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Bifunctional Heterogeneous Catalysis of Silica–Alumina-Supported Tertiary Amines with Controlled Acid–Base Interactions for Efficient 1,4-Addition Reactions

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Abstract: We report the first tunable bifunctional surface of silica–alumina-supported tertiary amines (SA–NEt_2) active for catalytic 1,4-addition reactions of nitroalkanes and thiols to electron-deficient alkenes. The 1,4-addition reaction of nitroalkanes to electron-deficient alkenes is one of the most useful carbon–carbon bond-forming reactions and applicable toward a wide range of organic syntheses. The reaction between nitroethane and methyl vinyl ketone scarcely proceeded with either SA or homogeneous amines, and a mixture of SA and amines showed very low catalytic activity. In addition, undesirable side reactions occurred in the case of a strong base like sodium ethoxide employed as a catalytic reagent. Only the present SA-supported amine (SA–NEt_2) catalyst enabled selective formation of a double-alkylated product without promotions of side reactions such as an intramolecular cyclization reaction. The heterogeneous SA–NEt_2 catalyst was easily recovered from the reaction mixture by simple filtration and reusable with retention of its catalytic activity and selectivity. Furthermore, the SA–NEt_2 catalyst system was applicable to the addition reaction of other nitroalkanes and thiols to various electron-deficient alkenes. The solid-state magic-angle spinning (MAS) NMR spectroscopic analyses, including variable-contact-time ^{13}C cross-polarization (CP)/MAS NMR spectroscopy, revealed that acid–base interactions between surface acid sites and immobilized amines can be controlled by pretreatment of SA at different temperatures. The catalytic activities for these addition reactions were strongly affected by the surface acid–base interactions.

Keywords: acid–base interactions • amines • C−C coupling • heterogeneous catalysis • silica–alumina

Introduction

Much attention has been paid to “double catalytic activation” of two substrates in a single reaction step for efficient organic synthesis. Because acidic and basic functions can activate electrophiles and nucleophiles, respectively, to make various carbon–carbon bond-forming reactions possible, many acid–base pairs have been examined in homogeneous reaction systems.[1] However, the use of both strong acidic and basic species in a homogeneous single reactor is impossible due to the neutralization that forms inactive salts. In addition, recovery and reuse of both catalytic species are often problematic in homogeneous systems. To overcome these problems in homogeneous systems, several acid–base bifunctional heterogeneous catalysts have been developed.[2,3] These heterogeneous catalyst systems make the coexistence of acid and base functions without complete neutralization possible.

Another feature of acid–base heterogeneous catalysts is their positioning control of acidic and basic sites, which enables not only the avoidance of the acid–base neutralization

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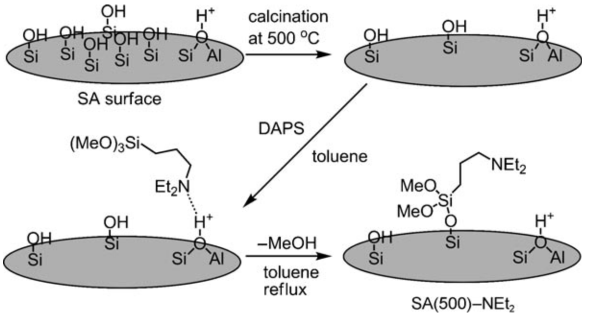
but also the creation of highly functionalized surfaces for selective reactions. We also expected that even unstable substrates, which are easily dimerized or oligomerized by a strong acid or base, can be used in the weak acid–base bifunctional catalyst system. However, there are few reports on such selective reactions by acid–base bifunctional heterogeneous catalysts.[4] In addition, appropriate spectroscopic techniques to estimate the acid–base interaction on solid surfaces have not been reported until now.

Our strategy for the design of acid–base bifunctional heterogeneous catalysts is to use acidic silica–alumina (SA) as a support on which basic alkyl amines are immobilized by silane-coupling reactions. The bifunctional SA surfaces may exhibit high catalytic activities for C−C bond-forming reactions without undesired neutralization at the surface. Recently, we have reported the high performance of the SA-supported tertiary and primary amine catalysts (SA–NR_2) for cyano-ethoxycarbonylation, the Michael reaction of nitriles, and the nitro-aldol reaction.[3] During the course of our research on SA–NEt_2 catalyses, we have found that the acid–base interaction between the SA surface and the immobilized amine group strongly affects its catalytic activities. It can be said that controlling the acid–base interaction to avoid neutralization is a key to improving the SA–NEt_2 catalyst for its application toward selective organic transformations.

In this study, we report the first tunable bifunctional surface active for catalytic 1,4-addition reactions of nitroalkanes and thiols to electron-deficient alkenes. The 1,4-addition reaction of nitroalkanes to electron-deficient alkenes is one of the most useful carbon–carbon bond-forming reactions and applicable toward a wide range of organic syntheses.[5] We also found that the surface density of silanol groups on SA plays a pivotal role in controlling the acid–base interactions of the SA–NEt_2 catalysts. This acid–base interaction was estimated by using several solid-state NMR spectroscopic techniques, such as variable-contact-time measurements in ^{13}C cross-polarization (CP)/magic-angle spinning (MAS) NMR spectroscopy.



Scheme 1. Preparation of SA(500)–NEt_2.

