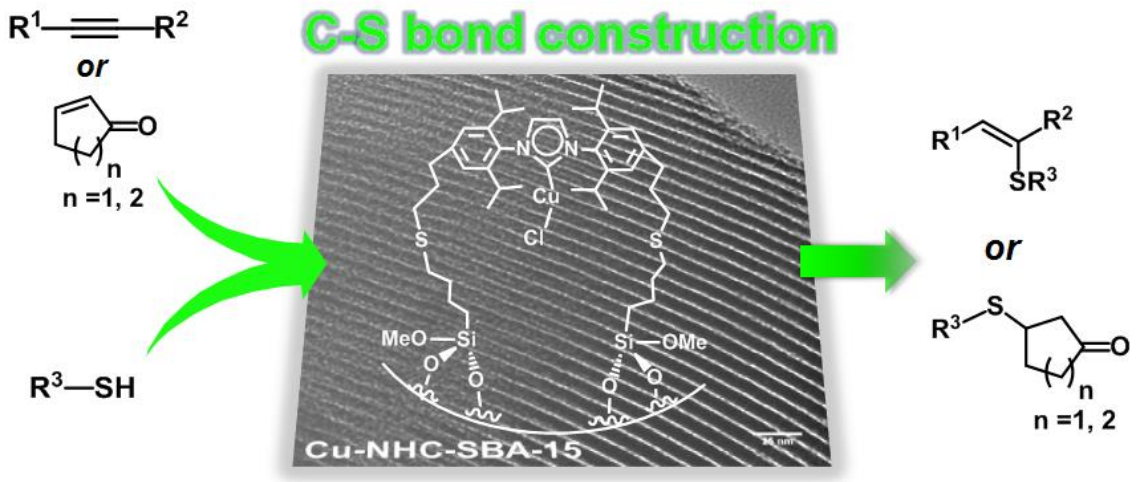
Green Chemistry

Accepted Manuscript

ROYAL SOCIETY OF CHEMISTRY

www.rsc.org/greenchem

TOC graphic



A Robust Supported Cu-NHC Complex Catalyzed Highly Stereoselective Anti-Markovnikov Hydrothiolation of Alkynes or Electron-deficient Alkenes to Construct C-S Bond Compounds was Developed.

Highly Stereoselective Anti-Markovnikov Hydrothiolation of Alkynes and Electron-Deficient Alkenes by a Supported Cu-NHC Complex

Yong Yang*

Department of Chemical Engineering

The Pennsylvania State University

University Park, PA 16802, USA

Current address: Organic Chemistry, Institute of Chemical & Engineering Sciences (ICES), 11 Biopolis Way, Helios Blk, #03-08, 138667 Singapore.

*Email: yangyo@ices.a-star.edu.sg

Abstract

A practical, efficient, and low-cost heterogeneous catalyst consisting of a Cu-NHC (N-heterocyclic carbene) complex grafted to SBA-15 silica for the catalytic hydrothiolation of alkynes and electron-deficient alkenes under mild reaction conditions has been developed. The heterogeneous catalyst displays higher activity and stereoselectivity to *Z*-*anti*-Markovnikov isomers compared with the homogeneous analog under otherwise identical reaction conditions. The catalytic system is applicable to a broad range of alkynes and thiols and is recyclable without significant loss in catalytic performance. High activity and perfect selectivity to alkyl sulfides formed by the addition of electron-deficient alkenes to various thiols catalyzed by the supported Cu-NHC complex were also realized.

Keywords: Hydrothiolation, Alkynes and thiols, Electron-deficient alkenes, Copper-carbene complex, SBA-15

1. Introduction

Vinyl sulfides are prevalent in many natural products, pharmaceuticals and are versatile intermediates for the synthesis of biologically active compounds, organic building blocks, and new materials.[1] Many approaches have been developed to construct vinyl sulfides compounds, such as the addition of thiols to alkynes in the presence of transition metals,[2] free radicals,[3] or bases,[4] Wittig olefination,[5] direct nucleophilic substitution with vinyl halides,[6] and reaction of sulfonyl hydrazides with terminal arylacetylenes using a DBU-based ionic liquid.[7] Despite considerable progress, these approaches generally suffer from harsh reaction conditions, costly starting materials, or low regio- and stereoselectivity. It remains a challenge to develop a highly regio- and stereo-controlled synthesis of vinyl sulfides under mild reaction conditions.

Transition metal catalyzed addition of S-H bond to alkynes is a straightforward and atom-efficient method for the formation of stereo- and regio-defined vinyl sulfides compounds. Markovnikov[2a-f, 2p] and *anti*-Markovnikov[2g-p] selectivity has been observed in transition metal catalyzed processes. In the case of *anti*-Markovnikov addition in the presence of transition metals, either *Z* (*cis*-configuration) or *E* (*trans*-configuration) isomer, or a mixture of *Z* and *E* isomers are produced. High stereoselectivity to the *E*-isomer is observed in most cases.[2i, 2j, 2n, 2o, 2p] In contrast, there are fewer demonstrations of catalytic hydrothiolation for the preparation of stereoselective *Z*-isomers. Kondoh et al.[4b] reported the synthesis of *Z*-vinyl sulfides catalyzed by Cs_2CO_3 as a base for alkyne hydrothiolation. However, such a process required the presence of 2,2,6,6-tetramethylpiperidine-N-oxyl (TEMPO) as a radical inhibitor, and demonstrated limit substrate versatility since it was only applicable to alkyl thiols. Frech[8] reported a Pd complex (dichlorobis[1-(dicyclohexylphosphanyl)piperidine]palladium) for the synthesis of *Z*-vinyl sulfides with good substrate generality. Very recently, copper-catalyzed processes for the highly

stereoselective synthesis of *Z*-vinyl sulfides have been reported by Beletskaya,[9] Zhang,[10a] and Liu,[10b] through CuI-catalyzed addition of alkynes with thiols, CO_2-mediated reductive coupling of alkynes and thiols, and decarboxylative C-S coupling reaction, respectively.

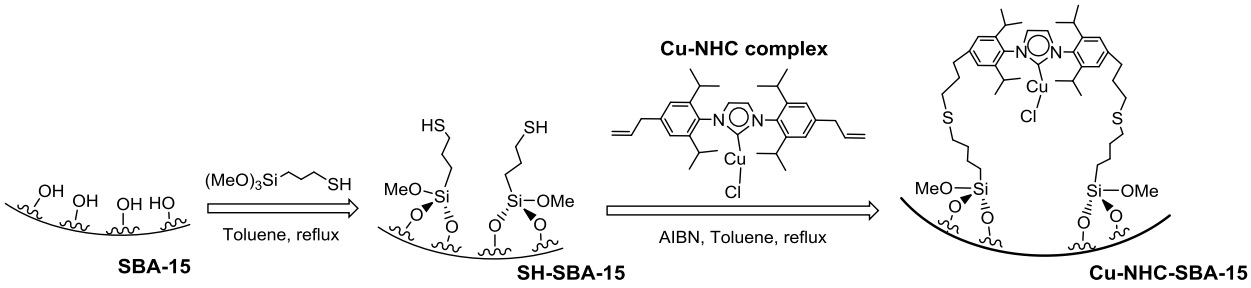
Due to reasons of commercial availability, lower cost, and abundance of copper, compared with noble metals, there is an incentive to replace these noble metal catalysts with low-cost copper complexes. Copper complexes have been extensively developed for applications in organic synthesis and catalysis.[11] Among the many complexes investigated, Cu-NHC (N-heterocyclic carbene) complexes have attracted great interest because the strongly σ-donating NHC ligand offers an opportunity to tune the reactivity and selectivity of transition metal catalysts.[12] Cu-NHC complexes have been successfully employed in hydroboration,[13] alkene hydrothiolation,[14] hydrosilylation,[15a] oxidative coupling,[15b] and carboxylation reactions.[16] No studies known to us have pursued the hydrothiolation of alkynes catalyzed by Cu-NHC complexes. Due to the unique electronic and steric properties of NHC ligands, we envisioned Cu-NHC complexes might be capable of facilitating alkyne hydrothiolation in a regio- and stereoselective fashion. Although homogeneous Cu-NHC complexes have advantages such as high activity and selectivity, their recovery and reuse detracts from their adoption in practical applications. Furthermore, residual metal along with the products could induce serious problems in the synthesis of bioactive and functional substrates. Heterogeneous catalysts offer potential advantages including easy product separation, long lifetime, and enhanced stability. Immobilization of transition metal complexes onto a solid support to produce a molecular heterogeneous catalyst is one way to make such catalysis practical.[17] The immobilization of metal complexes through covalent bond formation with functional groups on high surface area silica materials is the most widely employed approach to form surface organometallic catalysts

that are applicable for a variety of catalytic chemistries. The structures of metal complexes upon immobilization on silica surface not only reduce metal leaching from the support and subsequent metal contamination of the products, but also can provide an enhancement in the reactivity and selectivity.[18] The chemical bonding between metal complexes and functional groups of the support can realize to maintain the isolated nature of metal complexes with controllable loadings, which can influence the catalytic performance in a manner that the homogeneous analogous does not exhibit in solution.[19]

Recently, we developed a well-defined supported Rh complex on SBA-15 for a broad range of alkyne hydrothiolation in high yield with excellent stereoselectivity to *E*-vinyl sulfides.[2p] The objective of this study was to develop a heterogeneous catalyst comprised of an inexpensive, earth-abundant element with the capability of producing the *Z*-vinyl sulfide product. Herein, we report a facile, efficient, and low-cost supported Cu-NHC complex on SBA-15 for regio- and stereoselective hydrothiolation of alkynes and electron-deficient alkenes to produce *Z*-vinyl sulfides and alkyl sulfides with high activity and recyclability.

