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# Influence of $Al_2O_3$ support on the activity of $Ag/Al_2O_3$ catalysts for SCR of NO with decane

Asima Sultana,* Masaaki Haneda, Tadahiro Fujitani, and Hideaki Hamada

*National Institute of Advanced Industrial Science and Technology (AIST), Research Institute for Innovation in Sustainable Chemistry,*
*AIST Tsukuba Central 5, 1–1–1 Higashi, Tsukuba, Ibaraki 305-8565, Japan*

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The role of the $Al_2O_3$ support on the activity of supported Ag catalyst towards the selective catalytic reduction (SCR) of NO with decane is elucidated. A series of $Ag/Al_2O_3$ catalysts were prepared by impregnation method and characterized by $N_2$ pore size distribution, XRD, UV–Vis, in-situ FT-IR and acidity measurement by $NH_3$ and pyridine adsorption. The catalytic activity differences of $Ag/Al_2O_3$ are correlated with different properties of $Al_2O_3$ supports and the active Ag species formed. 4wt% Ag supported on sol-gel prepared $Al_2O_3$ ($Ag/Al_2O_3$ (SG), showed higher $NO_x$ conversion (65% at 400 °C), compared with the respective catalysts made from commercial $Al_2O_3$ ($Ag/Al_2O_3$ (GB), $Ag/Al_2O_3$ (ALO), (~26 and 7% at 400 °C). The higher surface area, acidity and pore size distribution in sol–gel prepared $Al_2O_3$ (SG) results in higher NO and hydrocarbon conversion. Based on the UV–vis characterization, the activity of NO reduction is correlated to the presence of $Ag_n^{\delta+}$ clusters and acidity of $Al_2O_3$ support was found to be one of the important parameter in promoting the formation and stabilization of $Ag_n^{\delta+}$ clusters. Furthermore from pyridine adsorption results, presence of more number of Bronsted acid sites in $Ag/Al_2O_3$ (SG) is confirmed, which could also contribute to low temperature hydrocarbon activation and improve NO conversion. *In situ* FT-IR measurements revealed the higher rate of –CN and –NCO intermediate species formation over 4wt% $Ag/Al_2O_3$ (SG). We conclude that the physico–chemical properties of $Al_2O_3$ play a crucial role in $NO_x$ conversion over $Ag/Al_2O_3$ catalysts. Thus, the activity of the $Ag/Al_2O_3$ catalyst can be tailored by using a proper type of $Al_2O_3$ support.

**KEY WORDS:** HC-SCR; $Ag/Al_2O_3$; acidity; pore size distribution; UV–vis; *in situ* FT-IR.

## 1. Introduction

The search for effective and durable SCR catalytic system that works with hydrocarbon reductants in oxygen-rich environments is a high-priority issue in $NO_x$ emission control and is the subject of intense research throughout the world. Among the various catalysts proposed for HC–SCR system, $Ag/Al_2O_3$ was found to be the most active and potential catalytic system, as it reduces the $NO_x$ with hydrocarbons typical of diesel exhaust, and has received considerable attention [1–4]. Extensive studies have been reported on $Ag/Al_2O_3$ catalysts for SCR of NO using different types of hydrocarbon reductant and the highest catalytic activity was achieved using long-chain paraffin's as reductant, which makes $Ag/Al_2O_3$ a potential candidate for application in cleaning of diesel engine exhaust [5–7]. Furthermore $NO_x$ can be converted at much lower temperatures, usually encountered in diesel exhaust in presence of hydrogen in the exhaust gas, and several research groups observed such a significant improvement in the activity over $Ag/Al_2O_3$ catalysts in the low temperature region [8–14]. However, using a method employing hydrogen to increase the rate of SCR–$NO_x$ could entail considerable problems in storage of hydrogen or its preparation on board in the current $NO_x$ reduction strategies.

