ORGANIC LETTERS

2009
Vol. 11, No. 6
1261−1264

Well-Defined Silica-Supported Olefin Metathesis Catalysts

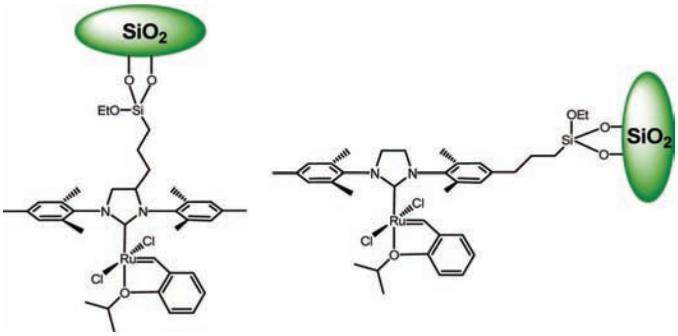
Daryl P. Allen,[†] Matthew M. Van Wingerden, and Robert H. Grubbs*

The Arnold and Mabel Beckman Laboratory of Chemical Synthesis, Division of Chemistry and Chemical Engineering, California Institute of Technology, Pasadena, California 91125

rhg@caltech.edu

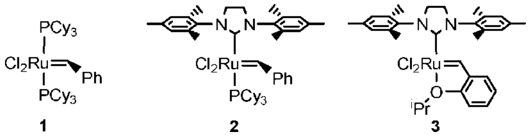
Received January 5, 2009

ABSTRACT



Two triethoxysilyl-functionalized *N*-heterocyclic carbene ligands have been synthesized and used to prepare the corresponding second-generation ruthenium olefin metathesis catalysts. These complexes were then grafted onto silica gel, and the resulting materials were efficient heterogeneous catalysts for a number of metathesis reactions. The solid-supported catalysts were shown to be recyclable over a number of reaction cycles, and no detectable levels of ruthenium were observed in reaction filtrates (ruthenium concentration of filtrate <5 ppb).

Olefin metathesis has emerged as a unique and powerful transformation for the interconversion of olefinic hydrocarbons in both organic and polymer chemistry.[1] The development of well-defined ruthenium-based catalysts (**1**−**3**, Figure 1)[2] has greatly expanded the scope and applications of this process due to their increased tolerance of organic functionality, moisture, and oxygen. [3] However, even with the advances in this area, catalyst lifetime and efficiency can represent a major limiting factor in the further advancement of this technology. Thus, over the past decade, significant emphasis has been placed on gaining a fundamental understanding of the various decomposition pathways leading to catalyst deactivation.[4] This has led to the advent of new catalyst architectures that provide improved reactivity and/or methods for eliminating or reducing particular decompostion pathways such as C−H activation of *ortho* *N*-aryl substituents.[5]



1 **2** **3**

Figure 1. Ruthenium-based olefin metathesis catalysts.[2]

[†] Current address: Materia Inc., 60 N. San Gabriel Blvd, Pasadena, CA 91107.

(1) (a) Grubbs, R. H. *Handbook of Metathesis*; Wiley-VCH: Weinheim, Germany, 2003. (b) Schrock, R. R.; Hoveyda, A. H. *Angew. Chem., Int. Ed.* **2003**, *42*, 4592–4633. (c) Ivin, K. J.; Mol, J. C. *Olefin Metathesis and Metathesis Polymerization*; Academic Press: San Diego, CA, 1997.

(2) (a) Schwab, P.; Grubbs, R. H.; Ziller, J. W. *J. Am. Chem. Soc.* **1996**, *118*, 100–110. (b) Scholl, M.; Ding, S.; Lee, C. W.; Grubbs, R. H. *Org. Lett.* **1999**, *1*, 953–956. (c) Garber, S. B.; Kingsbury, J. S.; Gray, B. L.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2000**, *122*, 8168–8179.