2. Results and discussion

2.1 Characterization of the supported Cu-NHC complex



Scheme 1. Procedure for the preparation of the Cu-NHC-SBA-15 catalyst.

SBA-15, a mesoporous hexagonal silica with large tunable uniform pores (6-9 nm^{-1}) and high specific surface area (700−900 m^2 g^{-1}), was synthesized according to the previous literature.[20] Preparation of the Cu-NHC-SBA-15 catalyst was performed via a covalent attachment strategy in a step-by-step manner under a N_2 atmosphere, as shown in Scheme 1. The terminal C=C bonds in the Cu-NHC complex coupled with –SH groups tethered on SBA-15 surface in the presence of AIBN (2-2'-azoisobutyronitrile) as an initiator in toluene, resulting in the immobilization of the Cu-NHC complex onto the surface of SBA-15. Characterization results from physical adsorption, X-ray diffraction (XRD), and high resolution transmission microscopy (HR-TEM) (Supporting Information, Figure S1, 2 and 3, Table S1) for a Cu-NHC-SBA-15 catalyst demonstrate preservation of the ordered mesoporous structure upon functionalization and immobilization of the Cu-NHC complex within the pores of SBA-15.

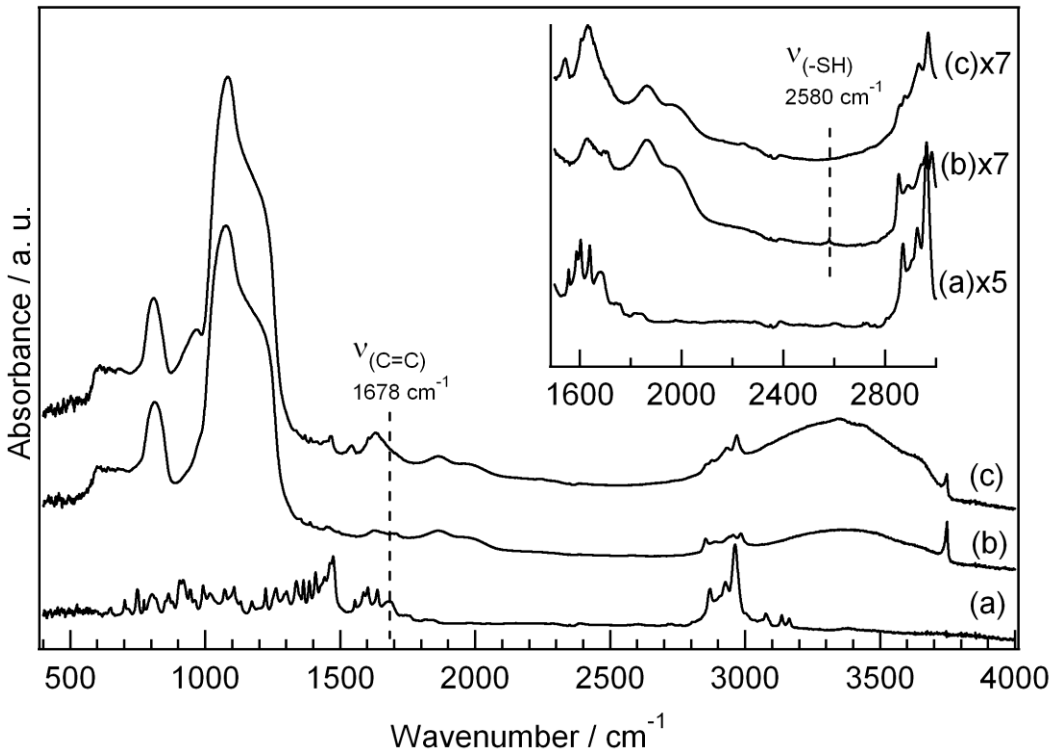


Figure 1. FT-IR spectra for (a) Cu-NHC complex; (b) SH-SBA-15; and (c) Cu-NHC-SBA-15. Insets are magnified views of the –SH stretching region for SH-SBA-15 and Cu-NHC-SBA-15, respectively. The inset shows the expanded spectra ranging from 1500-3000 cm^{-1}.

Figure 1 shows the FT-IR spectra for the homogeneous Cu-NHC complex, SH-SBA-15, and the supported Cu-NHC-SBA-15 catalyst, respectively. Upon immobilization of the Cu-NHC complex onto the support SH-SBA-15, the characteristic FT-IR peaks at 1678 and 2580 cm^{-1}, assigned to the stretching of C=C bond in the Cu-NHC complex (spectrum a) and -SH of the grafted thiol (spectrum b) on SBA-15 disappeared, suggesting the effective coupling between C=C bond and -SH groups in the presence of AIBN. The characteristic peaks of the Cu-NHC complex appeared upon immobilization onto SBA-15 (spectrum c), indicating the Cu-NHC complex was covalently tethered to the surface of SBA-15. During preparation of the SH-SBA-15 material, the nominal loading of (3-mercaptopropyl)trimethoxysilane was 3.0 molar excess relative to the amount of Cu-NHC complex added to the SH-SBA-15 (accounting for the 2:1 stoichiometry between –SH:Cu-NHC; see Scheme 1) (see Supporting Information for Experimental details). Elemental analysis of the supernatant demonstrated the nominal amount of Cu added during synthesis was retained in the final Cu-NHC-SBA-15 catalyst. The enlarged regions where the –SH vibration occurs demonstrate that a weak –SH resonance is observable in SH-SBA-15 (Figure 1b) but absent in Cu-NHC-SBA-15 (Figure 1c). The decreased concentration of grafted –SH groups after coupling reaction of the Cu-NHC complex with SH-SBA-15 reduces the infrared –SH signal below the noise level of the instrument since –SH groups were grafted in excess of the nominal amount of Cu-NHC complex added during the synthesis. The maximum surface density of –SH groups on the surface of Cu-NHC-SBA-15

after grafting is 0.195 nm^{-2} compared with 0.415 nm^{-2} for the SH-SBA-15 (these surface densities are normalized by the BET surface area for the corresponding material, see Supporting Information Table S1).

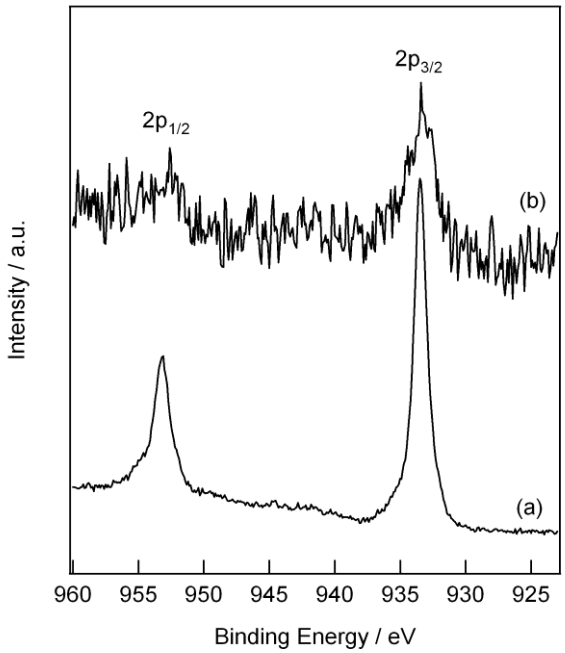


Figure 2. Cu $2p_{3/2}$ XPS spectra for (a) Cu-NHC complex and (b) Cu-NHC-SBA-15.