Extensive research on characterization and reaction mechanism over $Ag/Al_2O_3$ catalysts has been carried out to determine the active species responsible for NO reduction activity and the reaction intermediates formed, in order to improve the $NO_x$ reduction activity in general and low temperature activity and catalysts stability in particular. The structure of alumina-supported Ag catalyst for HC-SCR has been well investigated and various types of silver species: isolated $Ag^+$ ions, small Ag-aluminate "clusters," or $Ag_2O$ and small charged metallic $Ag_n^{\delta+}$ like clusters have been proposed as the active sites for the HC-SCR reaction [15–19]. However most of the studies were concentrated on the active silver species characterization and a few studies delt with the support influence on active species formation and NO conversion. Luo et al. [20] used different methods for the preparation of $Ag/Al_2O_3$ catalysts and tested for NO reduction with propene. It was found that the sol–gel prepared 5wt% $Ag/Al_2O_3$ showed the improved activity and was ascribed due to suitable surface area and pore size distribution. However the

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*To whom correspondence should be addressed.
E-mail: asima.sultana@aist.go.jp

correlation with support properties was not clear as the catalyst/support preparation was similar, derived from sol–gel preparation. Despite vast research work done on NO reduction over $Ag/Al_2O_3$ catalyst no general consensus was reached on support, active metal species and catalytic correlations. Thus, further fundamental investigations are still required in order to get more insight in to the effectiveness of $Ag/Al_2O_3$ catalyst and improve its activity, which is still insufficient for real life $NO_x$ abatement from exhaust gases of diesel engines. A systematic revision is therefore undertaken to study various influences of the catalyst properties on $NO_x$ reduction activity. In this article the influence of support surface characteristics on the formation of active Ag species and its activity in NO removal ability is presented. Though alumina is widely used as a support, only a few attempts have been devoted to study the role of $Al_2O_3$ support properties in the formation of active Ag species and the NO conversion enhancement of $Ag/Al_2O_3$ catalysts. The present study aims at investigating the influence of physico–chemical properties of sol–gel prepared $Al_2O_3$ on nature of the Ag species formed and its effect on reduction of NO with decane under lean burn conditions.

## 2. Experimental

### 2.1. Catalyst preparation

A series of Ag (4wt%) supported on $Al_2O_3$ catalysts ($Ag/Al_2O_3$), from three different sources of $Al_2O_3$ (i) prepared by sol–gel method (described below) designated as $Ag/Al_2O_3$ (SG) (ii) GB-45 supplied by Mizusawa Chemical Industries $Ag/Al_2O_3$ (GB) and (iii) JRC-ALO-7 supplied by Catalysis Society of Japan ($Ag/Al_2O_3$ (ALO) were prepared by wet impregnation of a calculated amount of aqueous silver nitrate solution. The impregnated samples were dried on a hot plate at 60 °C, followed by drying at 110 °C overnight in air with subsequent calcination in air at 600 °C for 3 h. $Al_2O_3$(SG) was prepared by sol–gel method by hydrolyzing aluminium tri-sec-butoxide (ASB) by drop wise addition of $H_2O$ (molar ratio $H_2O/ASB = 7$) at room temperature with continuous stirring. The obtained gel was aged at room temperature for 12 h without agitation, then dried in an oven at 110 °C overnight, followed by calcination at 450 °C for 5 h.

### 2.2. Catalyst characterization

XRD patterns of the calcined powder samples were recorded using Mac Science M18XHF22 X-ray diffractometer with Cu–K$\alpha$ radiation. The BET surface area of the catalysts was determined by $N_2$ physisorption at −196 °C using Micromeritics Flowsorb II 2300, after evacuating the samples at 300 °C for 30 min. The Nitrogen adsorption and desorption isotherms were measured using a Quantachrome Autosorb system after the samples were pretreated at 150 °C overnight in vacuum (below 0.01 mmHg). The data were analyzed by the BJH (Barrett–Joyner–Halenda) method.

The acidity was measured by ammonia adsorption/desorption technique using Quadrapole mass spectrometer unit (BEL JAPAN). Ca. 100 mg of the sample was out gassed at 500 °C for 1 h in a helium flow before ammonia adsorption. Ammonia adsorption was carried out at 100 °C for 1 h and then the sample was flushed with helium for 30 min at 100 °C to remove physically adsorbed ammonia. Ammonia desorption was carried out by rising the temperature to 600 °C with a heating rate of 10 °C/min. Pyridine adsorption was studied in a high vaccum system using infrared (FTIR) technique to determine the type of acid sites on the samples. Prior to pyridine adsorption, the samples were heated to 600 °C at 10 °C/min in vacuum and then cooled down to room temperature. After this pretreatment, they were exposed to saturated pyridine vapor for 10 min and infrared spectra were recorded after out gassing at 150, 250, 350 and 450 °C, respectively.