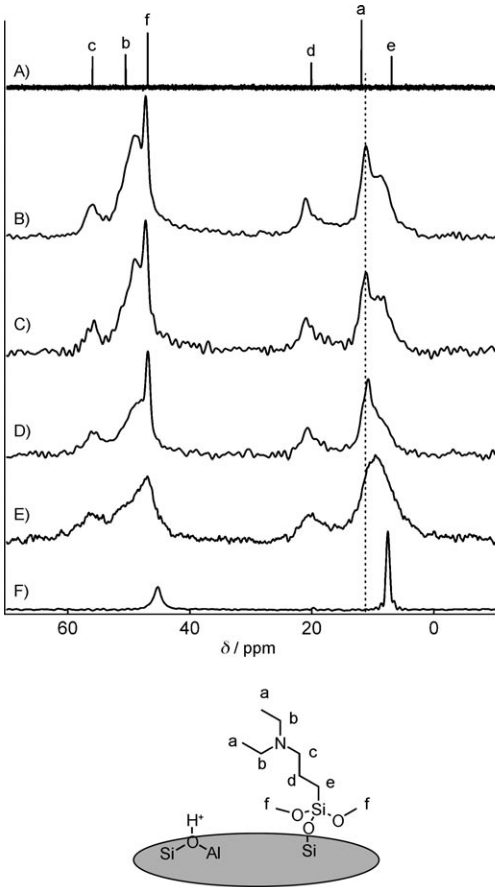


Figure 1. A) ^{13}C NMR spectrum of DAPS in $CDCl_3$. Solid-state ^{13}C CP/MAS NMR spectra of B) SA(500)–NEt_2, C) SA(400)–NEt_2, D) SA(200)–NEt_2, E) SA(120)–NEt_2, and F) triethylamine adsorbed on SA(500).

Results and Discussion

Preparation and characterization of catalysts: SA (silica 66.5, alumina 25.1 %; 380 $m^2 g^{-1}$) was pretreated at 120–500 °C under vacuum before use as a support for amines. The treated samples are denoted as SA(treatment temperature: *T*). Tertiary amines were immobilized on the SA(*T*) by treatment of the SA(*T*) with a solution of 3-(diethylamino)-propyltrimethoxysilane (DAPS) in toluene under reflux for 24 h (Scheme 1). Then the immobilized SA was filtered and washed with dichloromethane, followed by drying under vacuum. The solid-state ^{13}C CP/MAS NMR spectrum for SA(*T*)–NEt_2 (Figure 1B–E) was similar to that of parent DAPS (Figure 1A), thereby indicating the retention of the DAPS structure after the DAPS immobilization. A stronger signal for methoxy groups (see Figure 1, peak f: $\delta = 47$ ppm) in SA(500)–NEt_2 (Figure 1B) than that for the SA(120)–NEt_2 (Figure 1E) indicates that the quantity of the methoxy groups that remained in the SA(500)–NEt_2 is larger than that in the SA(120)–NEt_2. This is in agreement with the ^{29}Si MAS NMR spectroscopic data for SA(*T*)–NEt_2, in which the peak intensity of the T^1 site ($T^1 = Si(OCH_3)_2$) at $\delta = -49$ ppm is larger than that of the T^2 site ($T^2 = Si(OCH_3)$) at $\delta = -56$ ppm in SA(500)–NEt_2 (Figure 2A),[6] but the peak intensity of the T^2 site increases and that of the T^1 site de-

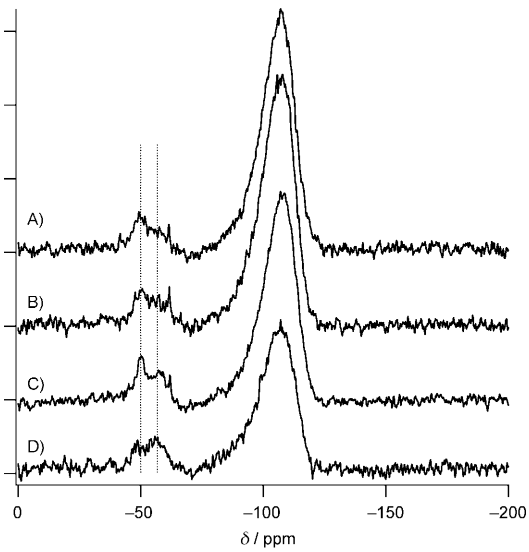
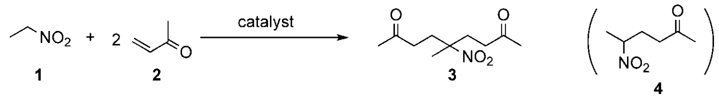


Figure 2. Solid-state ^{29}Si MAS NMR spectra of A) SA(500)–NEt$_2$, B) SA-(400)–NEt$_2$, C) SA(200)–NEt$_2$, and D) SA(120)–NEt$_2$.

Table 1. 1,4-Addition of **1** to **2** by various catalysts.[a]