(3) (a) Trnka, T. M.; Grubbs, R. H. *Acc. Chem. Res.* **2001**, *34*, 18–29. (b) Grubbs, R. H. *Tetrahedron* **2004**, *60*, 7117–7140. (c) Schrodi, Y.; Pederson, R. L. *Aldrichim. Acta* **2007**, *40*, 45–52. (d) Grubbs, R. H. *Adv. Synth. Catal.* **2007**, *349*, 34–40.

10.1021/ol9000153 CCC: $40.75

Several decompostion pathways involve bimetallic species due to the propensity for ruthenium to dimerize via thermodynamically stable chloride (**4** and **6**) or carbide bridges (**5**) (Figure 2).[4b−e] One approach to prevent these undesirable bimolecular decomposition pathways is to immobilize the catalyst onto a solid support that inhibits intermolecular catalyst−catalyst interactions via site isolation.[6] Furthermore, supported catalysts have the added advantages of generating products free of ruthenium contamination and possess the ability to be recovered and subsequently recycled. A number of reports have been published employing various strategies to obtain solid-supported olefin metathesis catalysts.[7] These consist of anchoring the catalytic moiety, via a number of positions within the catalyst framework, to a variety of solid supports, such as organic polymers or inorganic oxides. Of the various strategies, immobilization through a chelating benzylidene has been the most widely employed. These catalysts operate via a release/return phenomenon[8] with all the catalytic activity arising from a homogeneous species, which is susceptible to the same bimetallic decomposition pathways. Likewise, such systems cannot realize all the benefits of solid-phase catalysis, such as desirable continuous flow processes.

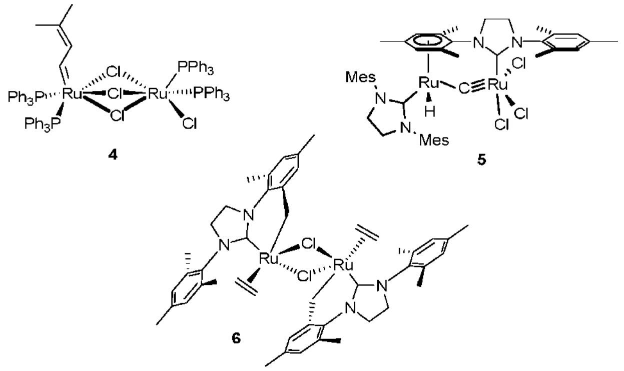
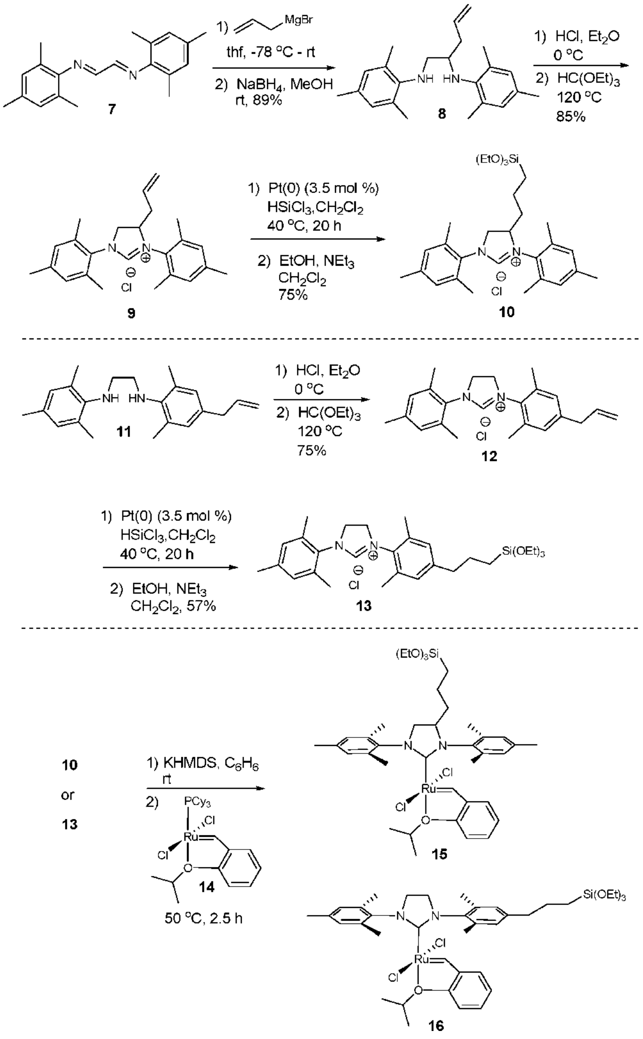