*In situ* UV–Vis spectra of the catalysts were recorded by using a UV–Vis (Cary, NIR-5000) spectrometer in a diffuse reflectance mode between 190 and 600 nm range at a step of 0.5 nm with a band width of 2 nm. The catalyst samples were calcined in air at 600 °C for 1 h before measurement. $BaSO_4$ was used as a reference sample to measure the baseline spectrum. *In situ* FT-IR spectra were taken with a Nicolet Nexus 670 FT-IR spectrometer, accumulating 64 scans at a resolution of 4 $cm^{-1}$. Prior to each experiment, 25 mg of a catalyst sample was placed in the diffuse reflectance high temperature cell (Spectra Tech) fitted with $CaF_2$ windows was activated *in situ* by heating in flowing 10% $O_2$ in He flow at 600 °C, followed by cooling to the desired temperature (300, 350 and 400 °C). The background spectrum of the clean surface was recorded at respective temperatures in inert atmosphere. Then, a gas mixture containing 500 ppm NO, 10% $O_2$ and 300 ppm $n$-$C_{10}H_{22}$ in He, at a flow rate of 60 $cm^3\ min^{-1}$, was fed to the catalyst and the spectra are recorded after every 5 min, with spectra recorded in He as background.

### 2.3. Catalytic activity measurement

The catalysts are evaluated for the selective catalytic reduction (SCR) of NO with decane in a fixed bed reactor with a simulated diesel exhaust gas containing 500 ppm NO, 300 ppm $n$-$C_{10}H_{22}$, 10 vol% $O_2$, 6 vol% $H_2O$ all diluted in He. The gas mixture was fed to 40 mg of the catalyst at a flow rate of 90 $cm^3\ min^{-1}$ (SV = ca.75,000 $h^{-1}$). The steady-state activity was measured at each reaction temperature by decreasing the temperature in 50 °C steps from 600 to 200 °C. The products were analyzed by gas chromatography (Shimadzu, GC-8A TCD detector) with a Molecular Sieve

5A column to separate $N_2$ and CO and a Porapak Q column to separate $N_2O$ and $CO_2$. The concentration of NO was continuously monitored using a $NO_x$ analyzer.

## 3. Results and discussion

### 3.1. Activity of $Al_2O_3$ support

Figure 1 compares the NO reduction and decane oxidation activity of different $Al_2O_3$ supports as catalysts. Using decane, $Al_2O_3$ support alone showed significant NO conversion activity above 350 °C. The NO conversion on supports alone is generally observed to occur in the high temperature range [21]. Among the activity of three alumina, $Al_2O_3$ (SG), $Al_2O_3$ (GB) and $Al_2O_3$ (ALO), the sol–gel prepared $Al_2O_3$ (SG) showed the maximum NO reduction of 55% at 550 °C and the conversion is observed over a considerably wider temperature window of 350–600 °C. No particular trend of HC conversion with NO conversion was observed over $Al_2O_3$ supports. At high temperatures two competing reactions, NO reduction with HC and HC oxidation to $CO_2$ take place. However, the decreasing trend of $NO_x$ conversion and >90% decane conversion at high temperatures indicates that the decrease in NO conversion at high temperature is due to complete HC conversion.

The preparation of $Al_2O_3$ support by sol–gel method results in the formation of large surface area support with relatively broad porosity and higher acidity [22]. Especially the properties such as surface area and active site accessibility are expected to play a major role in the NO conversion with larger hydrocarbons such as decane. Surface area measurement of the three $Al_2O_3$ supports showed that the $Al_2O_3$ prepared by sol-gel method (SG) has higher surface area (350m$^2$ g$^{-1}$)than the two commercial $Al_2O_3$ supports GB and ALO (140 and 143 m$^2$g$^{-1}$, respectively). The pore size distributions of the supports are shown in figure 2. Three $\gamma$-$Al_2O_3$ supports show different pore volume, and pore size distribution. The most active $Al_2O_3$ (SG) showed maximum number of pores in 50–250 Å range compared with $Al_2O_3$ (GB) (very narrow) and ALO (very broad but relatively less number) pores. The surface area and pore size distribution indicated that the sol–gel prepared $Al_2O_3$ has higher and easily accessible surface active sites (acid) for large hydrocarbons such as decane and this can have a significant positive influence on NO conversion. Jen [21], and Luo et al. [20] have shown a similar observation of the presence of pores in 20–100Å range results in higher NO reduction activity with relatively smaller molecule, propene. Furthermore the obvious increase in NO and HC conversion with increase in surface area of the supports indicates that these reactions are occurring on the surface of the support where surface hydroxyl groups (acidity) are expected to play an important role in the formation of reaction intermediates [18].