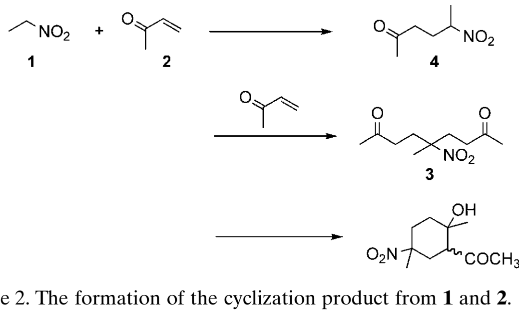


Entry	Catalyst	Amine loading [mmol g^{-1}][b]	Conversion of **1** [%][c]	Yield of **3** [%][c]	Initial rate [mmol h^{-1}][c,d]
1	SA(120)–NEt$_2$	0.89	99	74	0.28
2	SA(200)–NEt$_2$	0.74	99	80	0.36
3	SA(400)–NEt$_2$	0.56	99	82	0.41
4	SA(500)–NEt$_2$	0.56	99	86	0.53
5[e]	SA(500)–NEt$_2$	0.56	99	93	0.53
6	SiO$_2$(120)–NEt$_2$	0.73	84	49	0.16
7	SiO$_2$(500)–NEt$_2$	0.69	76	14	0.13
8	H-USY–NEt$_2$	0.45	37	33	0.01
9[f]	SA(500)	–	22	0	0.02
10	DAPS	–	8	8	0.03
11	NEt$_3$	–	16	2	<0.01
12[f]	SA(500)+NEt$_3$	–	99	28	0.27
13	NaOEt	–	99	1[g]	n.d.[h]
14	none	–	0	0	–

[a] Reaction conditions: **1** (1 mmol), **2** (3 mmol), catalyst (4.5×10^{-2} mmol), toluene (1 mL), 50 °C, 20 h. [b] Determined by elemental analysis. [c] Determined by ^{1}H NMR spectroscopy and GC using an internal standard technique. Based on **1**. Other byproducts were not detected except for **4** in the case of supported catalysts. [d] Initial formation rate of the addition products (**3**+**4**). [e] 24 h. [f] 0.08 g of SA was used. [g] A byproduct was formed from **3** by a cyclization reaction. [h] n.d. = not determined.

creases with a decrease in the pretreatment temperature of SA (Figure 2B–D) because the number of surface silanol groups decreases when the calcination temperature is increased.[7] These results suggest that the DAPS precursor is immobilized on the SA surface by Si-O-Si covalent bonding. The amine loading in the SA(*T*)–NEt$_2$ was determined typically as 0.56 mmol g^{-1} for SA(500)–NEt$_2$ by elemental analysis. These loading amounts decreased when the calcination temperature was increased because of a decrease in the amount of surface Si–OH groups of SA by dehydration (Table 1). A Lewis base of *N,N*-dimethylaminopyridine could adsorb on the SA(500)–NEt$_2$ (1.36 mmol g^{-1}, 2.2 per nm^2), thereby indicating the retention of acid sites after the amine immobilization. In the case of SA(120)–NEt$_2$, 2.25 mmol g^{-1} of pyridine derivative was adsorbed, which also suggests that the amount of acidic Si–OH was decreased by the thermal pretreatment of SA.

Catalysis of SA(*T*)-supported amines for 1,4-addition of nitroalkanes: The 1,4-addition reaction of nitroalkanes to electron-deficient alkenes is traditionally promoted by homogeneous strong bases. However, there are several problems, such as difficulties in their handling in air due to moisture and carbon dioxide sensitivities and unavoidable undesirable side reactions. To develop an effective 1,4-addition catalyst system that overcomes the problems in carbon–carbon bond-forming processes, we used the SA–NEt$_2$ as heterogeneous catalysts and examined the 1,4-addition reaction of nitroethane (**1**) to methyl vinyl ketone (MVK; **2**). As shown in Table 1, the catalyst SA(500)–NEt$_2$ was found to be remarkably active to afford the double-alkylated product **3** in 93 % yield (Table 1, entry 5). Decreasing the pretreatment temperature of SA reduced the catalytic activity of SA(*T*)–NEt$_2$ (entries 1–4). Amine catalysts on other supports such as silica and zeolite were much less effective for this reaction (entries 6–8). Monoalkylated nitroethane (**4**), which is regarded as an intermediate, was also detected during the double addition reaction. It is to be noted that this reaction scarcely proceeded with either SA(500) or homogeneous amines (entries 9–11). A mixture of SA(500) and triethylamine showed catalytic activity, but the yield of **3** was very low (entry 12). In the case of a strong base like sodium ethoxide as a homogeneous catalyst, the selectivity toward **3** was as low as 1–7 % during the whole course of the reaction due to further conversion of **3** toward an undesired cyclization product (entry 13, Scheme 2).[8] In addition, there were several reports of a double addition reaction of simple nitroalkanes to MVK; however, the selectivities were usually less than 50 %.[9] It is to be noted that the present report is the



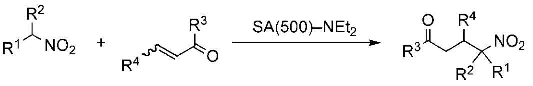
Scheme 2. The formation of the cyclization product from **1** and **2**.

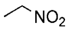
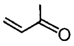
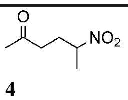
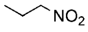
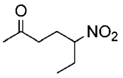
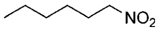
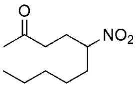
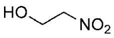
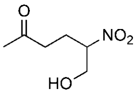
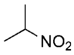
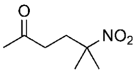
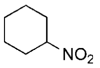
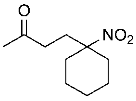
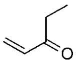
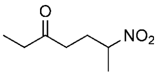
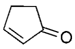
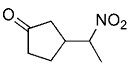
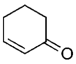
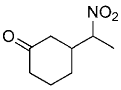
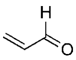
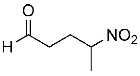
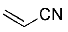
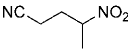
first one for selective formation of the double-alkylated nitroalkane product.

