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Oxidative Cycloaddition of 1,1,3,3-Tetramethyldisiloxane to Alkynes Catalyzed by Supported Gold Nanoparticles

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S *Supporting Information*

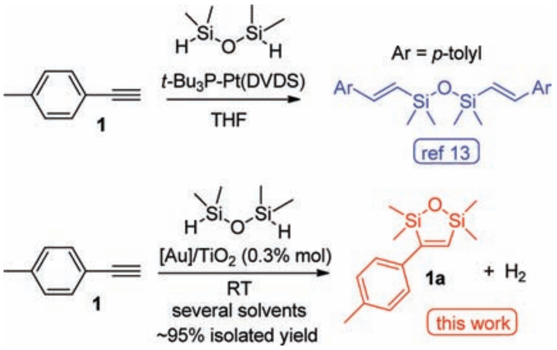
ABSTRACT: Gold nanoparticles supported on TiO_2 (0.1−1% mol) catalyze at room temperature and at extremely mild conditions the unprecedented oxidative cycloaddition of 1,1,3,3-tetramethyldisiloxane to alkynes, forming substituted 2,5-dihydro-1,2,5-oxadisiloles, with concomitant evolution of hydrogen gas. For the majority of the substrates, the yields are exceptional (up to 99%). The reaction proceeds at room temperature, tolerates a variety of functional groups, and can be performed in several solvents.

Supported gold nanoparticles have emerged as powerful heterogeneous catalysts for various organic transformations.[1] During the past decade, they have been mainly applied as catalysts in aerobic oxidation processes.[2] More recently, superior activity of gold nanoparticles in other reaction types, including Fenton,[3] Sonogashira coupling,[4] deoxygenation of epoxides,[5] etc., was recognized. We have shown that gold nanoparticles supported on titania ($[Au]/TiO_2$), a commercially available catalyst,[6] activate epoxides[7] (isomerization to allylic alcohols) and alkynes[8] (hydroarylation of propargyl aryl ethers). Gold ionic species (Au^I and/or Au^{III}) stabilized by the support[9] were invoked as the active catalytic sites. Generally, the mechanisms of these gold-catalyzed reactions are more complicated[10] than initially thought and require further theoretical and experimental work.

Following our recent interest for novel applications of $[Au]/TiO_2$ as a heterogeneous catalyst in organic transformations,[7,8] we focused on the scope and limitations of the hydrosilylation of alkynes. So far, some sporadic examples using gold nanoparticles as catalysts in this reaction have been presented in the literature.[11] Our findings in brief reveal that $[Au]/TiO_2$ is an excellent and wide range catalyst for the regioselective *cis*-hydrosilylation of alkynes.[12] Yet, apart of using monohydrosilanes, we extended our studies to dihydrodisilanes employing 1,1,3,3-tetramethyldisiloxane (TMDS) as a silylation reagent. It is known[13] that in the presence of TMDS, terminal alkynes, such as *p*-tolylacetylene (**1**), undergo facile regioselective hydrosilylation (Scheme 1) catalyzed by *t*-Bu_3P-modified Pt(0)-1,3-divinyl-1,1,3,3-tetramethyldisiloxane, Pt(DVDS), forming doubly alkenylated disiloxanes. These dimeric products were proven ideal substrates for Pd-catalyzed cross coupling reactions.[14]

To our surprise, we found that upon adding 0.3% mol $[Au]/TiO_2$ to a mixture of *p*-tolylacetylene (1.0 equiv) and 1,1,3,3-tetramethyldisiloxane (1.0 equiv) in dry dichloromethane at room temperature (in the open air), an instantaneous reaction takes place with evolution of hydrogen gas. After 30 min, **1** had been consumed, and the only product seen by NMR and GC-MS analysis was 2,2,5,5-tetramethyl-3-tolyl-2,5-dihydro-1,2,5-oxadisilole, **1a** (96% isolated yield, 99% pure, Scheme 1). Even <0.1% mol of the catalyst can drive the reaction to completion, yet longer reaction time is necessary (>3 h). With 1−2% mol catalyst load, the reaction occurs instantaneously with violent evolution of H_2. A Pt-catalyzed dehydrogenative double silylation of alkynes and alkenes by bis(hydrosilane) compounds was reported earlier by Tanaka and co-workers.[15] However, under their conditions, TMDS provided in the presence of an alkyne (single example) the oxidative cycloaddition product in merely 8% relative yield.