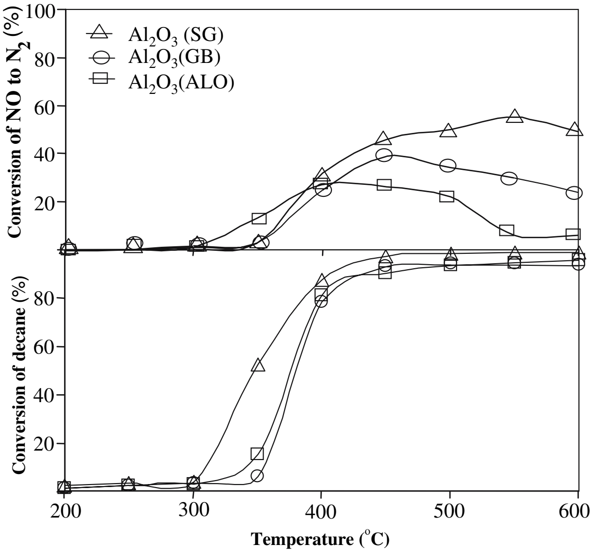

Figure 1. NO and decane conversion at different reaction temperatures during NO SCR with decane over different $Al_2O_3$ supports. Reaction conditions: 500 ppm NO, 300 ppm $n$-$C_{10}H_{22}$, 10 vol% $O_2$ and 6 vol% $H_2O$ all diluted in He, SV −75,000 h$^{-1}$.

Figure 3 shows the acidity of the different $Al_2O_3$ supports measured by $NH_3$-TPD. The total acidity of sol–gel prepared $Al_2O_3$ (SG) is much higher than the commercial $Al_2O_3$ supports (GB and ALO). Though acidity seems to be important in determining the catalytic activity, the differences in acidity are not proportionally reflected on the $NO_x$ conversion. One main reason for this is different pore size distribution of alumina. It can be expected that the higher acidity and large number of pores in sol–gel prepared $Al_2O_3$ leads to higher rate of hydrocarbon adsorption, and the uniformity of the pores may help in confining the adsorption and formation of reactive oxygenated hydrocarbon species. The differences $NO_x$ conversion over $Al_2O_3$

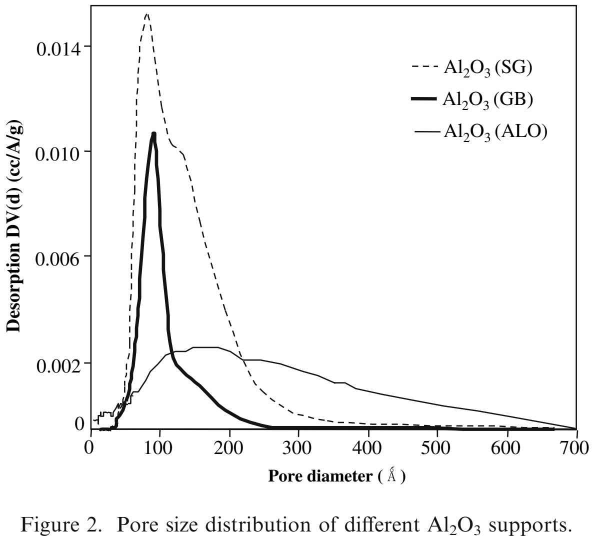

Figure 2. Pore size distribution of different $Al_2O_3$ supports.

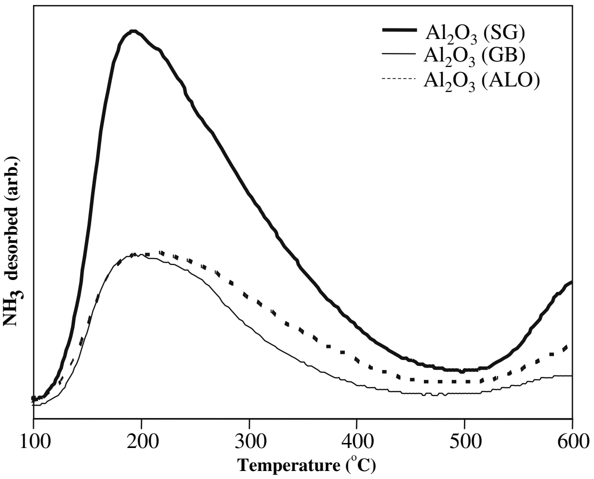

Figure 3. $NH^3$-TPD profiles of different $Al_2O_3$ supports.

catalysts having similar acidity could be explained by the differences in pore size distribution. One interesting observation that can be made from the NO conversion trends (figure 1) is that the activity is not shifted to significantly lower temperatures with different support surface area/accessibility, but only increased at respective temperatures among different supports. This indicates that the $NO_x$ conversion is occurring on similar active sites on all the support only the population of these sites are increasing.

