Catalytic ring-opening allylation of cyclic acetals with allylsilanes using silica-alumina†

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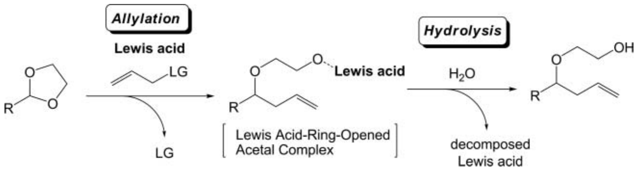
Ring-opening allylation of cyclic acetals has required stoichiometric amounts of Lewis acids. In this paper, catalytic ring-opening allylation in the presence of silica-alumina is reported. This ring-opening allylation showed high atom economy. Consecutive allylation/hydrolysis using silica-alumina afforded homoallyloxyalcohols in good to high yields.

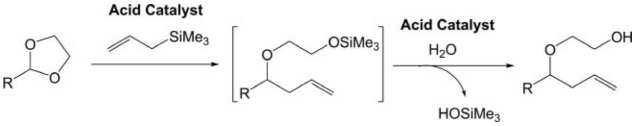
Introduction

Homoallyloxyalcohol is an important building block for the synthesis of organic compounds such as amino sugars[1] because it has allyl, hydroxyl, and ether functional groups. Consecutive ring-opening allylation/hydrolysis affords the homoallyloxyalcohol (Scheme 1). Ring-opening allylation of cyclic acetals has been demonstrated in the presence of stoichiometric amounts of Lewis acid reagents, such as $TiCl_4$,[2–11] $AlCl_3$,[6] $SnCl_4$,[6] Ti(O*i*-Pr)$_4$,[7–11] $BF_3{\cdot}Et_2O$[12,13] and TMSOTf.[13] Recently, Spafford and co-workers reported using a Bi(OTf)$_3$ catalyst for ring-opening allylation in the presence of acid anhydrates.[14] The acid anhydrate reacts with a "Lewis acid-ring-opened acetal complex", regenerating the Bi catalyst and producing an ester instead of the corresponding homoallyloxyalcohols.



Scheme 1 Consecutive ring-opening allylation/hydrolysis using a stoichiometric amount of Lewis acid.

We have attempted the catalytic synthesis of homoallyloxyalcohols from cyclic acetals, allylsilanes and water *via* ring-opening allylation/hydrolysis using a Brønsted acid catalyst in a single reactor (Scheme 2). Because Brønsted acid catalysts have been reported in the deacetalization of cyclic acetals,[15] it can be said that Brønsted acids activate cyclic acetals as electrophiles. If the interaction between a Brønsted acid site and ring-opened acetal is weaker than that for the Lewis acids, it is possible that the ring-opening allylation, affording homoallyloxysilylether, occurs catalytically. It is also well known that the hydrolysis of silylether is promoted by Brønsted acids.[16] In the catalytic consecutive ring-opening allylation/hydrolysis, silanol is expected to be the only by-product.



Scheme 2 Catalytic consecutive ring-opening allylation/hydrolysis using acid.

Results and discussion

Ring-opening allylations of 2-phenyl-1,3-dioxolane (**1**) with allyltrimethylsilane (**2**), using various Brønsted acids, are summarized in Table 1. Silica-alumina showed high activity and selectivity, affording an 83% yield of homoallyloxysilylether (**3**) (entry 1).[17] A moderate yield of **3** was obtained with H$^+$-beta zeolite (entry 2). H$^+$-montmorillonite displayed a high conversion of acetal **1**; however, selectivity toward desired allylated product **3** was much lower than that of the silica-alumina, owing to the formation of by-product **4** (entries 3 and 4). Amberlyst and Nafion also showed low selectivity (entries 5 and 6). Other zeolites we tested were found to be less active (entries 7–10). Silica with a mesoporous structure (FSM-16) can promote the allylation reaction to afford an 18% yield of **3** (entry 11). The selectivity of product **3** was very low with triflic acid (entry 12). The desired reaction scarcely proceeded with other homogeneous Brønsted acids, such as H_2SO_4 and *p*-toluenesulfonic acid (entries 13 and 14).