The general applicability of the SA(500)–NEt$_2$ catalyst to 1,4-addition reactions of nitroalkanes to electron-deficient alkenes is listed in Table 2. The use of a nitroalkane in an amount three times larger than that of an alkene induced selective formation of a monoalkylated product. Various nitroalkanes such as 1-nitropropane, 1-nitrohexane, 2-nitroethanol, and nitrocyclohexane reacted with **2** to give the corresponding addition products in good to excellent yields (62–96 %; Table 2, entries 1–7). The SA(500)–NEt$_2$ catalyst was also active for other alkenes. The 1,4-addition reactions of **1** to not only acyclic **2** and ethyl vinyl ketone but also cyclic α,β-unsaturated ketones proceeded smoothly and afforded the corresponding 4-nitroketones (entries 8–10). Acrolein was also found to be a good acceptor to form 4-nitro-1-heptylaldehyde in 92 % yield (entry 11). The reactions of acrylonitrile did not proceed effectively (entry 12). After the catalytic addition reaction of **1** to **2**, the used SA(500)–NEt$_2$ catalyst was easily recovered from the reaction mixture by simple filtration, and reusable with retention of its catalytic activity and selectivity (entry 2). However, the product yield decreased in the third use (64 %) compared with the second use, and the preservation of amine loading after the catalytic reaction was confirmed by elemental analysis and NMR spectroscopy. The catalyst might be deactivated after the second use by the adsorption of some organic molecules on active sites.

Relationship between surface acid–base interaction and catalytic performances: After the immobilization of tertiary amine groups onto SA(120), the ^{13}C NMR spectroscopic signal of the terminal carbon (see Figure 1, peak a: $\delta = 9.5$ ppm) shifted upfield compared with that of the amine precursor ($\delta = 11.8$ ppm; Figure 1A and C). The signal for the mixture of SA(500) and triethylamine also showed a large upfield shift (Figure 1F).[3] On the other hand, a signal for SA(500)–NEt$_2$ was observed at $\delta = 11.0$ ppm, which showed only a very small shift from the precursor (Figure 1B). The sharpness of the carbon signals increased with increasing pretreatment temperature, thereby suggesting an increase of molecular mobility. Thus, contact-time array ^{13}C CP/MAS NMR spectroscopic measurements of SA(500)–NEt$_2$ and SA(120)–NEt$_2$ were conducted to determine the molecular mobility of immobilized amines, as shown in Figures 3 and 4, respectively. This variable-contact-time ^{13}C CP/MAS NMR spectroscopy is a technique used to determine the molecular motion of solid materials.[10] Since CP is a measure of the efficiency of magnetization transfer by the dipolar coupling from ^{1}H to ^{13}C, it is most efficient for the static ^{1}H–^{13}C dipolar interactions. As a result, the less mobile carbon groups exhibit the faster cross-polarization rate, and the NMR spectroscopic signal intensity becomes stronger with relatively short CP contact time. This signal intensity becomes weak with prolonged contact time due to attenuation of the transferred magnetization. On the other hand, the signal intensity of a molecule with high mobility shows a strong intensity with

Table 2. 1,4-Addition of nitroalkanes to alkenes by SA(500)–NEt$_2$.[a]



Entry	Nitroalkane	Alkene	Product	Yield [%][b]
1				85
2[c]	**1**	**2**	**4**	83
3		**2**		87
4		**2**		96
5[d]		**2**		62
6[e]		**2**		96
7		**2**		78
8[f]	**1**			87
9[g]	**1**			83
10[g, h]	**1**			93
11[i]	**1**			92
12[d]	**1**			24

[a] Reaction conditions: nitroalkane (3 mmol), alkene (1 mmol), SA(500)–NEt$_2$ (4.5×10^{-2} mmol), toluene (1 mL), 50 °C, 24 h. [b] Determined by ^{1}H NMR spectroscopy and GC. Based on alkene. [c] Reuse experiment. [d] 70 h. [e] 12 h. [f] 80 °C. [g] 100 °C. [h] 50 h. [i] Room temperature, 1 h.

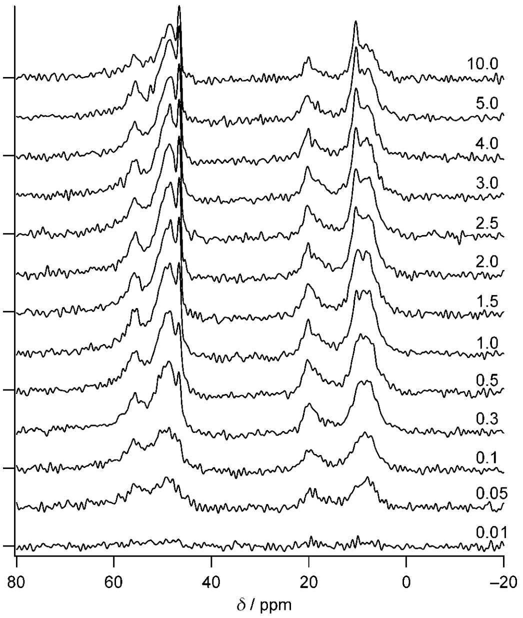


Figure 3. Contact-time-array ^{13}C CP/MAS NMR spectra for SA(500)–NEt$_2$. The values on the spectra are contact times [ms].