### 3.2. *Activity of $Ag/Al_2O_3$ catalyst*

Addition of Ag to $Al_2O_3$ increased the NO conversion and shifted the temperature range of both NO reduction and hydrocarbon conversion significantly to lower temperature region, from 350–600 °C to 250–450 °C range (figure 4). Furthermore high NO conversion is observed compared with the $Al_2O_3$ supports alone. Among the catalysts 4 wt% Ag supported on $Al_2O_3$ (SG) showed maximum $NO_x$ conversion 65% at $400^0$C and significant NO conversion in a wider temperature window (250–450 °C) compared with the catalysts made from commercial $\gamma$-$Al_2O_3$ ($\sim$26 and 7% at 400°C) as supports. NO conversion decreased over all the catalysts above 400 °C due to complete HC conversion. The decane conversion to $CO_x$ ($CO + CO_2$) over $Ag/Al_2O_3$ (SG) was also found to be much higher especially, in the low temperature region (250–350°C) compared to $Ag/Al_2O_3$ catalysts prepared from commercial $Al_2O_3$. Unlike $Al_2O_3$ supports as catalysts, over $Ag/Al_2O_3$ catalysts the HC conversion followed the trend of NO conversion.

### 3.3. *Active sites of $Ag/Al_2O_3$ catalysts*

UV–vis spectra of 4wt% Ag supported on three different $Al_2O_3$ samples after subtracting the respective $Al_2O_3$ spectrum are shown in figure 5. The bands obtained upon deconvolution are shown below each respective spectra. The UV–Vis spectra are deconvoluted and, the bands at 250–290 nm and 330–385 nm are attributed to $Ag_{n1}$ small clusters, and $Ag_{n2}$ larger clusters, respectively. The band at 220 nm is assigned to the electronic transition from $4d^{10}$ to $4d^95s^1$ of highly dispersed $Ag^+$ species. It is clear from the deconvoluted spectra that $Ag/Al_2O_3$ (ALO) has relatively more number of larger Ag clusters. The area under 220 nm

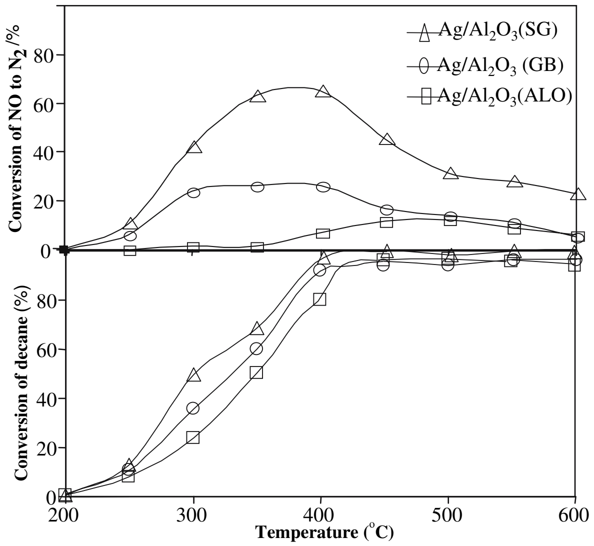

Figure 4. NO and decane conversion at different reaction temperatures during NO SCR with decane over different 4 wt% $Ag/Al_2O_3$ supports. Reaction conditions : 500 ppm NO, 300 ppm $n$-$C_{10}H_{22}$, 10 vol% O2 and 6 vol% $H_2O$ all diluted in He, SV –75,000 $h^{-1}$.