Scheme 1. Addition of 1,1,3,3-Tetramethyldisiloxane to *p*-Tolylacetylene Catalyzed by *t*-Bu_3P−Pt(DVDS) and $[Au]/TiO_2$



The reaction can be performed in a variety of solvents including 1,2-dichloroethane, hexane, toluene, diethyl ether or ethyl acetate, with a narrow variation in reaction rate, isolated yield, and product selectivity. Most importantly, nondried solvents can be used; however, it is necessary to add a 10−20% mol excess of TMDS, to compensate its partial hydrolysis from the moisture present in the solvent. GC-MS analysis reveals that if water is present 1,1,3,3-tetramethyldisiloxane transforms primarily at the initial steps to 1,1,3,3,5,5,7,7-octamethyltetrasiloxane (dimer), minor amounts of trimer, while at a later stage the dimeric tetrasiloxane transforms mainly to octamethylcyclotetrasiloxane (cyclic dimer). The oxidation of TMDS by moisture (to form oligomers) is rapidly catalyzed by $[Au]/TiO_2$, as proven by independent experiments in the absence of the alkyne. There are recent reports in the literature presenting gold-catalyzed oxidation of silanes with H_2O, to form silanols or disiloxanes.[16]

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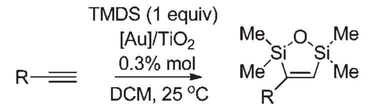
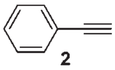
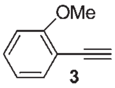
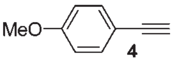
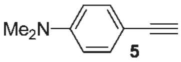
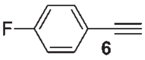
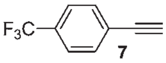
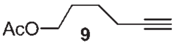
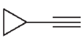
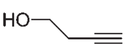
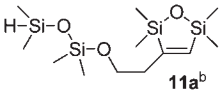
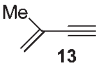
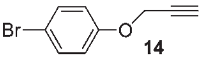
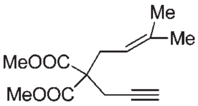
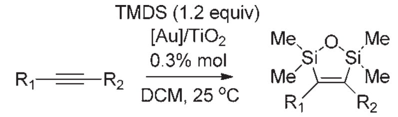
Table 1. Oxidative Cycloaddition of 1,1,3,3-Tetramethyldisiloxane (TMDS) to Terminal Alkynes Catalyzed by [Au]/TiO_2



		Yield[a]/Time
 **2**	**2a**	84%/30 min
 **3**	**3a**	99%/40 min
 **4**	**4a**	96%/40 min
 **5**	**5a**	81%/40 min
 **6**	**6a**	85%/20 min
 **7**	**7a**	91%/20 min
n-$C_5H_{11}{-}{\equiv}$ **8**	**8a**	97%/30 min
 **9**	**9a**	98%/30 min
 **10**	**10a**	92%/30 min
 **11**	 **11a**[b]	95%/30 min
$Me_3Si{-}{\equiv}$ **12**	**12a**	87%/1 h
 **13**	**13a**	78%/40 min
 **14**	**14a**[c]	72%/30 min
 **15**	**15a**	79%/6 h
${\equiv}{-}COOEt$ **16**	**16a**[c]	42%/1 h

[a] Isolated yield. [b] TMDS (2.2 equiv) was used. [c] The lower yield is due to the competing formation of hydrosilylation products.