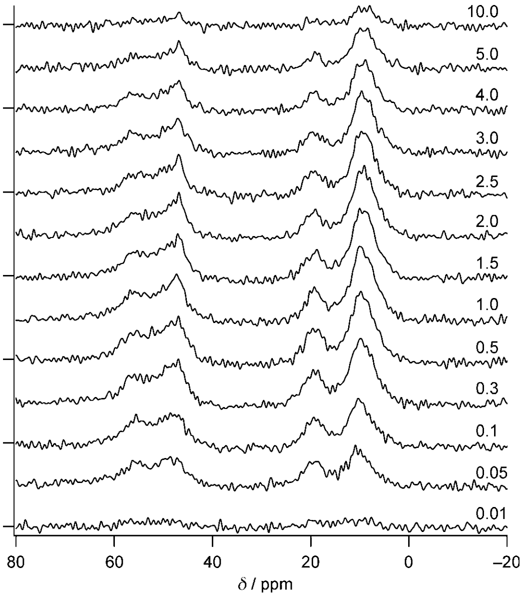


Figure 4. Contact-time-array ^{13}C CP/MAS NMR spectra for SA(120)–NEt$_2$. The values on the spectra are contact times [ms].

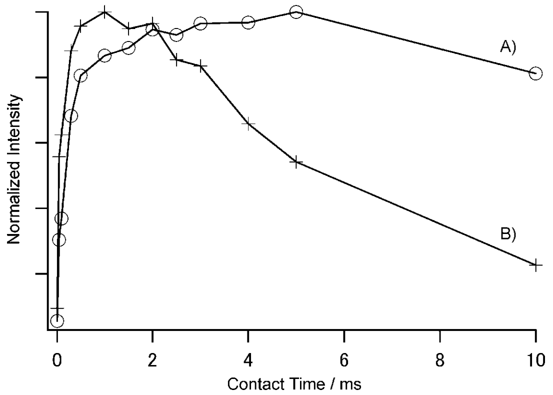


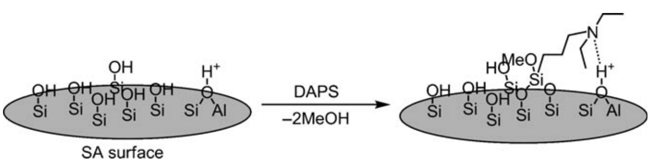
Figure 5. Dependence of the normalized intensity of variable-contact-time ^{13}C CP/MAS NMR spectra for the terminal carbon (a) on contact time: A) SA(500)–NEt$_2$ (○) and B) SA(120)–NEt$_2$ (+).

Table 3. Contact times with highest peak intensities derived from contact-time-array solid-state ^{13}C CP/MAS NMR spectroscopic measurements.

Sample	Contact time with highest peak intensity [ms]	
	Terminal carbon (a: δ=8–11 ppm)	Carbon next to nitrogen (b: δ=48 ppm)
SA(500)–NEt$_2$	5.0	≈1.5–3.0
SA(120)–NEt$_2$	1.0	0.5
SA(500)–NEt$_2$+thiol	1.0	≈0.9–2.0

relatively long contact time.[10] Figure 5 shows the normalized intensity of ^{13}C CP/MAS NMR spectra versus contact time curves for amine terminal carbon atoms (a: $\delta = 9$–11 ppm) on SA(500)–NEt$_2$ and SA(120)–NEt$_2$. Contact times with the highest peak intensities of the terminal carbon atom and the carbon atom next to the nitrogen atom (b: $\delta = 48$ ppm) derived from the variable-contact-time measurements are summarized in Table 3. Variable-contact-time data for SA(500)–NEt$_2$ showed the highest intensity of the terminal carbon with 5.0 ms contact time. In contrast, the highest intensity for SA(120)–NEt$_2$ was at 1.0 ms contact time. Thus, the cross-polarization time constant (T_{CH}) values of SA(500)–NEt$_2$ are much longer than those of SA(120)–NEt$_2$, thereby indicating the much higher mobility of the tertiary amine group in SA(500)–NEt$_2$. The strong acid–base interaction between the amine nitrogen and the SA acid site in SA(120)–NEt$_2$ suppressed the tertiary amine mobility compared with SA(500)–NEt$_2$. Based on the chemical shifts of the terminal carbon atoms and molecular motility of the immobilized amines, it seems that the acid–base interaction in SA(500)–NEt$_2$ is much weaker than that in SA(120)–NEt$_2$[11,12] in spite of the increasing acid strength of the SA surface by the pretreatment at 500 °C.[13,14]

It can be expected that the amines are immobilized on a neighboring position of a Brønsted acid site on SA (SiO(H$^+$)Al) because of the following amine-immobilization mechanism: 1) the nitrogen atom of free DAPS interacts with the strong Brønsted acid (SiO(H$^+$)Al) on the SA surface, and 2) one Si–OMe of DAPS reacts with a surface Si–OH species near the strong acid site to form a covalent Si-O-Si (surface) bond (Scheme 1).[3] The calcination of SA at 500 °C reduced the amount of surface silanol groups, thus resulting in a high dispersion of silanols on the SA surface, and as a result, DAPS may be immobilized on positions far away from a strong acid site (Scheme 1). On the other hand, in the case of a SA(120) support with a higher concentration of acid sites, the amine–acid site distance can become close, thereby suggesting strong acid–base interaction (Scheme 3).



Scheme 3. Preparation of SA–NEt_2 with untreated or low-temperature calcined SA.