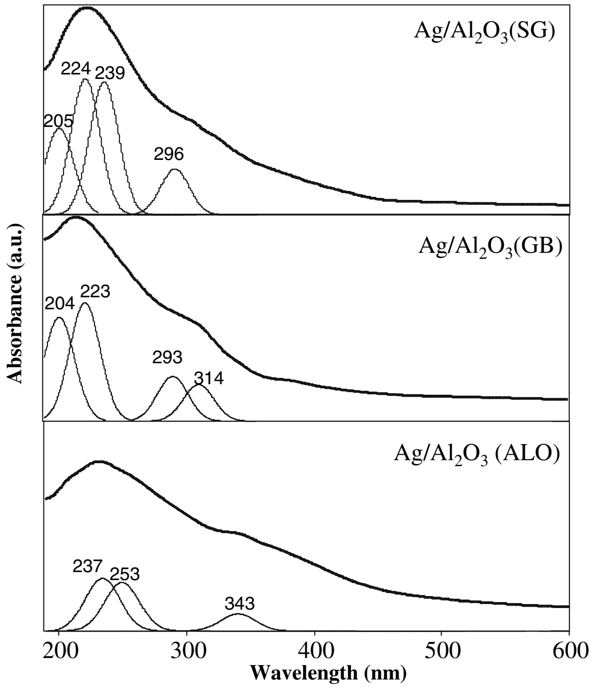

Figure 5. Diffuse reflectance UV–Vis spectra of 4 wt% $Ag/Al_2O_3$ catalysts.The deconvoluted bands are shown below each respective spectrum.

deconvoluted curve for $Ag/Al_2O_3$ (SG), $Ag/Al_2O_3$ (GB) and $Ag/Al_2O_3$ (ALO) are 16, 10 and 5 (arb. units), respectively. Among the three spectra, the $Ag/Al_2O_3$ (SG) which is the most active catalyst showed an intense absorption band around 220 nm compared to $Ag/Al_2O_3$ (GB) and $Ag/Al_2O_3$ (ALO), corresponding to small $Ag_n^{\delta+}$ clusters which are reported to be the catalytically active species for NO reduction with decane [15, 23]. It can also be noted that relatively large $Ag_n^{\delta+}/Ag^{\circ}$ species (bands above 300 nm) can be observed over $Ag/Al_2O_3$ (ALO). Despite the fact that the surface area and acidity of $Al_2O_3$ (GB-45) and $Al_2O_3$ (ALO) are similar, these two supports have shown entirely different population of silver species. One reason for the observed large silver species over $Ag/Al_2O_3$ (ALO) can be derived from its pore size data shown in figure 2. $Al_2O_3$ (ALO) has relatively broad (above 10 nm) pore size distribution and the small silver clusters initially formed during the impregnation can be more easily prone to agglomeration over $Al_2O_3$ (ALO). Therefore increase in surface area of the support is expected to increase the population of $Ag_n^{\delta+}$ species. Furthermore the increased number of hydroxyl groups will also stabilize such silver species compared with low surface area commercial supports. Although the silver species were not quantified by UV–Vis spectroscopy, the deconvolution of the spectra clearly shows a qualitative relationship between $Ag_n^{\delta+}$ species giving a band around 220 nm and $NO_x$ conversion. The $Ag/Al_2O_3$ (ALO) catalyst which has relatively larger $Ag_n^{\delta+}$ clusters and metallic $Ag^{\circ}$ clusters (340 nm) has shown $^{\delta}$ wer NO conversion compared with $Ag/Al_2O_3$ (GB) and $Ag/Al_2O_3$ (SG) catalysts which have small dispersed $Ag_n^{\delta+}$ clusters. Though the acidity is similar for $Ag/Al_2O_3$(GB) and $Ag/Al_2O_3$ (ALO), deconvoluted UV–Vis spectra clearly showed that, the distribution of silver species over both the compared aluminas are very different, which may be arising due to differences in pore size distribution which is again reflected over $NO_x$ conversion. It can be expected that over larger silver clusters or metallic silver clusters hydrocarbon can be easily oxidized, at high temperatures, where as these are mostly inactive at low temperatures. Furthermore due to lower number of silver species that can form intermediate nitrate species, necessary for the conversion to $N_2$, are decreased leading to lower NO conversion over $Ag/Al_2O_3$(ALO). The high performance of $Ag/Al_2O_3$(SG) catalyst in general can be correlated to $Ag_n^{\delta+}$ species (220 nm) as seen in UV spectrum of $Ag/A_2O_3$ (SG) (figure 5).