To optimize the reaction conditions, the ring-opening allylation of **1** was carried out using silica-alumina in various solvents, as shown in Table 2. The reaction proceeded smoothly with non-polar solvents such as toluene and heptane (entries 1 and 2), but the product **3** was hardly formed when using polar solvents with high dielectric constant values (entries 4–6).

During the allylation of **1**, silica-alumina was filtrated at 40% conversion of **1**. No allylation reaction occurred when the filtrate was treated at 60 °C for 26 h. This result suggests that the active site for the ring-opening allylation is on the silica-alumina surface. In order to estimate the active species, the ring-opening allylation of **1** was carried out using silica-alumina treated with a NaCl/NaOH solution (Na-silica-alumina) and amorphous SiO_2 (Table 1, entries 16 and 17). The allylation did not occur when using Na-silica-alumina instead of silica-alumina. This result demonstrated that an acid site on the silica-alumina promotes the allylation reaction. Silica-alumina has

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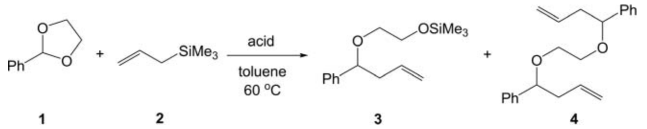
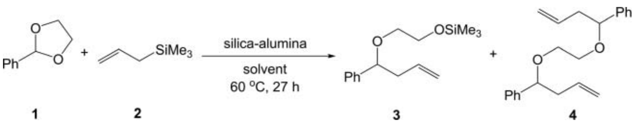
Table 1 Ring-opening allylation of 2-phenyl-1,3-dioxolane (**1**) with allyltrimethylsilane (**2**) using acids [a]



				Conversion (%) [b]		Yield (%) [b]	
Entry	Acid	Amount/g	t/h	**1**	**2**	**3** [c]	**4** [d]
1	Silica-alumina	0.05	8	95	94	83	7
2	H$^+$-Beta	0.05	27	75	86	43	3
3	H$^+$-Montmorillonite	0.05	1	>99	>99	38	48
4	H$^+$-Montmorillonite	0.01	1.5	53	58	13	23
5	Amberlyst	0.05	1	58	76	22	29
6	Nafion	0.05	3	52	63	22	18
7	H$^+$-Mordenite	0.15	27	42	56	8	<1
8	H$^+$-USY	0.15	27	24	52	1	1
9	H$^+$-L	0.15	27	10	44	<1	3
10	H$^+$-ZSM-5	0.15	27	24	33	<1	<1
11	FSM-16	0.05	27	25	45	18	2
12	CF_3SO_3H [e]	—	1	79	95	8	35
13	*p*-TsOH·H_2O [f]	—	27	11	41	2	<1
14	H_2SO_4 [g]	—	27	27	71	<1	2
15	$AlCl_3$ [h]	—	27	18	43	1	<1
16	Na-Silica-alumina	0.05	27	11	40	1	<1
17	Amorphous SiO_2	0.05	27	4	37	<1	<1

[a] Reaction conditions: **1** (3.7 mmol), **2** (4.4 mmol), toluene (3.0 mL), 60 °C, Ar atmosphere. [b] Determined by GC using internal standard. [c] Yield based on acetal **1**. [d] Yield = [**4** (mmol) × 2/**1** (mmol)] × 100. [e] CF_3SO_3H (0.18 mmol). [f] *p*-TsOH·H_2O (0.26 mmol). [g] H_2SO_4 (0.18 mmol). [h] $AlCl_3$ (0.18 mmol).