Figure 2. Various dimeric ruthenium decomposition products.[4]

Scheme 1. Synthesis of Ruthenium Complexes **15** and **16**



Other strategies involve immobilization via alternative X-type ligands that replace the ancillary chlorides, such as fluorinated carboxylates,[9] or via functionalized NHC ligands.[10] The latter is a very attractive approach as the NHC forms a strong bond to the ruthenium center and is the most substitutionally inert ligand within the catalyst coordination sphere.[11] Herein, we report the syntheses of two triethoxysilyl functionalized NHC ligands (**10** and **13**) and their use in the generation of ruthenium complexes **15** and **16**.[12] The subsequent grafting of these complexes onto silica is described and the utility of the silica-supported analogues as heterogeneous catalysts is evaluated.

The synthesis of **10** began with the allylation of bisimine **7** followed by reduction to furnish diamine **8**. This was treated with HCl and triethyl orthoformate to generate the imidazolium

---

(4) (a) Ulman, M.; Grubbs, R. H. *J. Org. Chem.* **1999**, *64*, 7202–7207. (b) Amoroso, D.; Yap, G. P. A.; Fogg, D. E. *Organometallics* **2002**, *21*, 3335–3343. (c) Amoroso, D.; Snelgrove, J. L.; Conrad, J. C.; Drouin, S. D.; Yap, G. P. A.; Fogg, D. E. *Adv. Synth. Catal.* **2002**, *344*, 757–763. (d) Hong, S. H.; Day, M. W.; Grubbs, R. H. *J. Am. Chem. Soc.* **2004**, *126*, 7414–7415. (e) Hong, S. H.; Wenzel, A. G.; Salguero, T. T.; Day, M. W.; Grubbs, R. H. *J. Am. Chem. Soc.* **2007**, *129*, 7961–7968. (f) Hong, S. H.; Chlenow, A.; Day, M. W.; Grubbs, R. H. *Angew. Chem., Int. Ed.* **2007**, *46*, 5148–5151. (g) van Rensburg, W. J.; Steynberg, P. J.; Meyer, W. H.; Kirk, M. M.; Forman, G. S. *J. Am. Chem. Soc.* **2004**, *126*, 14332–14333.

(5) (a) Berlin, J. M.; Campbell, K.; Ritter, T.; Funk, T. W.; Chlenov, A.; Grubbs, R. H. *Org. Lett.* **2007**, *9*, 1339–1342. (b) Stewart, I. C.; Ung, T.; Pletnev, A. A.; Berlin, J. M.; Grubbs, R. H.; Schrodi, Y. *Org. Lett.* **2007**, *9*, 1589–1592. (c) Anderson, D. R.; Lavallo, V.; O'Leary, D. J.; Bertrand, G.; Grubbs, R. H. *Angew. Chem., Int. Ed.* **2007**, *46*, 7262–7265. (d) Vougioukalakis, G. C.; Grubbs, R. H. *J. Am. Chem. Soc.* **2008**, *130*, 2234–2245. (e) Chung, C. K.; Grubbs, R. H. *Org. Lett.* **2008**, *10*, 2693–2696.

(6) (a) Collman, J. P.; Belmont, J. A.; Brauman, J. J. *J. Am. Chem. Soc.* **1983**, *105*, 7288–7294. (b) Drago, R. S.; Pribich, D. C. *Inorg. Chem.* **1985**, *24*, 1983–1985. (c) Tollner, K.; Popovitv-Biro, R.; Lahav, M.; Milstein, D. *Science* **1997**, *278*, 2100–2102. (d) Annis, D. A.; Jacobsen, E. N. *J. Am. Chem. Soc.* **1999**, *121*, 4147–4154.