### *3.4. Role of acid sites in SCR of NO with decane*

Figure 3 shows the acidity of the different $Al_2O_3$ supports measured by $NH_3$-TPD. The total acidity of sol–gel prepared $Al_2O_3$ (SG) is much higher than the commercial $Al_2O_3$ supports (GB and ALO). Therefore, it can be presumed that the Ag species will more efficiently interact and stabilized with the acidic $Al_2O_3$ (SG) having large number of surface hydroxyl groups than the less acidic commercial alumina supports. This leads to the formation of more stable active silver species. Over such supports it is also possible to load relatively high amounts of silver which can improve the low temperature $NO_x$ conversion desirable for diesel exhaust treatment. Scarce number of studies has been reported concerning the correlation between the acidic properties of supported $Ag/Al_2O_3$ catalyst and their de-$NO_x$ activity, even though these surface properties are of crucial importance for the choice of a catalyst.

FTIR spectra of pyridine adsorbed on different $Al_2O_3$ and $Ag/Al_2O_3$ are shown in (figure 6). The interaction of silver species with surface hydroxyl groups is further

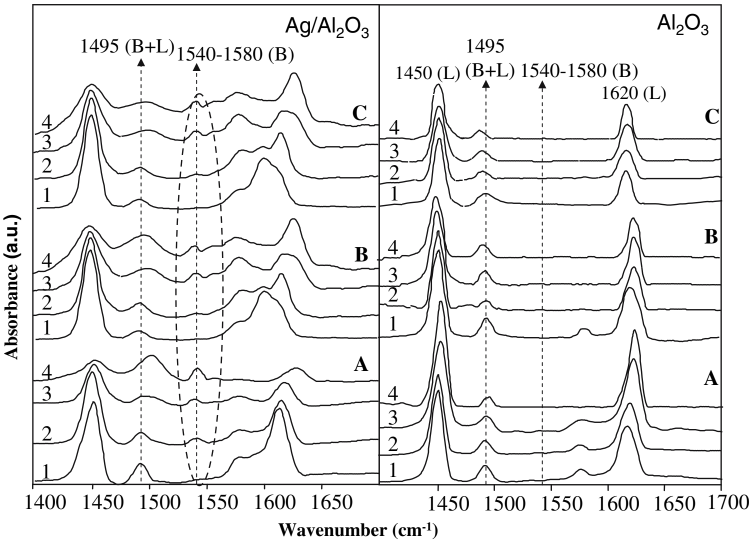

Figure 6. Infrared spectra of pyridine desorbed on $Al_2O_3$ and 4 wt% $Ag/Al_2O_3$ catalysts. A) SG, B) GB and C) ALO at 1) 150 °C 2) 250 °C 3) 350 °C and 4) 450 °C.

evident from the IR spectra of pyridine adsorbed catalysts. The bands corresponding to Bronsted (1540 cm$^{-1}$), Lewis (1450 cm$^{-1}$ and 1590–1620 cm$^{-1}$) and Bronsted/Lewis (1490 cm$^{-1}$) sites are observed in both the materials. Over $Al_2O_3$, pyridine is strongly adsorbed on Lewis sites as indicated by the unchanged intensity of band at 1450–1590 cm$^{-1}$. Whereas over Ag/$Al_2O_3$ catalysts, the Lewis acid site intensity is much lower especially, at 450 °C indicating the occupation of alumina Lewis acid sites with silver species, which weakly adsorbs pyridine. It is therefore concluded that acid sites (hydroxyl groups) of $Al_2O_3$ support plays an important role in the formation of $Ag_n^{\delta+}$ cluster formation and their dispersion [14]. Furthermore the Bronsted acid sites increased in Ag/$Al_2O_3$catalysts as seen from the relative intensity of 1490–1500 cm$^{-1}$ band. This result is in accordance with earlier report by Wang et al [18] who has shown by using different adsorption techniques that the Ag ions on impregnation are preferably deposited on the –OH groups (Lewis acid sites) and creates Bronsted acid sites on the surface of alumina and forms a dominant $Ag^+$ species. Increase in Bronsted acid sites was found to be higher in Ag/$Al_2O_3$ (SG) compared to Ag/$Al_2O_3$(GB) and Ag/$Al_2O_3$ (ALO). The presence of Bronsted acid sites in Ag/$Al_2O_3$ catalysts are further likely to contribute for enhanced hydrocarbon activation and may also act as active centers for NO adsorption [24–26].