Figure 2 shows Cu $2p_{3/2}$ XPS spectra for the homogeneous Cu-NHC complex and the supported Cu-NHC-SBA-15. Cu $2p_{3/2}$ XPS analysis showed the oxidation state of Cu does not change after immobilization (Figure 2b). We have provided additional confirmation that the electronic structure of the Cu(I) center is minimally perturbed when grafted to the SH-SBA-15 support utilizing UV-Vis spectroscopy (see Supporting Information Figure S4). In the UV/Vis spectra, similar peaks before and after immobilization were observed at 363 nm (Cu d $\rightarrow$ carbene π) and 498 nm (Cl p $\rightarrow$ Cu d).[21] The presence of the d-π transition in the spectrum of the grafted copper complex (curve b) indicates the presence of a carbene ligand, Cu(I) oxidation state and a local coordination that resembles the Cu-NHC complex.

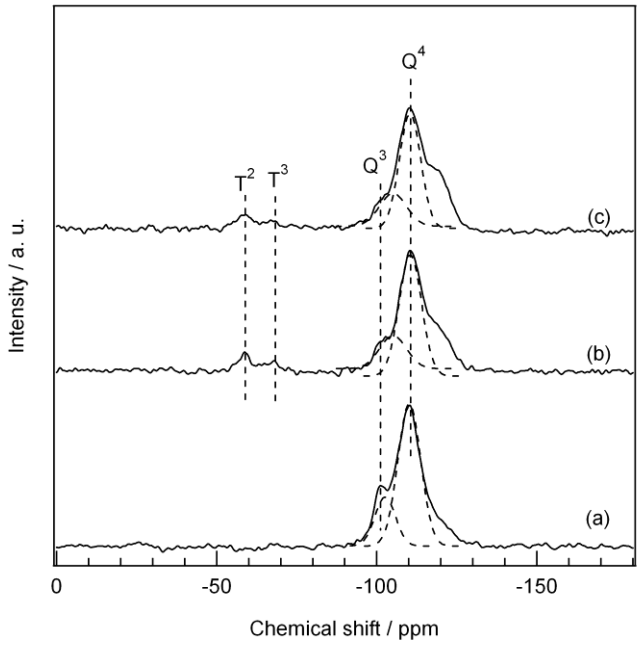


Figure 3. ^{29}Si solid-state NMR spectra for (a) SBA-15; (b) SH-SBA-15; and (c) Cu-NHC-SBA-15.

Further evidence for the successful immobilization was provided by ^{13}C and ^{29}Si solid-state CP-MAS NMR results (Figures 3 and 4). The appearance of new peaks at δ = -67 and -58 ppm in the ^{29}Si solid-state NMR spectrum (Figure 3, spectra b and c), corresponding to T^2 ($RSi(OSi)_2(OH)$) and T^3 ($RSi(OSi)_3$) sites,[22] respectively, revealed (3-mercaptopropyl)trimethoxysilane reacted with SiOH groups on the SBA-15 surface and formed covalent linkages of approximately of 73% -$Si(OSi)_3$ and 27% -$Si(OSi)_2(OCH_3)$ type. Two signals around -100, and -110 ppm were observed for the pure SBA-15 (Figure 3, spectrum a), characteristic of Q^3 and Q^4 silicon sites of the SiO_4-substructures ($Q^n = Si(OSi)_n(OH)_{4-n}$, n = 2-4) in the silica framework.[22] Upon grafting (3-mercaptopropyl)trimethoxysilane to the surface of silica, there are no significant differences among the Q^3 and Q^4 species with an exception of a reduction in intensity of the Q^3 species, consistent with studies of silicate materials.[23, 24]

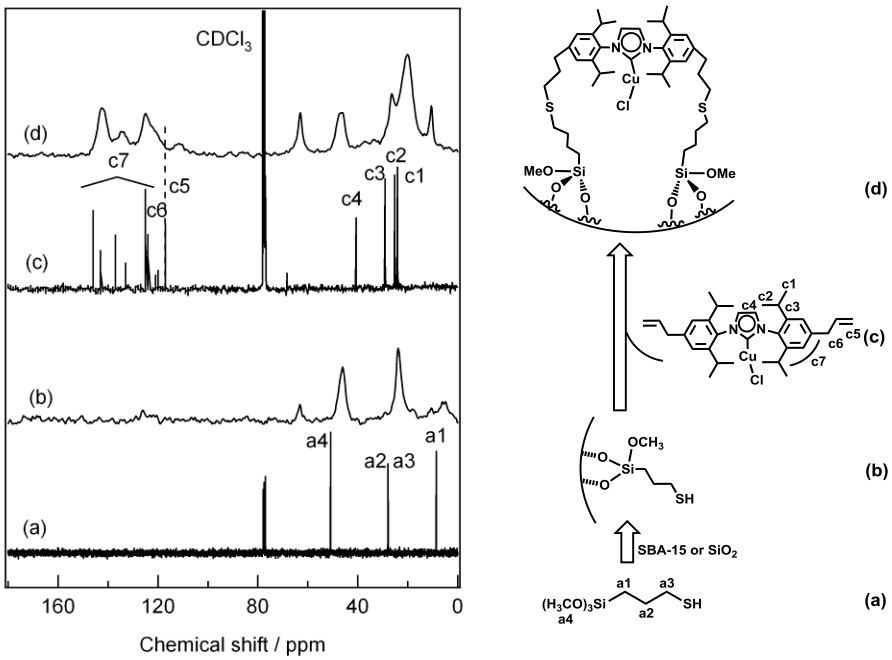


Figure 4. ^{13}C liquid and solid-state NMR spectra for (a) $SH(CH_2)_3Si(OCH_3)_3$; (b) SH-SBA-15; (c) Cu-NHC complex; and (d) Cu-NHC-SBA-15.

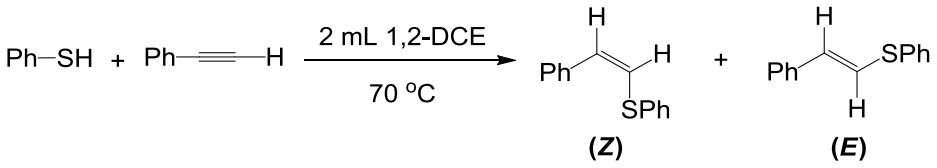
The presence of ^{13}C NMR peaks corresponding to Cu-NHC complex in the expected regions is good evidence of successful immobilization of the Cu-NHC complex onto the SH-SBA-15 support due to the coupling reaction in the presence of AIBN, consistent with FT-IR results. The loading of the Cu-NHC-SBA-15 catalyst was determined to be 0.69 wt% (Cu) by ICP-OES, which corresponds to a copper density of 0.2 nm^{-2}. This rather low density ensured a high probability that individually-grafted Cu-NHC complexes were site-isolated.

The occurrence of the grafting reaction between the Cu-NHC complex and –SH groups on the surface of silica is confirmed by a combination of infrared spectroscopy, ^{13}C solid-state NMR spectroscopy and Cu elemental analysis. None of the techniques individually are sufficient enough to confirm the occurrence of grafting since the spectra become complex when Cu-NHC complex is grafted to the silica surface due to broad spectral contributions of silanol and siloxane

stretches in the infrared spectra and the inherent broadening observed in solid-state NMR. However, the apparent disappearance of the –SH (~2580 cm^{-1}) and C=C (~1678 cm^{-1}) vibrations coupled with the solid-state ^{13}C NMR results demonstrate the characteristic resonance of the terminal C=C peak (117 ppm) in the Cu-NHC disappears after grafting to the SH-functionalized surface (Figure 4d) is confirmation that the reaction between the grafted alkylthiol and Cu-NHC complex occurred. Elemental analysis of the immobilised Cu catalyst demonstrated the actual weight loading of Cu was 0.69 wt.% which agreed with the nominal weight loading. Therefore, all of the Cu-NHC complex was grafted to the surface of the SH-modified SBA-15 silica. In total, the three techniques provide evidence that the grafting reaction occurred.

2.2 Hydrothiolation of phenylacetylene with thiophenol over different catalysts

Table 1. Activity and selectivity of homogeneous and heterogeneous Cu-based catalysts[a]



Entry	Catalyst	Time (h)	Conv.[b]	Selectivity (%)[c] *Z*:*E*	$TOF_{ini}(h^{-1})$[d]
1	Blank[e]	24	41.2	51:49	-
2	SBA-15[f]	24	39.6	52:48	-
3	SH-SBA-15[g]	24	40.8	56:44	-
4	CuCl[h]	3	>99.0	58:42	65.9
5	Cu-NHC[i]	24	79.2	72:28	3.2

6	Cu-NHC-SBA-15[j]	20	98.0	89:11	28.7
7	Cu-NHC-SiO_2[k]	24	71.0	81:19	10.8

[a] Reaction conditions: 1.0 mmol phenylacetylene, 1.1 mmol thiophenol, 2 mL 1,2-DCE, 70°C. [b] Conversion of phenylacetylene. [c] Determined by ^{1}H NMR analysis of the crude mixture. [d] The initial turnover frequency for phenylacetylene disappearance at conversion < 30%. [e] In the absence of catalyst. [f] 50 mg SBA-15. [g] 50 mg SH-SBA-15. [h] 20 μmol CuCl. [i] 10 μmol Cu-NHC complex (as-synthesized, see the Supporting Information for details).[j] 50 mg Cu-NHC-SBA-15 (5.3 μmol Cu). [k] 50 mg Cu-NHC-SiO_2 (5.4 μmol Cu) (see the Supporting Information for details).