IR spectra for SA(500)–NEt_2 and SA(120)–NEt_2 revealed that there were no clear signals assignable to $\tilde{\nu}$(N−H), whereas strong signals for $\tilde{\nu}$(N−H) were observed in triethylamine adsorbed on SA(500) around 2500–2800 cm^{-1} (Figure 6).[15] ^{13}C CP/MAS NMR spectra for triethylamine adsorbed on SA(500) showed the largest upfield shift of the terminal carbon signal (Figure 1F) than those for immobilized amines on SA (Figure 1B–E), thereby suggesting the strongest acid-site–amine-base interaction. It has been reported that the acid–base neutralization is suppressed at the immobilized surface.[2a,f,g,3] In conclusion, the proposed surface structures of SA(500)–NEt_2, SA(120)–NEt_2, and triethylamine on SA(500) with acid–base interactions are illustrated in Scheme 4. Thus, it is suggested that both surface acidic and basic species in SA(500)–NEt_2 without acid–base neutralization act as effective catalytic sites, which agrees with the highest catalytic activity of SA(500)–NEt_2 among the performances listed in Table 1.

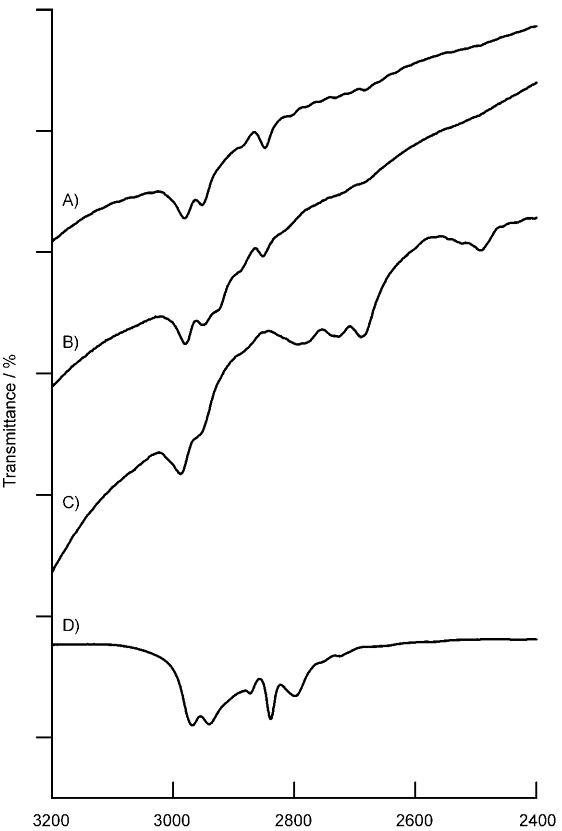
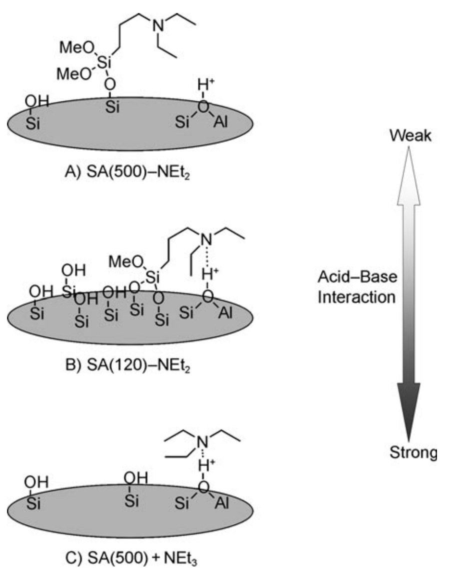
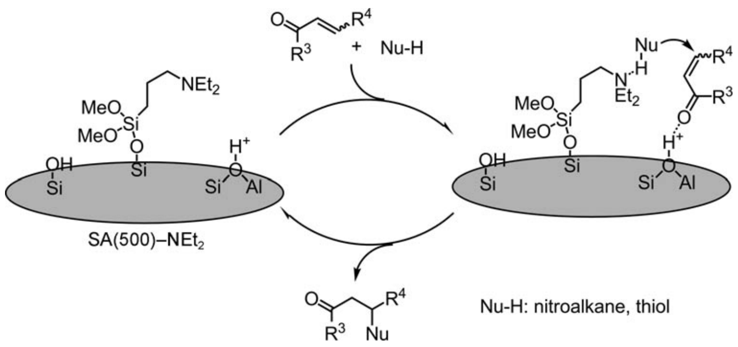


Figure 6. FTIR spectra of A) SA(500)–NEt_2, B) SA(120)–NEt_2, C) SA(500) with triethylamine, and D) DAPS. These spectra were obtained at room temperature in a transmission mode. The solid was pressed into a disk with KBr and subjected to IR measurements.



Scheme 4. Proposed surface structures for A) SA(500)–NEt_2, B) SA(120)–NEt_2, and C) SA(500) with triethylamine.

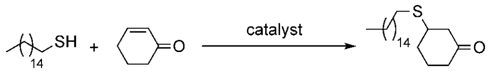
In the SA(500)–NEt_2-catalyzed 1,4-addition reaction of **1** to **2**, nonpolar solvents such as toluene and heptane were good solvents, and the strongly electron-donating DMF solvent gave a poor result.[16] In comparison, a typical solid base of MgO showed high catalytic performances with polar solvents. These results suggest that the SA(500)–NEt_2-catalyzed reaction mechanism involves not only proton abstraction by basic amine groups from nitroalkane but also activation of carbonyl compounds by surface strong acid sites of SA (Scheme 5), which are easily deactivated by electron-donating solvents.



Scheme 5. Proposed catalytic cycle for the 1,4-addition reaction with SA(500)–NEt_2.