Table 2 Silica-alumina-catalyzed ring-opening allylation of 2-phenyl-1,3-dioxolane (**1**) with allyltrimethylsilane (**2**) using various solvents [a]



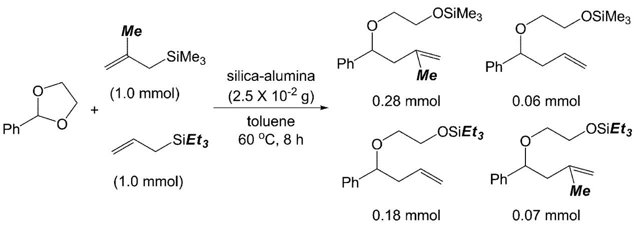
		Conversion (%) [b]		Yield (%) [b]	
Entry	Solvent	**1**	**2**	**3** [c]	**4** [d]
1	Toluene	95	94	81	7
2	*n*-Heptane	96	92	76	12
3	1,4-Dioxane	90	93	76	13
4	Acetonitrile	15	51	3	1
5	2-Propanol	36	29	<1	<1
6	DMF	<1	33	<1	<1

[a] Reaction conditions: **1** (3.7 mmol), **2** (4.4 mmol), silica-alumina (0.05 g), solvent (3.0 mL), 60 °C, Ar atmosphere. [b] Determined by GC using internal standard. [c] Yield based on acetal **1**. [d] Yield = [**4** (mmol) × 2/**1** (mmol)] × 100.

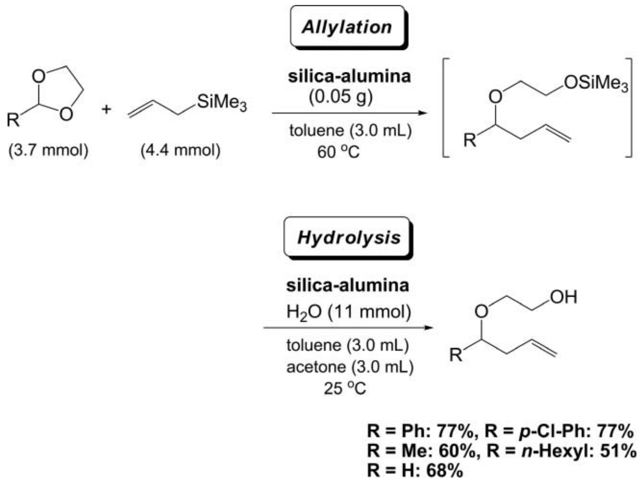
Brønsted acid sites due to the [Si–O(H$^+$)–Al] moiety and the weakly acidic Si–OH group.[18] The product yield was less than 1% in the case of amorphous SiO_2 having a Si–OH group (Table 1, entry 17), so the Brønsted acid site due to the [Si–O(H$^+$)–Al] moiety is more likely to be the main active site promoting the ring-opening allylation.[19] The amount of acid sites, including the active Brønsted acid sites in silica-alumina, was estimated to be 0.154 mmol g^{-1} by NH_3-TPD analysis. This clearly indicates that the Brønsted acid site acts as a catalytically active species for the ring-opening allylation.

Catalytic activity and selectivity for the allylation may depend on the accessibility of the Brønsted acid site on the solid surface. In Table 1, almost all zeolites showed low catalytic performance due to restricted pore size. On the other hand, a large by-product (**4**) was obtained in the case of H$^+$-montmorillonite, Amberlyst and Nafion, due to high accessibility to the acid site. Production of large molecules such as polyarene has been reported using these solid acids.[20] Accessibility to the Brønsted acid site on silica-alumina is expected to be suitable for the selective production of homoallyloxysilylether (**3**).