Initial efforts concentrated on screening Cu catalysts for the stereo-defined synthesis of vinyl sulfides. The addition of phenylacetylene to thiophenol was chosen as a model reaction; a summary of the results are compiled in Table 1. The addition proceeded quite slowly and gave poor conversion with a mixture of (*E* + *Z*) vinyl sulfide (*Z*/*E* ratio = 51/49, 52/48, 56/44, respectively) in the absence of catalyst, in the presence of the support SBA-15 or SH-SBA-15 (entries 1-3) in 1,2-dichloroethane (1,2-DCE), respectively. Upon the addition of the precursor Cu(I)Cl to the reaction mixture, the activity increased dramatically, affording complete conversion but with roughly identical stereoselectivity to *Z* and *E* vinyl sulfide isomers after 3 h (entry 4). The Cu-NHC complex as a homogeneous catalyst, synthesized from Cu(I)Cl and the N-heterocyclic carbene (1,3-bis-(4-allyl-2,6-diisopropyl-phenyl)imidazolium chloride) ligand in the presence of NaO^{t}Bu (see the Experimental Section), showed a relatively low reaction rate (79.2% conversion after 24 h) compared with Cu(I)Cl under otherwise identical reaction conditions. However, there was a substantial change in stereoselectivity; the *Z*-vinyl sulfide was the predominant product, demonstrating the N-heterocyclic carbene ligand facilitates stereoselective-reaction control. Upon immobilization of the Cu-NHC complex onto SBA-15,

the catalytic activity was significantly enhanced under otherwise identical reaction conditions. The initial turnover frequency of Cu-NHC-SBA-15 was 9 times higher than the Cu-NHC complex. More importantly, the stereoselectivity to *Z*-vinyl sulfide increased even with the increased activity.

The rates of both the homogeneous and heterogeneous reactions were proven to be free of transport artifacts. For the homogeneous reactions, initial turnover frequency (normalized to the moles of Cu) does not change with catalyst loading and reactions were conducted in a regime where the stirring speed had no influence on the measured rate of reaction. For the heterogeneous reaction, we applied the Weisz-Prater test[25a,b] to confirm the rates over the heterogeneous catalyst were not influenced by mass transfer. Utilizing a procedure identical to Mukherjee and Vannice[25c], calculated values for the W-P parameter were on the order of $\sim 10^{-2}$ demonstrating transport limitations were insignificant in the supported catalyst system.

Initial rate experiments were carried out to shed light on the differences in catalytic performance between the Cu-NHC complex and Cu-NHC-SBA-15. The results, shown in Figure 5, demonstrate the Cu-NHC complex exhibited a lower reaction rate and the reaction proceeded sluggishly without deactivation of the catalyst; while the Cu-NHC-SBA-15 catalyst displayed a higher initial reaction rate. We postulate the higher catalytic activity of the supported Cu-NHC-SBA-15 originates from the formation of site-isolated catalytically active sites on the surface of SBA-15, while the slower reaction rate of the homogeneous Cu-NHC complex is likely due to the formation of an inactive Cu species through bimolecular condensation reactions between Cu-NHC complexes. A control experiment involving the as-synthesized Cu-NHC complex in 1,2-DCE without the addition of thiophenol at 70°C demonstrated that the color of the solution changed to dark brown after reaction for 24 h. UV-Vis spectroscopic analysis of the solution

contained a small plasmon band at ~565 nm, which is consistent with literature[26] and suggestive of the formation of small metallic Cu particles. These particles are believed to be small since there was no evidence of Cu precipitation. Further work is necessary to completely characterize the Cu species formed during the reaction of the homogeneous Cu-NHC complex. Extended X-ray absorption fine structure (EXAFS) measurements would be required to confirm the presence of Cu-Cu bonding which is beyond the intended scope of this work.

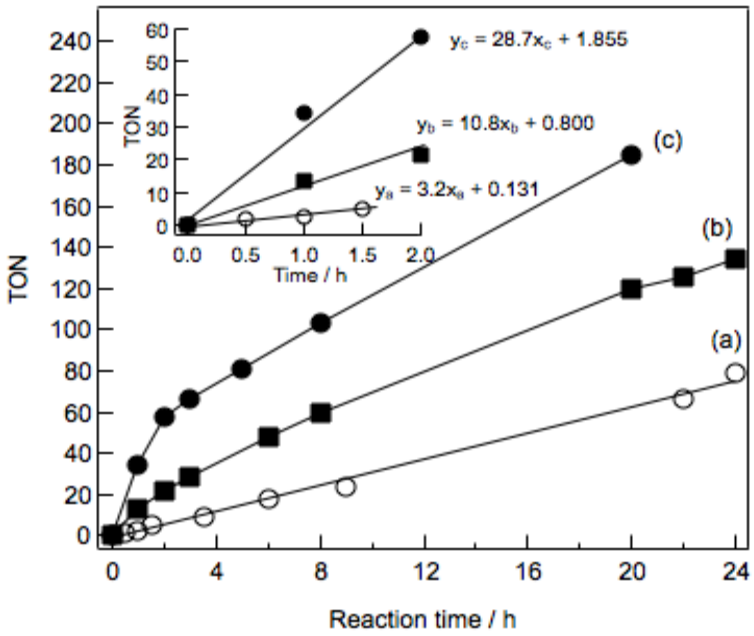


Figure 5. TON as a function of reaction time for the reaction of phenylacetylene and thiophenol catalyzed by (a) the homogeneous Cu-NHC complex; (b) Cu-NHC-SiO_2; and (c) Cu-NHC-SBA-15. The inset shows the initial reaction rate for both catalysts. Reaction conditions: 1.0 mmol phenylacetylene, 1.1 mmol thiophenol, 2 mL 1,2-DCE, 70°C.

Apart from this, we observed the Cu-NHC-SBA-15 catalyst displayed higher stereoselectivity to the *Z*-vinyl sulfide isomer than in the homogeneous catalyst, which is possibly due to the confinement of the Cu-NHC complex in the nanopores of SBA-15 (5.8 nm). This was further

supported by the catalytic performance of the Cu-NHC-SiO_2 catalyst (0.71 wt. % Cu loading) which had a relatively lower surface area (166 m^2/g) and larger pore size (9.7 nm) (Table 1, entry 7; and Figure 5). It is apparent from Table 1 that a significant background reaction occurred over the time period of 24 h in the absence of catalysts which was not influenced by the presence of SBA-15 and SH-SBA-15. The homogeneous hydrothiolation was limited to ~40% conversion based on the concentration of phenylacetylene and a *Z*:*E* selectivity of ~50:50 which was invariant with time (i.e., there was no conversion between the *Z* and *E* isomers with time). Upon the addition of catalyst, the conversion of phenylacetylene increased significantly and the *Z*:*E* isomer was invariant with time with a *Z* stereoselectivity of ~90% (Figure 6). Therefore the supported Cu-NHC-SBA-15 catalyst either controls the overall hydrothiolation kinetics or is a sufficient *Z* stereoselective controlled catalyst. It is proposed that former explanation is the more likely scenario of the two.

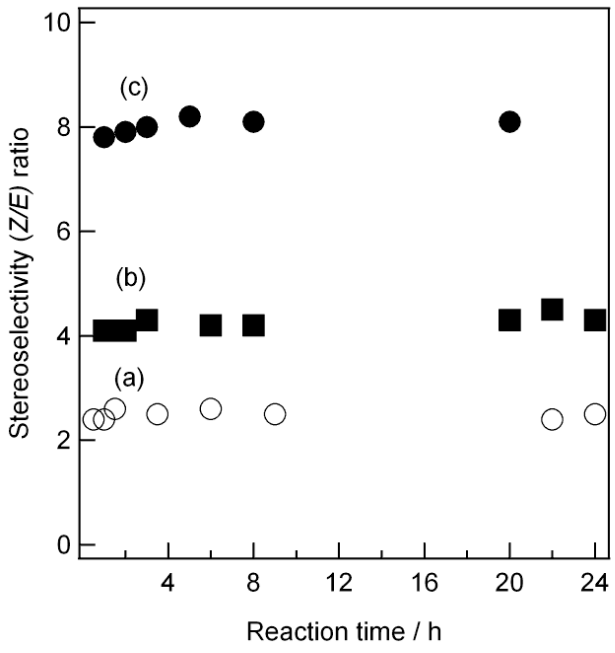


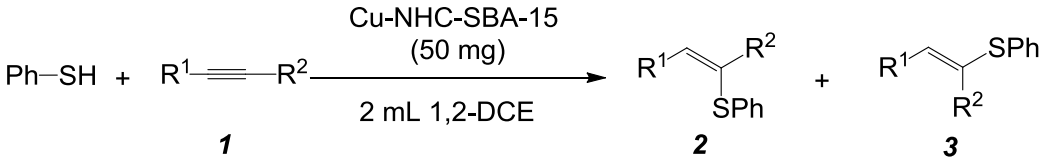
Figure 6. Stereoselectivity (*Z*/*E*) ratio as a function of time for the reaction of phenylacetylene and thiophenol catalyzed by (a) the homogeneous Cu-NHC complex; (b) Cu-NHC-SiO_2; and (c)

Cu-NHC-SBA-15. Reaction conditions: 1.0 mmol phenylacetylene, 1.1 mmol thiophenol, 2 mL 1,2-DCE, 70°C.

