contents of these two types of oxygen species are also listed in Table 2. The CrO\textsubscript{x}/C-450 sample exhibited more surface −OH groups than Cr\textsubscript{2}O\textsubscript{3}. Notably, the peak belonging to the lattice oxygen of CrO\textsubscript{x}/C-450 shifts to the high binding energy side, contrasting with that of Cr\textsubscript{2}O\textsubscript{3} and Cr\textsubscript{2}O\textsubscript{3}/C-WI. It is evident that the lattice oxygen of CrO\textsubscript{x}/C-450 carries less negative charge than Cr\textsubscript{2}O\textsubscript{3} and Cr\textsubscript{2}O\textsubscript{3}/C-WI. Materials with an ultrasmall size are deemed to have abundant dangling bands and their surface atoms are usually unsaturated-coordinated. In case of CrO\textsubscript{x}/C-450, some surface oxygen atoms are inferred to be unsaturated coordinated for ultrasmall size of CrO\textsubscript{x} nano-particles. This unsaturated oxygen is considered to have less negative charge and is expected to be more active than the saturated coordinated oxygen of bulk Cr\textsubscript{2}O\textsubscript{3}.

Furthermore, to determine whether the lattice oxygen participates in the NH\textsubscript{3}-SCR reaction, ex situ XPS analysis was carried out. The CrO\textsubscript{x}/C-450 catalyst was heated under NH\textsubscript{3} + NO flow at 150 °C for 1 h; the XPS spectra of CrO\textsubscript{x}/C-450 before and after treatment are displayed in Fig. 6c and d. In the Cr 2p spectra (Fig. 6c), the peak of Cr\textsuperscript{6+} at 578.6 eV disappeared after NH\textsubscript{3} + NO treatment, while the peak of Cr\textsuperscript{3+} at 576.7 eV enhanced. This infers that Cr\textsuperscript{6+} species on the surface of CrO\textsubscript{x}/C
can react with the reagent molecules and eventually get consumed. Moreover, in the O 1s spectra (Fig. 6d), the peak intensity of lattice oxygen at 530.4 eV decreased after treatment, while the intensity of the peak attributed to the surface –OH group at 531.7 eV increased, which indicates the loss of surface lattice oxygen. Therefore, lattice oxygen was believed to take part in the NH3-SCR on the CrOx/C catalyst. Thus, CrOx/C-450, which has more active lattice oxygen, can exhibit enhanced NH3-SCR activity than Cr2O3.

### 3.4. Mechanism of NH3-SCR on CrOx/C catalyst

In “fast NH3-SCR”, NO catalytically reduced NH3 in assistance of NO2, which was reported to have lower activation energy and enhanced catalytic activity compared with the typical NH3-SCR. Herein, the CrOx/C catalyst was proved to have activated lattice oxygen. It is reasonable to deduce that NO can be oxidized to NO2 by the activated oxygen on the CrOx/C surface, making the NH3-SCR on CrOx/C proceed as the “fast NH3-SCR” pathway. To verify this conjecture, NO oxidation on CrOx/C-450 and CrOx/C-WI catalysts was carried out. As displayed in Fig. 7a, NO could be oxidized to NO2 on both CrOx/C-450 and Cr2O3/C-WI. However, the mass of formed NO2 on CrOx/C-450 exceeded as compared to that on Cr2O3/C-WI. Moreover, the normalized rate by surface area of NO oxidation on CrOx/C-450 clearly surpassed that on Cr2O3/C-WI (Fig. 7b). This indicated that NO is more easily oxidized to NO2 on CrOx/C-450 catalyst with activated oxygen, which probably resulted in the superb NH3-SCR performance of CrOx/C-450.

In order to confirm whether the formed NO2 participated in the NH3-SCR on the CrOx/C catalyst, further information about the reaction mechanism was obtained using DRIFTS. In the spectra of the absorption NO + O2 saturated CrOx/C-450 sample (Fig. 8a), the bands centered at 1280, 1335, and 1520 cm⁻¹, and a wide band divided into bands at 1730, 1690, and 1660 cm⁻¹ were detected. As reported elsewhere, these IR bands were attributed to weakly bound NO2 (1730 cm⁻¹), nitrite anion (1335 cm⁻¹), r(N=O) and rass(N=O) of symmetric N2O3 (1690 and 1660 cm⁻¹), bidentate nitrates (1520 cm⁻¹), and monodentate nitrates (1280 cm⁻¹). When the feed gas was switched to NH3, the bands belonging to NO2 and bidentate nitrates gradually disappeared, replacing with the bands of NH3 absorbed on Lewis acid sites (1620 and 1217 cm⁻¹),5,6 while the bands corresponding to symmetric N2O3, nitrite anion, and monodentate nitrates were still present. Indeed, it is apparent that NO2 and bidentate nitrates participated in the surface reaction on CrOx/C-450 and were consumed by NH3, which is a typical “fast NH3-SCR” pathway.

To determine the role of NH3, co-adsorption of NO + O2 on CrOx/C-450 after pre-adsorption of NH3 was investigated (Fig. 8b). In the spectra of the absorption NH3 saturated CrOx/C-450 sample, only a weak band at 1620 cm⁻¹ corresponding to NH3 on Lewis acid sites was detected, indicating the low acidity of CrOx/C-450 as mentioned in NH3-TPD analysis. With the addition of NO and O2, this band gradually disappeared, accompanied by the appearance of bands belonging to weakly bound NO2 (1732 cm⁻¹), nitrite anion (1333 cm⁻¹), r(N=O) and rass(N=O) of symmetric N2O3 (1691 and 1657 cm⁻¹), and bidentate nitrates (1515 cm⁻¹).