(7) For recent review articles, see: (a) Buchmeiser, M. R. *New. J. Chem.* **2004**, *28*, 549–557. (b) Coperet, C.; Basset, J.-M. *Adv. Synth. Catal.* **2007**, *349*, 78–92. (c) Clavier, H.; Grela, K.; Kirschning, A.; Mauduit, M.; Nolan, S. P. *Angew. Chem., Int. Ed.* **2007**, *46*, 6786–6801.

(8) (a) Kingsbury, J. S.; Harrity, J. P. A.; Bonitatebus, P. J.; Hoveyda, A. H. *J. Am. Chem. Soc.* **1999**, *121*, 791–799. (b) Hoveyda, A. H.; Gillingham, D. G.; van Veldhuizen, J. J.; Kataoka, O.; Garber, S. B.; Kingsbury, J. S.; Harrity, J. P. A. *Org. Biomol. Chem.* **2004**, *2*, 8–23.

chloride **9**. A Pt(0)-catalyzed hydrosilylation of **9** using $HSiCl_3$ and subsequent treatment with ethanol/NEt_3 produced the triethoxysilyl backbone functionalized NHC salt **10**. A similar strategy was used to prepare NHC salt **13**. Diamine **11** was prepared in three steps from commercially available starting materials (see the Supporting Information) and used to generate *p*-allyl NHC salt **12**. This was transformed to the triethoxysilyl-functionalized NHC salt **13** via the Pt(0)-catalyzed hydrosilylation procedure described above. Ruthenium complexes **15** and **16** were subsequently prepared by deprotonation of the respective NHC salts, **10** and **13**, with potassium bis(trimethylsilyl)amide and treatment of the resulting free carbene with ruthenium complex **14**.

Next, solutions of **15** and **16** were stirred with silica at 25 °C for 72 h to obtain the corresponding silica-supported catalysts **15-SiO_2** and **16-SiO_2** (Figure 3). At this time, the ruthenium-loaded material was transferred to a Soxhlet extraction thimble and continuously extracted with CH_2Cl_2 for 48 h. This step was necessary to remove any traces of **15** or **16** that were not covalently immobilized to the silica support.

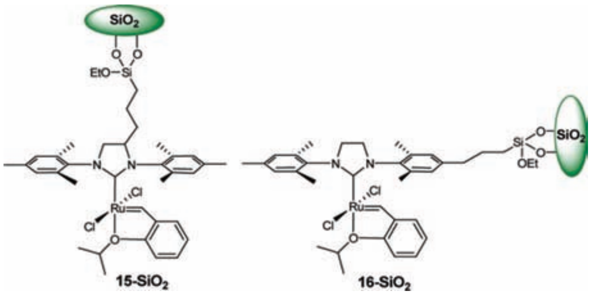


Figure 3. Silica-supported catalysts **15-SiO_2** and **16-SiO_2**.

With silica-supported analogues **15-SiO_2** and **16-SiO_2** in hand, we first wanted to gauge their catalytic activity, along with determining their degree of heterogeneity. This was necessary to ensure that the catalytic activity arises from the supported catalyst and not from some *active* species leaching from the solid support. This was done by performing a split or hot-filtration test.[13] We examined the RCM of diethyldiallyl malonate at 60 °C for both supported catalysts, where, after 10 min half of the reaction was filtered at a conversion of 67% (**15-SiO_2**) and 31% (**16-SiO_2**), respectively. After an additional 50 min reaction time, the silica-supported catalyst containing suspensions proceeded to >95% (**15-SiO_2**) and 86% (**16-SiO_2**), whereas the filtered portions showed no further reactivity (Figure 4). Thus, the catalytic activity arises from the supported complex and not from catalyst that leached from the solid support. Also worth noting is that the filtered reaction mixture involving **15-SiO_2** was analyzed for ruthenium content and contained <5 ppb ruthenium contamination (below detection limit of ICP-MS).