2.3 Scope of alkynes and thiols for hydrothiolation over the Cu-NHC-SBA-15 catalyst

Initial screening results indicated higher stereoselectivity to *Z*-isomer was achieved when phenylacetylene hydrothiolation was catalyzed by the Cu-NHC-SBA-15 catalyst. We subsequently examined the scope of alkynes using thiophenol as the substrate in the presence of the Cu-NHC-SBA-15 catalyst in 1,2-DCE, and the results are summarized in Table 2. A wide range of alkynes including aromatic, aliphatic, and internal was hydrothiolated to the *Z-anti*-Markovnikov products in moderate to high yield with excellent regio- and stereo-selectivity irrespective of the nature of the substrate. Electron-rich substituents at *m*, *o*, and *p* positions on

Table 2. Cu-NHC-SBA-15 catalyzed hydrothiolation of various alkynes with thiophenol[a]



Entry	R^1	R^2	Temp (°C)	Time (h)	Yield[b]	Selectivity (%)[c] ***Z*:*E***
1	Ph	H	70	20	98.0	89:11
2	4-Me-Ph	H	70	20	98.0	87:13
3	2-Me-Ph	H	70	20	>99.0	90:10
4	3-Me-Ph	H	70	20	>99.0	91:9
5	4-MeO-Ph	H	70	20	>99.0	91:9

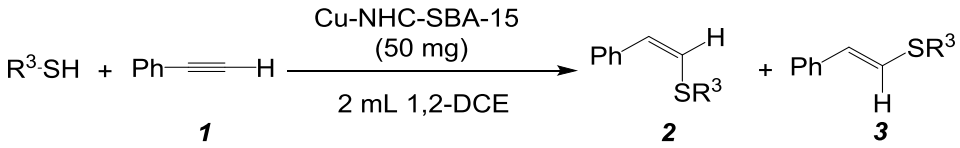
6	2-MeO-Ph	H	70	20	>99.0	91:9
7	4-F-Ph	H	70	20	84.1	94:6
8	4-Br-Ph	H	70	20	50.9	93:7
9	*n*-C_5H_{11}	H	100	72	>99.0	91:9
10	*n*-$C_{10}H_{21}$	H	100	72	85.6	92:8
11	HO-(C_2H_4)	H	100	72	64.5	88:12
12	Cl-(C_2H_4)	H	100	72	>99.0	89:11
13	cyclohexene	H	100	72	83.2	90:10
14	Ph	Me	70	48	88.0	91:9
15	Ph	Ph	100	72	8.0	91:9

[a] Reaction conditions: 1.0 mmol alkyne, 1.1 mmol thiophenol, 50 mg Cu-NHC-SBA-15 (5.3 μmol Cu), 2 mL 1,2-DCE. [b] Isolated yield. [c] Determined by ^{1}H NMR analysis.

the phenyl ring of aromatic alkynes all provided high yields (entries 2-6). Electron-poor substituents dramatically decreased the activity but caused no alteration in the high stereoselectivity (entries 7 and 8). Aliphatic alkynes reacted with thiophenol to afford the corresponding *Z-anti*-Markovnikov vinyl sulfides as the major product in satisfactory yield, but required both longer reaction time and elevated temperature (entries 9-13). The internal alkyne, 1-phenyl-1-propyne, underwent stereoselective hydrothiolation but required longer reaction time (entry 14); however, only a small amount of the addition products was isolated when the addition of thiophenol with diphenylacetylene was performed (entry 15). A variety of functional groups, such as fluoro, chloro, hydroxyl, methoxy, and olefinic were tolerated under the reaction conditions, and the corresponding addition products were obtained in high yield. In all cases listed in Table 2, no disulfide adduct formed, and no double bond dimerization reaction occurred.

We next explored the influence of the thiol substrate in the hydrothiolation reaction. Aliphatic and aromatic thiols reacted with phenylacetylene efficiently under similar reaction conditions. Electron-rich substituents on the phenyl ring of aromatic thiols provided high yield and good stereoselectivity to *Z*-vinyl sulfides (Table 3, entries 1 and 2). Electron-poor substituents decreased the activity but did not cause any modification to the stereoselectivity (entries 3 and 4). Aliphatic thiols reacted with phenylacetylene to afford the corresponding *Z*-vinyl sulfides as the major product in satisfactory yield after longer reaction times and elevated temperatures (entries 5-7).

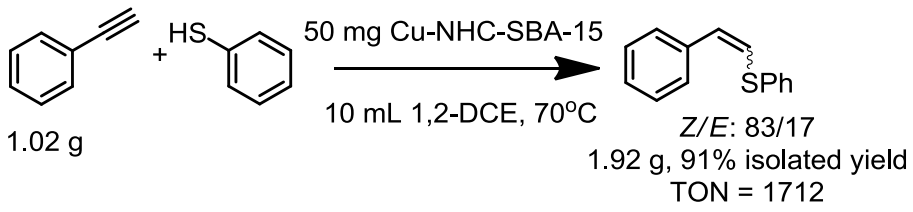
Table 3. Cu-NHC-SBA-15 catalyzed hydrothiolation of phenylacetylene with various thiols[a]



1 2 3

Entry	R^3	Temp (°C)	Time (h)	Yield(%)[b]	Selectivity (%)[c] ***Z*:*E***
1	4-Me-Ph	70	20	>99.0	91:9
2	4-MeO-Ph	70	20	>99.0	87:13
3	4-Cl-Ph	70	20	75.4	90:10
4	4-Br-Ph	70	20	86.3	85:15
5	$PhCH_2$	100	72	52.5	81:19
6	Cyclohexane	100	72	56.9	80:20
7	$CH_3(CH_2)_5$	100	72	79.5	82:18

[a] Reaction conditions: 1.0 mmol alkyne, 1.1 mmol thiophenol, 50 mg Cu-NHC-SBA-15 (5.3 μmol Cu), 2 mL 1,2-DCE. [b] Isolated yield. [c] Determined by ^{1}H NMR analysis.



Scheme 2. Gram scale hydrothiolation.

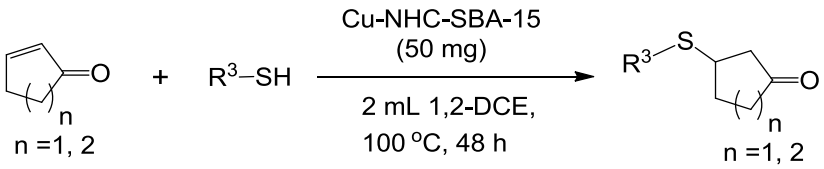
Additionally, we investigated the capability of the Cu-NHC-SBA-15 catalyst for gram-scale synthesis (Scheme 2). The reaction of 1.02 g (10 mmol) of phenylacetylene with 1.1 equivalent of thiophenol under the optimized conditions yielded 1.92 g (91% of isolated yield) of the desired vinyl sulfide with high selectivity to *Z*-isomer product after 26 h.