### 3.5. *In situ IR studies of SCR of NO by decane*

Formation of various reaction intermediates is reflected in IR bands characteristic for adsorbed nitrite –$NO^{2-}$ or bridging bidentate nitrite (1230 cm$^{-1}$) [17], monodentate (1300 and 1550 cm$^{-1}$) and bidentate –$NO^{3-}$ (1580 cm$^{-1}$) [5], acetate (1460 cm−1) and bands corresponding to C–H stretching vibration mode (2800–3000 cm$^{-1}$) [27]. In 4wt% Ag/$Al_2O_3$ (SG), the intensity of nitrites, nitrates and $CH_x$–O containing reaction intermediates decreased, while the intensity of –NCO (2230 cm$^{-1}$) and –CN (2150 cm$^{-1}$) bands increased with increase in reaction temperature. The result indicates that the reaction between nitrites, nitrates and surface oxygenates is leading to the formation of –NCO and –CN which is in accordance with our earlier reports [15, 17]. On the other hand, in Ag/$Al_2O_3$ (GB-45) and Ag/$Al_2O_3$ (ALO) catalysts the intensity of peak corresponding to -NCO species did not significantly change and –$NO^{3-}$ and –CHx–O peaks did not decrease with increase in reaction temperature which can be explained by the presence of scarce number of active Ag species responsible for the formation of –NCO species. It is generally established that the adsorption of hydrocarbon and the intermediate –CN and –NCO species formation during SCR of NO with decane is responsible for NO conversion to $N_2$. *In situ* FT-IR measurement (figure 7) clearly shows the higher rate of –CN and –NCO intermediate formation evident from the evolution of bands at 2150 cm$^{-1}$ and 2230 cm$^{-1}$, respectively, over Ag/$Al_2O_3$ (SG) catalysts. These intermediates are furthermore observed over a broad temperature window under the reaction conditions in insitu IR experiments, which explains the observed increase in NO conversion over a broad temperature window over sol-gel prepared Ag/$Al_2O_3$ (SG) catalysts.

## 4. Conclusions

In conclusion it may be stated that:

1. The Ag/$Al_2O_3$, prepared by sol–gel method, exhibits the highest $NO_x$ conversion in a broad temperature window compared with traditional alumina supports.

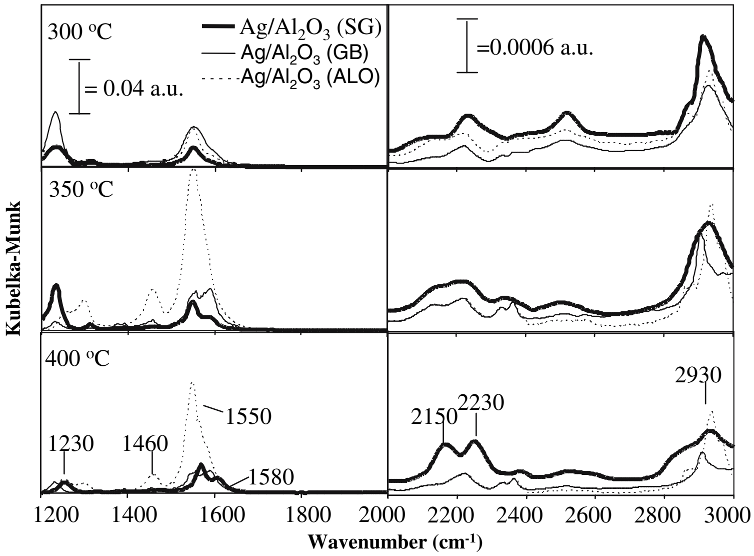

Figure 7. FTIR spectra of adsorbed species on different 4 wt% Ag/$Al_2O_3$ catalysts in flowing gas mixture of NO (500 ppm), n-$C_{10}H_{22}$ (300 ppm) and $O_2$ (10 vol%) at temperatures as indicated.

2. The characterization and conversion differences in the Ag supported on different types of $Al_2O_3$ indicated that these differences are arising from the differences in surface area, pore size distribution and acidity of the support. Acidity and pore size distribution can significantly influence the formation of active $Ag_n^{\delta+}$ clusters and their stabilization on $Al_2O_3$ support by strong metal support interaction as indicated by UV–Vis and FTIR spectroscopy.
3. Thus, we can conclude, that the NO reduction with higher hydrocarbons over $Ag/Al_2O_3$ catalyst can be significantly improved by tuning acidity and pore size distribution of the alumina support.

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