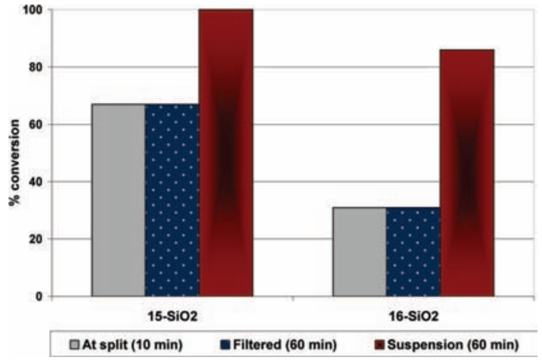
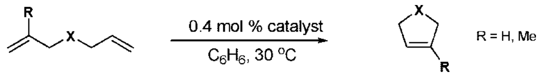
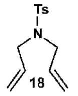
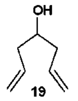


Figure 4. Split tests to determine the degree of catalyst heterogeneity for **15-SiO_2** and **16-SiO_2**. Reactions were performed in C_6D_6 (0.1 M) using 0.25−0.5 mol % of catalyst and percent conversion determined by ^1H NMR.

With the positive results obtained from the split tests, the catalysts were next examined in a series of RCM reactions as displayed in Table 1. The results show that both catalysts are

Table 1. RCM Reactions Employing **15-SiO_2** and **16-SiO_2**



entry	RCM substrate	catalyst	time	conversion (%)[a]
1	 17	15-SiO_2	1 h	> 95
		16- SiO_2	1 h	84
2	 18	15-SiO_2	2 h	> 95 [b]
		16- SiO_2	2 h	85 [b]
3	 19	15-SiO_2	1 h	83
		16- SiO_2	1 h	13
4	 (E = CO_2Et) 20	15-SiO_2	4 h	> 95
		16- SiO_2	4 h	55

[a] Reactions were not run to completion, rather only for the alloted time. Percent conversions determined by ^1H NMR. [b] ICP-MS analysis of the RCM product isolated by filtration and concentration indicated <5 ppb ruthenium contamination.

---

(9) For a representative example, see: Halbach, T. S.; Mix, S.; Fischer, D.; Maechling, S.; Krause, J. O.; Sievers, C.; Blechert, S.; Nuyken, O.; Buchmeiser, M. R. *J. Org. Chem.* **2005**, *70*, 4687–4694.

(10) For representative examples, see: (a) Schürer, S. C.; Gessler, S.; Buschmann, N.; Blechert, S. *Angew. Chem., Int. Ed.* **2000**, *39*, 3898–3901. (b) Mayr, M.; Buchmeiser, M. R.; Wurst, K. *Adv. Synth. Catal.* **2002**, *344*, 712–719. (c) Prühs, S.; Lehmann, C. W.; Fürstner, A. *Organometallics* **2004**, *23*, 280–287.

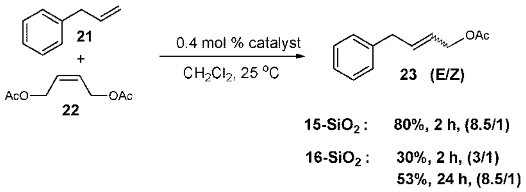
(11) For evidence of exchange between the X-type ligands, see: Tanaka, K.; Böhm, V. P. W.; Chadwick, D.; Roeper, M.; Braddock, D. C. *Organometallics* **2006**, *25*, 5696–5698.

(12) Merck & Co., Inc. have filed patents in this research area. For a representative patent see: Koehler, K. Immobilizable N-heterocyclic Carbene Metal Complexes with Alkoxysilyl Groups International Patent No. WO 2007/017047 A1.