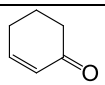
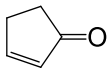
2.4 Hydrothiolation of electron-deficient alkenes over the Cu-NHC-SBA-15 catalyst

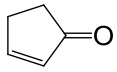
As demonstrated above, the Cu-NHC-SBA-15 catalyst exhibited good activity and high stereoselectivity for hydrothiolation over a broad substrate scope with respect to alkyne and thiol. Further investigation of alkene hydrothiolation catalyzed by the Cu-NHC-SBA-15 catalyst was conducted to extend its potential applications in organic synthesis. Utilizing a series of α,β-unsaturated carbonyls as substrates, we demonstrate the heterogeneous Cu-NHC-SBA-15 catalyst is effective for the hydrothiolation of electron-deficient alkenes with thiophenol, as shown in Table 4. Unfortunately, the addition of alkenes (1-hexene and styrene, results not shown) to thiophenol didn't proceed even with prolonged reaction times and elevated reaction temperatures. However, thiophenol reacted quantitatively with the electron-deficient alkene, 2-cyclohexene-1-one in the presence of the Cu-NHC-SBA-15 catalyst in 1,2-DCE to afford the corresponding anti-Markovnikov β-sulfido carbonyl product (Table 4, entry 1), an important organic intermediate for synthesis of bioactive compounds.[27] Based on this finding, a set of

thiophenols bearing electron-rich or electron-poor substituents (Table 4, entries 3 and 4) were reacted with 2-cyclohexen-1-one to yield the corresponding β-sulfido carbonyl products in high yield without the formation of any side-reaction products such as those derived from dimerization and/or polymerization reactions which proceed simultaneously with the addition reaction in the presence of acid or base.[28] The addition of aliphatic thiols to electron-deficient alkenes generated the corresponding β-sulfido carbonyl products in satisfactory yield (Table 4, entries 5-7).

Table 4. Cu-NHC-SBA-15 catalyzed hydrothiolation of electron-deficient alkenes with various thiols.[a]



Entry	Thiol	Alkene	Yield [%][b]
1	PhSH		99.0
2	PhSH		99.0
3	4-MeOPhSH		97.2
4	4-ClPhSH		98.3
5	$CH_3(CH_2)_4SH$		62.1
6	$PhCH_2SH$		69.1

7	$PhCH_2SH$		60.6

[a] Reaction conditions: 1.0 mmol electron-deficient alkene, 1.1 mmol thiol, 50 mg Cu-NHC-SBA-15 (5.3 μmol Cu), 2 mL 1,2-DCE, 100°C, 48 h. [b] Yield of the desired product.

2.5 Recyclability of the Cu-NHC-SBA-15 catalyst

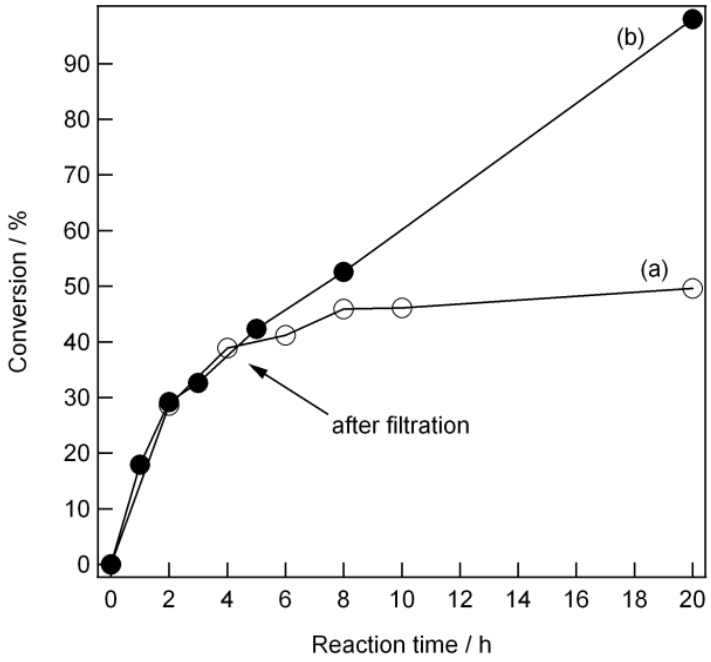


Figure 7. Effect of removal of the Cu-NHC-SBA-15 catalyst druing the hydrothiolation of phenylactylene with thiophenol (a) after removal of Cu-NHC-SBA-15 and (b) without removal of Cu-NHC-SBA-15. The arrow indicates the time when the Cu-NHC-SBA-15 catalyst was removed from the reaction mixture. Reaction conditions: 1.0 mmol phenylacetylene, 1.1 mmol thiophenol, 50 mg Cu-NHC-SBA-15 (5.3 μmol Cu), 2 mL 1,2-DCE, 70°C.

To verify whether the observed catalysis was due to the heterogeneous Cu-NHC-SBA-15 catalyst or a leached copper species in solution, we carried out the addition of phenylacetylene to thiophenol and removed the catalyst from the reaction mixture by hot filtration at approximately 40% conversion of phenylacetylene (Figure 7). After removal of the Cu-NHC-SBA-15 catalyst, the filtrate was again held at 70°C under an atmosphere of N_2. In this case, no significant increase in conversion was observed, indicating that leached copper species from the catalyst (if any) are not responsible for the observed activity. It was confirmed by ICP-AES analysis that no copper species could be detected in the filtrate (below detection limit). Recycling studies confirm the stability of the Cu-NHC-SBA-15 catalyst under reaction conditions (Table 5). The supported catalyst exhibited good stability and was recycled 6 times without significant loss of activity and selectivity with the exception of 10% of loss in activity after the first recycle, which is most likely due to the cleavage of a trace amount of tethered Cu-NHC complex from the support under reaction conditions or the loss of the catalyst during recovery.

Table 5. Recyclability of the Cu-NHC-SBA-15 catalyst for hydrothiolation of phenylacetylene with thiophenol[a]

Run	1	2	3	4	5	6
Yield (%)[b]	98	86	86	84	85	85

[a] Reaction conditions: 1.0 mmol phenylacetylene, 1.1 mmol thiophenol, 50 mg Cu-NHC-SBA-15 (5.3 μmol Cu), 2 mL 1,2-DCE, 70°C, 24 h. [b] Isolated yield.

3. Conclusions

We developed a new heterogeneous Cu-NHC complex covalently linked to SBA-15 for the highly stereoselective hydrothiolation of alkynes and electron-deficient alkenes under mild reaction conditions. The supported Cu-NHC complex is an efficient and recyclable heterogeneous hydrothiolation catalyst exhibiting broad substrate scope and higher activity and product stereoselectivity to *Z*-vinyl sulfides than its homogeneous analog. In addition, the Cu-NHC-SBA-15 catalyst demonstrated high activity and perfect selectivity for the hydrothiolation of electron-deficient alkenes. The process represents a green methodology for synthesizing regio-defined C-S bond compounds and extends the synthetic utility of hydrothiolation reactions.

4. Experimental section

4.1 Synthesis of Cu-NHC complex

4.1.1 Synthesis of 4-Allyl-2,6-diisopropylaniline[29]

Allyl chloride (5.80 g, 75.8 mmol) and 2,2-diisopropylaniline (15.1 g, 85.1 mmol) were mixed in 40 mL xylene and heated to 120°C for 12 h. After the mixture was cooled to room temperature, stirred with 20% NaOH (20 mL), washed with saturated NaCl (3 × 20 mL), and then dried by distilling off the xylene. Fractional distillation afforded the pure N-allyl-2,6-diisopropylaniline as a colorless liquid.

N-Allyl-2,6-diisopropylaniline (5.80 g, 26.7 mmol) and $ZnCl_2$ (4.0 g, 29.4 mmol) were mixed in 15 mL of xylene and heated to reflux for 4 h to induce an aza-Claisen rearrangement. The mixture was cooled to room temperature and then stirred with NaOH (4.5 g in 20 mL H_2O). The organic layer was extracted with ether, washed with saturated NaCl, and dried over anhydrous $MgSO_4$. The pure 4-allyl-2,6-diisopropylaniline was separated from the unreacted N-allyl-2,6-diisopropylaniline through fractional distillation as a colorless liquid (2.68 g, 46%). ^1H NMR

($CDCl_3$, 300 MHz): δ 6.85 (s, 2H, Ar*H*), 5.95-6.06 (m, 1H, C*H*=CH_2), 5.05-5.15 (m, 2H, C*H*=CH_2), 3.71 (s, 2H, NH_2), 3.35 (d, 2H, Ph-CH_2), 2.93-3.02 (m, 2H, C*H*(CH_3)$_2$), 1.29 (d, 12H, CH(CH_3)$_2$). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 138.9, 133.1, 130.2, 123.4, 115.4, 40.5, 28.5, 22.9. The spectral data matched that previously reported.[29]

4.1.2 Synthesis of N, N'-bis-(4-allyl-2,6-diisopropyl-phenyl)ethanediimine[30]

A 50 mL round-bottom flask was charged with 4-allyl-2,6-diisopropylaniline (1.32 g, 6.08 mmol), 40% aqueous solution of glyoxal (0.44 g, 3 mmol) and 25 mL of absolute isopropyl alcohol. A few drops of formic acid were added as catalyst. The color of the reaction mixture turned from colorless to yellow gradually, and a yellow precipitate appeared after a few hours. The reaction mixture was stirred for 2 days at room temperature. The solid was collected by filtration and thoroughly washed with cold methanol, followed by drying under vacuum (2.25 g, 81%). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 8.12 (s, 2H, N=C*H*), 7.03 (s, 4H, Ar*H*), 5.98-6.11 (m, 2H, C*H*=CH_2), 5.11-5.19 (m, 4H, C*H*=CH_2), 3.42 (d, 4H, Ph-CH_2), 2.89-3.01 (m, 4H, C*H*(CH_3)$_2$), 1.23 (d, 24H, CH(CH_3)$_2$). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 163.7, 146.6, 138.1, 137.2, 136.9, 123.7, 116.1, 40.6, 28.4, 23.8. The spectral data matched that previously reported.[30]