This acid–base bifunctional catalysis of SA(500)–NEt_2 was also highlighted by the 1,4-addition reaction of thiol to an electron-deficient alkene (Table 4). The reaction of 1-hexadecanethiol to 2-cyclohexen-1-one was promoted by acid

Table 4. 1,4-Addition of 1-hexadecanethiol to 2-cyclohexen-1-one.[a]



Entry	Catalyst	Conversion [%][b]	Selectivity [%][b]
1	SA(500)–NEt$_2$	97	>99
2[c]	SA(500)	70	>99
3[c]	SA(500)+NEt$_3$	60	>99
4	NEt$_3$	trace	–

[a] Reaction conditions: 1-hexadecanethiol (1 mmol), 2-cyclohexen-1-one (1.5 mmol), amine (4.5×10^{-2} mmol), toluene (1 mL), RT, 7 h. [b] Determined by ^{1}H NMR spectroscopy. Based on the thiol. [c] 0.08 g of SA was used.

sites on SA(500) (Table 4, entry 2).[17] The acidic performance decreased by exposure to triethylamine due to deactivation of acid sites (entry 3). The reaction hardly occurred with only triethylamine (entry 4). However, the amine immobilization of the SA(500) promoted excellent catalytic performance to form the addition product in 97% yield (entry 1). These results strongly indicate a significant contribution of the weak interaction between the surface acidic site and the NEt$_2$ group to the catalytic function of SA(500)–NEt$_2$, in which the amine group activates the nucleophile by proton abstraction, thereby resulting in cooperative promotion of addition reactions. In fact, activation of the SH group by the tertiary amine for the 1,4-addition was considered to be the reason for the improved performance. Shorter contact-time values of the highest peak intensity of 1-hexadecanethiol-adsorbed SA(500)–NE$_2$ than those of the parent SA(500)–NEt$_2$ were observed in solid-state ^{13}C CP/MAS NMR spectroscopic analysis (Figure 7 and Table 3), which indicates the interaction between SH groups and immobilized tertiary amines.

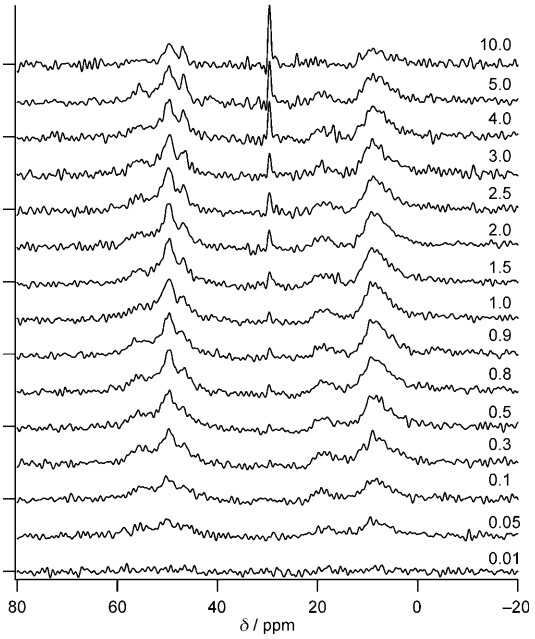
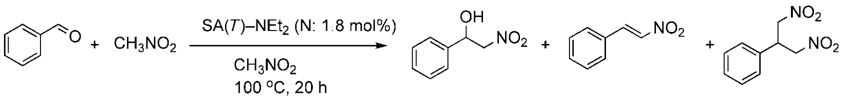


Figure 7. Contact-time-array ^{13}C CP/MAS NMR spectra for 1-hexadecanethiol-adsorbed SA(500)–NEt$_2$. Values with spectra are contact times [ms]. A signal at around $\delta=30$ ppm is derived from thiol adsorbed on SA(500)–NEt$_2$.



SA(500)–NEt$_2$: 59% conversion (product ratio: 52:14:34).
SA(120)–NEt$_2$: 57% conversion (product ratio: 53:15:35).

Scheme 6. Nitro-aldol reaction with SA(*T*)–NEt$_2$ catalysts.

We also examined the 1,2-addition reaction of nitromethane to benzaldehyde with SA(500)–NEt$_2$ and SA(120)–NEt$_2$ (Scheme 6). The catalytic activity and selectivity of SA(500)–NEt$_2$ are similar to those of SA(120)–NEt$_2$ in spite of its better performance in 1,4-addition reactions. The amount of weak acidic Si–OH groups, which are amine-immobilizing sites, on SA(120) and SA(500) are estimated to be 5 and 2 nm^2, respectively.[7] It can be expected that the amines are immobilized on the neighboring position of the strong acid site (SiO(H$^+$)Al) on SA,[3] thus the averaged distance between the amine-immobilizing site and the strong acid site on SA(120) and SA(500) are calculated to be 4.1 and 5.7 Å, respectively. These distances are not too different from those in the 1,4-addition reactions of nucleophiles to α,β-unsaturated carbonyl compounds, in which an estimated distance from the carbonyl oxygen in electrophiles to the carbon atom in nucleophiles is approximately 4.4 Å. However, an estimated distance from the oxygen to the carbon atom in the case of a 1,2-addition is approximately 2.4 Å. The far positioning between amines and acid sites in SA(500)–NEt$_2$ is not so effective for a 1,2-addition reaction, such as a nitro-aldol reaction, regardless of its higher nucleophilicity and acidity than SA(120)–NEt$_2$.