To reveal the reaction pathway, ring-opening allylation of **1** using two differently substituted allylsilanes, methallyltrimethylsilane and allyltriethylsilane, was carried out. The results are shown in Scheme 3. Allylated products having methallyl-$SiMe_3$ or allyl-$SiEt_3$ groups formed more preferentially than allyl-$SiMe_3$ or methallyl-$SiEt_3$. This result indicates that at least part and possibly all of the reaction proceeds *via* intermolecular silyl transfer. Stoichiometric amounts of Lewis acid reagent are reported in literature to be necessary for the ring-opening allylation of acetals.[2–13] Bi(OTf)$_3$ acts as a catalyst for ring-opening allylation, but the reaction scarcely proceeds unless an acid anhydride is used as a trapping reagent for the Lewis acid-ring-opened acetal complex.[14] The Lewis acid-ring-opened acetal complex



Scheme 3 Ring-opening allylation of **1** using two differently substituted allylsilanes.



Scheme 4 Catalytic synthesis of homoallyloxyalcohols using silica-alumina.

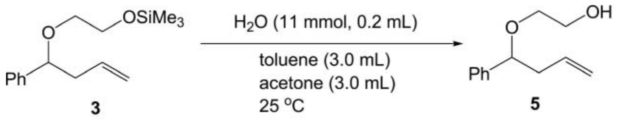
is thus expected to be stable under anhydrous conditions. On the other hand, in our heterogeneous Brønsted acid-catalyzed reaction system (Table 1), additives such as acid anhydrides were not required. This suggests that the interaction between the solid Brønsted acid and the ring-opened acetal is weaker than that of the homogeneous acids. Effective exchange between H^+ on the ring-opened acetal and the $SiMe_3$ species occurs on the solid surface after the nucleophilic addition of the allylsilane.

To obtain homoallyloxyalcohol from homoallyloxysilylether (**3**), water and acetone were added to the reactor following the ring-opening allylation of **1** with **2** using silica-alumina. Acetone acted as a good co-solvent for the hydrolysis. The hydrolysis was carried out at 25 °C to avoid side-reactions and the resulting reaction mixture was stirred for 23 h. The corresponding homoallyloxyalcohol (**5**) was obtained with a 77% yield, based on the acetal (**1**) used (Scheme 4, R–Ph).[21] After the hydrolysis of silyl ether product **3**, silanol and siloxane formed as by-products. As shown in Scheme 4, this consecutive allylation/hydrolysis could be extended to other acetals, giving good yields of the corresponding homoallyloxyalcohols. 2-Aryl- and alkyl-1,3-dioxolanes behaved as substrates in the presence of silica-alumina. Simple 1,3-dioxolane (R–H) also reacted with allylsilane and H_2O, to afford 2-(homoallyloxy)ethanol with a 68% yield. The reaction of a ketal, such as 2,2-dimethyl-1,3-dioxolane, scarcely proceeded under identical conditions.

In order to examine the activity of silica-alumina in the hydrolysis of the silylether, the reaction of **3** and water was carried out in the absence of silica-alumina. The hydrolysis of **3** barely occurred when no silica-alumina catalyst was used (Scheme 5). This result indicates that silica-alumina promotes the hydrolysis.

Summary

In summary, silica-alumina was found to be a catalyst for the synthesis of homoallyloxyalcohols from cyclic acetal, allylsilane, and water. Surface Brønsted acid sites acted as the catalytically active species for the ring-opening allylation of various cyclic acetals. Hydrolysis of silylethers was also promoted by silica-alumina. A detailed reaction mechanism and a study of a larger scope of substrates are underway.



	Yield of **5**
with silica-alumina	45%(3 h), 77%(23 h)
no catalyst	3%(3 h)

Scheme 5 Hydrolysis of **3** with and without silica-alumina.

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21 After the hydrolysis reaction, reuse of the silica-alumina catalyst was examined. The used silica-alumina was separated from the reaction mixture, then calcined at 500 °C. The catalytic activity of the used catalyst for ring-opening allylation decreased compared with fresh silica-alumina (yield of **3**: 83% for 8 h (fresh), 52% for 8 h (reused)). However, after the prolonged reaction time, a satisfactory yield of **3** was obtained (73% for 20 h). Hydrolysis of **3** also proceeded with the used catalyst to afford **5** in 70% yield based on **1**.