4.1.3 Synthesis of 1,3-bis-(4-allyl-2,6-diisopropyl-phenyl)imidazolium chloride[30]

Under N_2, chloromethylethyl ether (0.49 mL, 5.2 mmol) in 10 mL THF was added to N, N'-bis-(4-allyl-2,6-diisopropyl-phenyl)ethanediimine (1.20 g, 2.6 mmol) in 10 mL THF, then 2 drops of water was added. The mixture was stirred at 40°C for 16 h. The solvent was removed to obtain an oil mixture which was purified using a SiO_2 column with eluent CH_2Cl_2/MeOH (15/1, v/v) to obtain a yellow solid (0.53 g, 41%). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 9.93 (s, 1H, NC(*H*Cl)N), 8.14 (s, 2H, N=C*H*), 7.15 (s, 4H, Ar*H*), 5.93-6.04 (m, 2H, C*H*=CH_2), 5.05-5.20 (m, 4H, C*H*=CH_2), 3.47 (d, 4H, Ph-CH_2), 2.40-2.44 (m, 4H, C*H*(CH_3)$_2$), 1.25 (d, 24H, CH(CH_3)$_2$). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 151.1, 145.3, 144.7, 139.4, 136.5, 128.4, 127.6, 125.3, 117.5, 40.9, 29.5, 25.3, 24.3. The spectral data matched that previously reported.[30]

4.1.4 Synthesis of Cu-NHC complex[31]

An oven-dried 25 mL Schlenk flask was charged with 1,3-bis-(4-allyl-2,6-diisopropyl-pehnyl)imidazolium chloride (0.50 g, 0.99 mmol), CuCl (0.098 g, 0.99 mmol), NaO^tBu (0.095 g, 0.99 mmol), and 10 mL anhydrous THF. The resulting mixture was stirred for 20 h at room temperature. The reaction mixture was filtered over Celite, and the solvent was removed in vacuo. The product was dried under vacuum to obtain a pale brown powder (0.48 g, 85%). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.13 (s, 4H, Ar*H*), 5.93-6.05 (m, 2H, C*H*=CH_2), 5.17-5.24 (m, 4H, C*H*=CH_2), 3.49 (d, 4H, Ph-CH_2), 2.52-2.59 (m, 4H, C*H*$(CH_3)_2$), 1.31 (d, 12H, CH(CH_3)$_2$), 1.24 (d, 12H, CH(CH_3)$_2$). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 186.0, 145.9, 142.8, 137.1, 124.7, 123.6, 117.0, 40.8, 29.1, 25.3, 24.3.$C_{33}H_{44}ClCuN_2$ (567.71): calcd. C 69.82, H 7.81, N 4.93; found C 69.93, H 7.93, N 4.56.

4.2 Preparation of the Cu-NHC-SBA-15 catalyst

Preparation of the Cu-NHC-SBA-15 catalyst was performed in a step-by-step manner under a N_2 atmosphere according to a similar approach employed by Jones.[30] An anhydrous toluene solution of Cu-NHC complex (0.09 g, 0.11 mmol, see the Supporting Information for detailed experimental synthesis procedure) and AIBN (2-2'-azoisobutyronitrile, 12.6 mg) was added to SH-SBA-15 (1.0 g) under a N_2 atmosphere. The resulting mixture was refluxed for 24 h. The solid was filtered by Soxhlet extraction with anhydrous toluene and then dried under vacuum for 24 h. The solid powder was labeled as Cu-NHC-SBA-15 and stored under a N_2 atmosphere. The Cu loading was determined to be 0.69 wt% by ICP-AES analysis.

4.3 Hydrothiolation reaction

In a typical catalytic hydrothiolation reaction, a given amount of catalyst and 1,2-dichloroethane were combined in a 10 mL Schlenk tube equipped with a magnetic stir bar. Alkyne (1.0 mmol), thiol (1.1 mmol) and CH_2Br_2 as an internal standard were then added under a N_2 atmosphere. The progress of the reaction was monitored by ^{1}H NMR. The catalyst was separated by centrifugation after reaction, the solvent was removed and the resulting mixture was purified by column chromatography with a hexane/ethyl acetate eluent to afford the pure product. The pure products were structurally confirmed by ^{1}H NMR, ^{13}C NMR, and high resolution mass spectrometry (HR-MS).

Acknowlegments

This work was supported by the Pennsylvania State University and the Penn State Institutes of Energy and the Environment through start-up funds and a 3M Non-Tenured Faculty Grant awarded to R. M. R. The author thanks Prof. Dr. Robert M. Rioux for his generous support for this research and Mr. Ji-Woong Chang for assistance with acquisition of the HR-TEM images.

References

1 (a) Mizuno, H.; Domon, K.; Masuya, K.; Tanino, K.; Kuwajima, I. *J. Org. Chem.* 1999, **64**, 2648-2656; (b) Trost, B. M.; Lavoie, C. A. *J. Am. Chem. Soc.* 1983, **105**, 5075-5090; (c) Cremlyn, R. J. *An Introduction to Organosulfur Chemistry*, John Wiley & Sons: Chichester, 1996.

2 (a) Di Giuseppe, A.; Castarlenas, R.; Perez-Torrente, J. J.; Crucianelli, M.; Polo, V.; Sancho, R.; Lahoz, F. J.; Oro, L. A. *J. Am. Chem. Soc.* 2012, **134**, 8171-8183; (b) Sabarre, A.; Love, J. A. *Org. Lett.* 2008, **10**, 3941-3944; (c) Cao, C. S.; Fraser, L. R.; Love, J. A. *J. Am. Chem. Soc.* 2005, **127**, 17614-17615; (d) Misumi, Y.; Seino, H.; Mizobe, Y. *J. Organomet. Chem.* 2006, **691**, 3157-3164; (e) Weiss, C. J.; Marks, T. J. *J. Am. Chem. Soc.* 2010, **132**, 10533-10546; (f) Weiss, C. J.; Wobser, S. D.; Marks, T. J. *J. Am. Chem. Soc.* 2009, **131**, 2062-2063; (g) Weiss, C. J.; Wobser, S. D.; Marks, T. J. *Organometallics* 2010, **29**, 6308-6320; (h) Kuniyasu, H.; Ogawa, A.; Sato, K.; Ryu, I.; Kambe, N.; Sonoda, N. *J. Am. Chem. Soc.* 1992, **114**, 5902-5903; (i) Thurow, S.; Ostosi, N. T.; Mendes, S. R.; Jacob, R. G.; Lenardáo, E. J. *Tetrahedron Lett.* 2012, **53**, 2651-2653; (j) Zhao, H.; Peng, J.; Cai, M. Z. *Catal. Lett.* 2012, **142**, 138-142; (k) Ogawa, A.; Ikeda, T.; Kimura, K.; Hirao, J. *J. Am. Chem. Soc.* 1999, **121**, 5108-5114; (l) Field, L. D.; Messerle, B. A.; Vuong, K. Q.; Turner, P. *Dalton Trans.* 2009, 18, 3599-3614; (m) Ananikov, V. P.; Orlov, N. V.; Beletskaya, I. P.; Khrustalev, V. N.; Antipin, M. Y.; Timofeeva, T. V. *J. Am. Chem. Soc.* 2007, **129**, 7252-7253; (n) Beletskaya, I. P.; Ananikov, V. P. *Pure Appl. Chem.* 2007, **79**, 1041-1056; (o) Corma, A.; González-Arellano, C.; Iglesias, M.; Sánchez, F. *Appl. Catal. A: Gen.* 2010, **375**, 49-54; (p) Yang, Y.; Rioux, R. M. *Chem. Commun.* 2011, **47**, 6557-6559; (q) Sarma, R.; Rajesh, N.; Prajapati, D. *Chem. Commun.* 2012, **48**, 4014-4016.

3 (a) Griesbaum, K. *Angew. Chem. Int. Ed.* 1970, ***9***, 273-287; (b) Zeni, G.; Stracke, M. P.; Nogueira, C. W.; Braga, A. L.; Menezes, P. H.; Stefani, H. A. *Org. Lett.* 2004, 6, 1135-1138; (c) Duan, Z.; Ranjit, S.; Zhang, P.; Liu, X. *Org. Lett.* 2010, **12**, 2430-2433.