![Fig. 7](image)

**Fig. 7** (a) NO oxidation performances and (b) normalized NO oxidation rate by surface area on CrOx/C-450 and C–Cr2O3 catalysts.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cr 2p Cr³⁺ (%)</th>
<th>Cr⁶⁺ (%)</th>
<th>O 1s OH groups (%)</th>
<th>Lattice oxygen (%)</th>
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<tr>
<td>Cr2O3</td>
<td>76.74</td>
<td>23.26</td>
<td>13.39</td>
<td>86.61</td>
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<tr>
<td>CrOx/C-450</td>
<td>78.86</td>
<td>21.14</td>
<td>18.36</td>
<td>81.64</td>
</tr>
<tr>
<td>CrOx/C-450-regeneration</td>
<td>79.37</td>
<td>20.63</td>
<td>18.7</td>
<td>81.3</td>
</tr>
<tr>
<td>CrOx/C-450 ex situ treatment</td>
<td>94.87</td>
<td>5.13</td>
<td>36.76</td>
<td>63.24</td>
</tr>
<tr>
<td>CrOx/C-450-SO2 poisoning</td>
<td>77.06</td>
<td>22.94</td>
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</tbody>
</table>

* Relative contents of Cr and O species were calculated from peak areas ratio of divided peaks in XPS spectra.
deionized water and the metal-ion contents in the eluate were measured by ICP analysis. As presented in Table S6,† Mn$^{2+}$ was detected in the eluate of the deactivated MnO$_2$ sample, while no Cr$^{3+}$ was detected in the eluate of the deactivated CrO$_x$/C-450 sample. It is evident that the CrO$_x$/C-450 sample was protected from sulfation.

To further understand the SO$_2$ poisoning and regeneration processes, the XPS spectra of the fresh CrO$_x$/C-450 catalyst, SO$_2$-poisoned sample, and regenerated sample were studied. As displayed in Fig. 6a and Table 2, the Cr state and relative content of Cr$^{6+}$ and Cr$^{3+}$ of each sample were similar, which indicated that, as it is designed, CrO$_x$/C-450 catalyst was difficult to be sulfated for the high lattice energy of Cr$_2$O$_3$. Comparing the O 1s peak of the fresh CrO$_x$/C-450 sample and the regenerated sample (Fig. 6b), their peaks of lattice oxygen were similar and both shifted to the high binding energy side than that of bulk Cr$_2$O$_3$. Since activated lattice oxygen still remained on the surface, the regenerated catalyst exhibited high NH$_3$-SCR activity, similar to the fresh catalyst.

In XPS spectra of the SO$_2$ poisoned sample, the peaks of S 2p and N 1s were detected. The S 2p peak (Fig. S7a†) consists of two peaks at 168.5 eV (S 2p$_{1/2}$) and 169.7 eV (S 2p$_{3/2}$), which belonged to SO$_4^{2-}$. The N 1s spectra (Fig. S7b†) can be divided into two peaks at 399.5 eV and 400.5 eV, contributed to NH$_3$ and NH$_4^+$, respectively. According to the relative atom contents listed in Table S7,† atoms-ratio of SO$_4^{2-}$ and NH$_4^+$ was nearly 1 : 1 on the surface of the SO$_2$-poisoned sample. This indicated that NH$_4$HSO$_4$ deposited on the surface of CrO$_x$/C-450 during the SO$_2$ poisoning process, which causes the deactivation of the catalyst. After heat treatment, the deposited NH$_4$HSO$_4$ could easily decompose and the CrO$_x$/C-450 catalyst with exposed activated lattice oxygen regains the superior activity.

4. Conclusions

In this study, we successfully designed and synthesized a novel chromium oxide nano-particles catalyst with excellent NH$_3$-SCR activity at 150 °C and remarkable SO$_2$ regenerative ability. The obtained CrO$_x$/C-450 catalyst was composed of CrO$_x$ nano-particles covered by amorphous carbon. A carbon species, which was derived from the organic linkers of the MOFs precursor, protected the CrO$_x$ nano-particles from aggregation. CrO$_x$/C catalysts primarily have Eskolaite phase Cr$_2$O$_3$ with average size of 3 nm and exhibit a large surface area. Due to the small size of CrO$_x$ nano-particles in CrO$_x$/C catalysts, the lattice oxygen atoms of CrO$_x$/C were activated, so that NO could be oxidized to NO$_2$ on the catalyst surface. The formed NO$_2$ participated in reaction and made NH$_3$-SCR on CrO$_x$/C proceed through a “fast NH$_3$-SCR” pathway. The large surface area and activated lattice oxygen of CrO$_x$/C catalysts caused the enhanced NH$_3$-SCR activities. Due to the stable lattice of Cr$_2$O$_3$, CrO$_x$/C catalyst could hardly be sulfated in the SO$_2$ poisoning process. Therefore, the regenerated catalyst still retained prominent activity when NH$_4$HSO$_4$ deposited on the surface of the catalyst was removed during the regeneration process.
Conflicts of interest
There are no conflicts to declare.

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