(13) Sheldon, R. A.; Wallau, M.; Arends, I. W. C. E.; Schuchardt, U. *Acc. Chem. Res.* **1998**, *31*, 485–493.

competent, even at the low catalyst loadings employed (0.4 mol %); however, in all cases the NHC backbone functionalized **15-SiO$_2$** outperforms the *p*-*N*-aryl-derived **16-SiO$_2$**.[14]

Next, the supported catalysts were screened for the cross-metathesis reaction between allylbenzene (**21**) and *cis*-1,4-diacetoxy-2-butene (**22**) (eq 1).[15] Again, **15-SiO$_2$** outperformed **16-SiO$_2$** supplying the cross product in 80% versus 30% yield after 2 h. However, **16-SiO$_2$** did continue to turnover, reaching a maximum of 53% conversion after 24 h.[16]



(1)

The reason for the greater reactivity of **15-SiO$_2$** compared to **16-SiO$_2$** is unknown; however, it is speculated to arise from an interaction between the ruthenium active site and the silica surface that is present in the case of **16-SiO$_2$** but is blocked by the steric bulk of the NHC ligand in the case of **15-SiO$_2$**. RCM studies involving the homogeneous complexes **15** and **16** were performed in hopes of gaining insight into this matter and revealed that **16** had a slightly longer induction period compared to **15**, however this does not appear to account for the sometimes dramatic differences in activity observed for the supported analogues (see the Supporting Information). The difference then is most likely a function of the silica support.

We were next interested in gaining some information into the recyclability of the supported catalysts. Due to the increased reactivity of **15-SiO$_2$**, it was utilized for a recycling experiment involving the RCM of diethylallylmethyallyl malonate (**20**). The results are depicted in Figure 5 and show that the catalyst was effectively recycled multiple times with an eventual gradual decrease in activity.

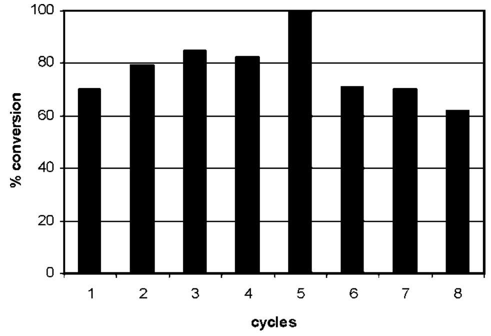


Figure 5. Recycling of **15-SiO$_2$** for RCM of substrate **20**. Reactions were performed in C_6H_6 (0.1 M) using 0.75 mol % of **15-SiO$_2$**/cycle and percent conversions determined by ^1H NMR. Each cycle was 2 h except for no. 5, which was run for 12 h.

In conclusion, we have successfully synthesized two triethoxysilyl-functionalized NHC ligands and the corresponding second-generation olefin metathesis catalysts which were anchored onto silica to furnish silica-supported catalysts **15-SiO$_2$** and **16-SiO$_2$**. These species were shown to be competent catalysts for a variety of olefin metathesis reactions, mimicking their homogeneous counterparts. Likewise, the activity of the supported catalysts is truly heterogeneous in nature as revealed by split tests and they can be recycled multiple times. Most importantly, the catalysts do not leach ruthenium under the standard reaction conditions as revealed by ICP-MS analysis of filtered reaction solutions (ruthenium concentration of filtrate <5 ppb in all cases).

Acknowledgment. We gratefully acknowledge financial support from DOE Grant No. DE-FG02-08ER15933 to R.H.G. and to NSERC of Canada for a postdoctoral fellowship to D.P.A.

Supporting Information Available: Experimental procedures and characterization data for new compounds and all procedures for catalytic studies. This material is available free of charge via the Internet at http://pubs.acs.org.

OL9000153

---

(14) A direct comparsion between the better heterogeneous catalyst **15-SiO$_2$** and the corresponding homogeneous catalyst **3** was not performed, but it is estimated that **3** is approximately 2−3 times more active in terms of reaction rate.

(15) Ritter, T.; Hejl, A.; Wenzel, A. G.; Funk, T. W.; Grubbs, R. H. *Organometallics* **2006**, *25*, 5740–5745.

(16) It was hoped that the bulky steric nature of the silica support may influence the *E*/*Z* selectivity of **23**; however, a plot of the *E*/*Z* ratio vs percent conversion of **23** employing **15-SiO$_2$** and **16-SiO$_2$** reveals that the supported catalysts behave similarly to homogeneous catalysts **1**−**3** (see the Supporting Information).