4 (a) Truce, W. E.; Simms, J. A.; Boudakian, M. M. *J. Am. Chem. Soc.* 1956, **78**, 695-696; (b) Kondoh, A.; Takami, K.; Yorimitsu, H.; Oshima, K. *J. Org. Chem.* 2005, **70**, 6468-6473.

5 (a) Aucagne, V.; Tatibouet, A.; Rollin, P. *Tetrahedron* 2004, **60**, 1817-1820; (b) Stephan, E.; Olaru, A.; Jaouen, G. *Tetrahedron Lett.* 1999, **40**, 8571-8574; (c) Silverira, C. C.; Begnini, M. L.; Boeck, P.; Braga, A. L. *Synthesis* 1997, 221-223.

6 (a) Cristau, H. J.; Chabaud, B.; Labaudiniere, R.; Christol, H. *J. Org. Chem.* 1986, **51**, 875-878; (b) Ogawa, T.; Hayami, K.; Suzuki, H. *Chem. Lett.* 1989, 769-771.

7 Singh, R.; Raghuvanshi, D. S.; Singh, K. N. *Org. Lett.* 2013, **15**, 4202-4205.

8 Gerber, R.; Frech, C. M. *Chem. Eur. J.* 2012, **18**, 8901-8905.

9 Trosktyanskaya, I. G.; Beletskaya, I. P. *Synlett* 2012, **4**, 535-540.

10 (a) Riduan, S. N.; Ying, J. Y.; Zhang, Y. G. *Org. Lett.* 2012, **14**, 1780-1783; b) Ranjit, S.; Duan, Z. Y.; Zhang, P. F.; Liu. X. G. *Org. Lett.* 2010, **12**, 4134-4136.

11 (a) Evano, G.; Blanchard, N.; Toumi, M. *Chem. Rev.* 2008, **108**, 3054-3131, and see the reference therein; (b) Reymond, S.; Cossy, J. *Chem. Rev.* 2008, **108**, 5359-5406; (c) Yamada, K. I.; Tomioka, K. *Chem. Rev.* 2008, **108**, 2874-2886.

12 (a) Diez-González, S.; Nolan, S. P. *Synlett.* 2007, **14**, 2158-2167; (b) Diez-González, S.; Nolan, S. P. *Aldrichimica ACTA.* 2008, **41**, 43-51.

13 (a) Jang, H. J.; Zhugralin, A. R.; Lee, Y. M.; Hoveyda, A. H. *J. Am. Chem. Soc.* 2011, **133**, 7859-7871; (b) Lee, Y. M.; Hoveyda, A. H. *J. Am. Chem. Soc.* 2009, **131**, 3160-

3161; (c) Rucker, R. P.; Whittaker, A. M.; Dang, H.; Lalic, G. *J. Am. Chem. Soc.* 2012, **134**, 6751-6754.

14 (a) Delp, S. A.; Munro-Leighton, C.; Goj, L. A.; Ramirez, M. A.; Gunnoe, T. B. *Inorg. Chem*. 2007, **46**, 2365-2367; (b) Munro-Leighton, C.; Delp, S. A.; Alsop, N. M.; Blue, E. D.; Gunnoe, T. B. *Chem. Commun*. 2008, 111-112.

15 (a) Kaur, H.; Zinn, F. K.; Stevens, E. D.; Nolan, S. P. *Organometallics* 2004, **23**, 1157-1160; (b) Liu, P.; Yang, J.; Li, P. H.; Wang, L. *Appl. Organometal. Chem.* 2011, **25**, 830-835.

16 (a) Ohishi, T.; Zhang, L.; Nishiura, M.; Hou, Z. M. *Angew. Chem. Int. Ed*. 2011, **50**, 8114-8117; (b) Yu, D. Y.; Zhang, Y. G. *Proc. Natl. Acad. Sci.* 2010, **23**, 20184-20189; (c) Boogaerts, I. I.; Fortman, G. C.; Furst, M. R. L.; Cazin, C. S. J.; Nolan, S. P. *Angew. Chem. Int. Ed*, 2010, **42**, 8856-8859.

17 (a) Iwasawa, Y. *Tailored Metal Catalysts*; D. Reidel Pub. Co.: Dordrecht ; Boston Hingham, MA, U.S.A., 1986; (b) Dusi, M.; Mallat, T.; Baiker, A. *Catal. Rev. - Sci. Eng.* 2000, **42**, 213-278; (c) Rioux, R. M. *Model Systems in Catalysis: Single Crystals to Supported Enzyme Mimics*; Springer: New York, 2010.

18 (a) Sandee, A. J.; Reek, J. N. H.; Kamer P. C. J.; van Leeuwen, P. W. N. M. J. *Am. Chem. Soc.* 2001, **123**, 8468-8476; (b) Merckle, C.; Blümel, J. *Adv. Synth. Catal*. 2003, **345**, 584-588; (c) Shyu, S. G.; Cheng, S. W.; Tzou, D. L. *Chem. Commun.*1999, 2337-2338.

19 (a) Tada, M.; Coquet, R.; Yoshida, J.; Kinoshita, M.; Iwasawa, Y. *Angew. Chem. Int. Ed.* 2007, **46**, 7220-7223; (b) Thomas, J. M.; Raja, R.; Lewis, D. W. *Angew. Chem. Int. Ed.* 2005, **44**, 6456-6482; (c) McMorn, P.; Hutchings, G. J. *Chem. Soc. Rev*. 2004, **33**, 108-

122; (d) Copéret, C.; Basset, J. M. *Adv. Synth. Catal*. 2007, **349**, 78-92; (e) Li, C. *Catal. Rev*. 2004, **46**, 419-492; (f) Terry, T. J.; Stack, T. D. P. *J. Am. Chem. Soc*. 2008, **130**, 4945-4953.

20 (a) Zhao, D. Y.; Feng, J. L.; Huo, Q. S.; Melosh, N.; Fredrickson, G. H.; Chmelka, B. F.; Stucky, G. D. *Science* 1998, **279**, 548-552; (b) Zhao, D. Y.; Huo, Q.; Feng, J.; Chmelka, B. F.; Stucky, G. D. *J. Am. Chem. Soc.* 1998, **120**, 6024-6036.

21 Hu, X. L. *Dissertation*, Univ. California, San Diego, 2004.

22 Sayari, A.; Jaroniec, M.; Pinnavaia, T. J. *Stud. Surf. Sci. Catal.: Naoporous Mater. II*, Elsiver, 2000, **129**.

23 Lippmaa, E.; Mägi, M.; Samoson, M.; Engelhardt, G.; Grimmer. A. R. *J. Am. Chem. Soc*. 1980, **102**, 4889-4893.

24 (a) Bayer, E.; Albert, K.; Reiners, J.; Nieder, M.; Muller, D. *J. Chromatog*. 1983, **264**, 197-213; (b) Mijatovic, J.; Binder, W. H.; Gruber, H. *Mikrochim. Acta* 1957, **133**, 175-181.

25 (a) Weisz, P. B. *Z. Physik Chem NF* 1957, **11**, 1-15; (b) Weisz, P. B.; Prater, C. D. *Adv. Catal*. 1954, **6**, 143-196; (c) Mukherjee, S. M.; Vannice, A. *J. Catal*. 2006, **243**, 108-130.

26 (a) Rice, K. P.; Walker Jr. E. J.; Stoykovich, M. P.; Saunders, A. E. *J. Phys. Chem. C* 2011, **115**, 1793-1799; (b) Chan, G. H.; Zhao, J.; Hicks, E. M.; Schatz, G. C.; Van Duyne, R. P. *Nano Lett.* 2007, **7**, 1947-1952.

27 (a) Fujita, E.; Nagao, Y. *Bioorg. Chem.* 1977, **6**, 287-309; (b) Trost, B. M.; . Keeley, D. E. *J. Org. Chem.* 1975, **40**, 2013-2013; (c) Kumar, A.; Salunkhe, R. V.; Rane, R. A.; Dike, S.

Y. *J. Chem. Soc., Chem. Commun.* 1991, 485-486.

28 Rajabi, F.; Razavi, S.; Luque, R. *Green Chem.* 2010, **12**, 786-789.

29 Elliot. M.; Janes, N. F. *J. Chem. Soc. C.* 1967,1780-1782.

30 Zhou, H.; Wang, Y.; Zhang, W. Z.; Qu, J. P.; Lu, X. B. *Green Chem.* 2011, **13**, 644-650.

31 Jurkauska, V.; Sadighi, J. P.; Buchwald, S. L. *Org. Lett.* 2003, **5**, 2417-2419.

32 Yu, K. Q.; Jones, C. W. *Organometallics* 2003, **22**, 2571-2580.