Conclusion

Silica–alumina-supported tertiary amine catalysts were found to be efficient heterogeneous acid–base bifunctional catalysts for 1,4-addition reactions of nitroalkanes and thiol to electron-deficient alkenes. The interaction between surface acidic sites and basic amine groups can be controlled by the pretreatment temperature of SA. The detailed amine–acid interactions, which strongly affect catalytic performance, are determined by variable-contact-time-array measurements of solid-state ^{13}C CP/MAS NMR spectroscopy. This simple preparation procedure of heterogeneous acid–base bifunctional catalysts (Scheme 1) can be widely applied to the design of new heterogeneous organic catalysts copromoted by oxide support surfaces.

Experimental Section

^{1}H and ^{13}C NMR spectra were obtained using JNM-AL400 spectrometers at 400 MHz in $CDCl_3$ with TMS as an internal standard. Solid-state ^{13}C and ^{29}Si MAS NMR spectra (MAS rate = 4 kHz) were recorded using a Chemagnetics CMX-300 spectrometer operating at 75.5 and 59.7 MHz, respectively. ^{13}C MAS NMR spectra with cross-polarization (CP) were acquired with a contact time of 5.0 ms. A single-pulse detection method with hydrogen decoupling was used in ^{29}Si NMR spectroscopic analyses, in which the pulse duration was 1.5 μs. The rotor spin rate was 4 kHz, with a delay time of 15 and 20 s for ^{13}C and ^{29}Si, respectively. Hexamethylbenzene (^{13}C: $\delta = 17.17$ and 176.46 ppm) and TMS (^{29}Si: $\delta = 0$ ppm) were used as external standards for the calibration of chemical shifts. The accumulation numbers were fixed at about 20000 (^{13}C) and 10000 (^{29}Si). The variable-contact-time ^{13}C CP/MAS NMR spectra were measured with a rotor spin rate of 4 kHz, 2 s of delay time, and an accumulation number of 2000. Infrared spectra were obtained using a JASCO FTIR-410. Analytical GLC and GLC–mass were performed using a Shimadzu GC-2010 with a flame ionization detector.

Unless otherwise noted, materials were purchased from Wako Pure Chemicals, Tokyo Kasei Co., and Aldrich Inc., and were used after appropriate purification. Amorphous silica–alumina (SA) was purchased from Nikki Chemical Co., Japan as N633HN (SiO_2 66.5, Al_2O_3 25.1%; 380 $m^2 g)^{-1}$. Silica (Aerosil® 300, 300 $m^2 g^{-1}$) and H-USY (Tosoh Co., Japan, HSZ-330HUA, Si/Al = 3.17, 626 $m^2 g^{-1}$) were used. The identities of products were confirmed by comparison with reported mass and NMR spectroscopic data.

Preparation of SA–NEt_2: SA was pretreated at 500 °C for 3 h under reduced pressure. SA (1.0 g) was added to a solution of 3-(diethylamino)-propyltrimethoxysilane in toluene (2 mmol, 20 mL) and heated at reflux for 24 h. Then the solvent was removed by filtration and the functionalized SA was washed with dichloromethane, followed by drying under vacuum, which afforded SA(500)–NEt_2. Elemental analysis (%) of SA–NEt_2: C 7.54, H 1.94, N 0.79. Other solid-supported amines (support–NR_2) were also synthesized by means of a similar procedure with different pretreatment temperatures. Elemental analysis (%) for SA(120)–NEt_2: C 8.40, H 2.16, N 1.27; SA(200)–NEt_2: C 8.35, H 2.15, N 1.03; SA-(400)–NEt_2, C 7.61, H 2.18, N 0.78; SiO_2(120)–NEt_2: C 6.58, H 1.42, N 0.99; SiO_2(500)–NEt_2: C 7.31, H 1.51, N 0.96; USY–NEt_2: C 7.38, H 2.19, N 0.63.

1,4-Addition reaction of nitroalkanes to olefins using SA(500)–NEt_2: SA-(500)–NEt_2 (8.0×10^{-2} g, 4.5×10^{-2} mmol), toluene (1 mL), nitroethane (3.0 mmol), and methyl vinyl ketone (1.0 mmol) were placed into a Pyrex glass reactor. The resulting mixture was vigorously stirred at 50 °C under an N_2 atmosphere. After 24 h, the catalyst was separated by filtration and the ^{1}H NMR spectroscopic and GC–MS analysis of the filtrate showed 85% yield of the addition product 5-nitro-2-hexanone.

1,4-Addition reaction of a thiol to an olefin using SA(500)–NEt_2: SA-(500)–NEt_2 (8.0×10^{-2} g, 4.5×10^{-2} mmol), toluene (1 mL), 1-hexadecanethiol (1.0 mmol), and 2-cyclohexen-1-one (1.5 mmol) were placed into a Pyrex glass reactor. The resulting mixture was vigorously stirred at room temperature under an N_2 atmosphere. After 7 h, the catalyst was separated by filtration and the ^{1}H NMR spectroscopic analysis of the filtrate showed 97% yield of the addition product.

Preparation of thiol-adsorbed SA(500)–NEt_2: SA(500)–NEt_2 (8.0×10^{-2} g, 4.5×10^{-2} mmol), toluene (1 mL), and 1-hexadecanethiol (4.5×10^{-2} mmol) were placed into a Pyrex glass reactor. The resulting mixture was vigorously stirred at room temperature. After 1 h, the solvent was evaporated and the solid was dried under vacuum, thus giving the thiol-adsorbed SA(500)–NEt_2 for the solid-state ^{13}C CP/MAS NMR spectroscopic measurements.

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