Table 2. Reaction of TMDS with Internal Alkynes Catalyzed by [Au]/TiO_2



		Yield[a]/Time
$Ph{-}{\equiv}{-}Ph$ **17**	**17a**	88%/24 h
$Ph{-}{\equiv}{-}COOMe$ **18**	**18a**[b]	44%/2 h
$Me{-}{\equiv}{-}COOEt$ **19**	**19a**[b]	64%/45 min
$MeOOC{-}{\equiv}{-}COOMe$ **20**	 **20a**	82%/24 h
$Ph{-}{\equiv}{-}R$ R = Me (**21**), *n*-Bu (**22**)		No reaction[c]

[a] Isolated yield. [b] The lower yield is due to the competing formation of hydrosilylation products. [c] 1,2-Dichloroethane was used as solvent, 70 °C, 12 h.

Byproducts oligo polysiloxanes are highly nonpolar and therefore can be easily removed by column chromatography eluting the crude reaction mixture with hexane. We emphasize that *p*-tolylacetylene neither reacts with TMDS under refluxing conditions (in the absence of catalyst), nor in the presence of unsupported TiO_2 (anatase or rutile). These blank experiments strongly support that gold nanoparticles are involved in the reaction.

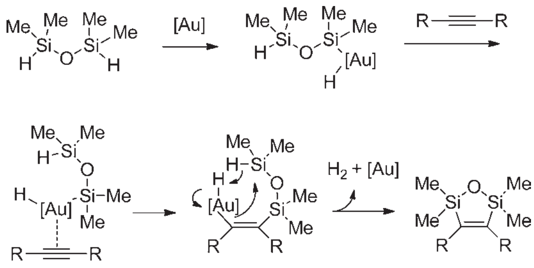
Prompted by this result, we undertook a further exploration of this unique reaction, by examining a series of alkynes (terminal and internal). We were pleased to find that for the case of terminal alkynes the oxidative cycloaddition pathway is general, and the yields are superb for the vast majority of the substrates examined, affording substituted 2,5-dihydro-1,2,5-oxadisiloles (Table 1).[17] For some of the substrates, minor byproducts (up to 10% relative yield) resulting from the competing hydrosilylation and/or hydrogenation of the triple bond were seen. Specifically, in the case of ethyl propiolate (**16**), these byproducts became substantial and reduced the isolated yield of cycloadduct **16a**.

The reaction tolerates a variety of functional groups bound either on aryl ring or alkyl chains. In the case of 3-butyn-1-ol (**11**), by using 2.2 equiv of TMDS, the product **11a** was isolated in almost quantitative yield, in which two TMDS moieties are incorporated into the starting material, the first forming the dihydro-1,2,5-oxadisilole ring on the triple bond, and the second attached as a protecting group on the hydroxyl functionality. This result indicates that TMDS and possibly other monohydrosilanes may rapidly protect alcohols as silyl ethers. We are currently working on that direction.

Additionally, for substrates **13** and **15** which possess a C−C double bond, the cycloaddition proceeds selectively on the triple bond in very good yield. It is important to emphasize that several homogeneous Au(I)-catalysts tested, do not provide any product (either of oxidative cycloaddition or hydrosilylation). Yet, in the presence of 3% mol $AuCl_3$ on the other hand (refluxing DCE, 5 h), alkynes such as **1**−**3** are quantitatively reduced by TMDS to the corresponding styrenes (GC-MS) and gradually to aryl alkanes, while cycloadducts **1a**−**3a** were detected in the crude reaction mixture in <10% relative yield.

Internal alkynes are less reactive (1% mol of [Au]/TiO_2 was used) and the product selectivity is lower (Table 2). Generally, in the entries where the isolated yield of 2,5-dihydro-1,2,5-oxadisiloles

Scheme 2. Postulated Mechanism for the Catalytic Oxidative Cycloaddition of 1,1,3,3-Tetramethyldisiloxane to Alkynes



is moderate, typical hydrosilylation products are formed from a competing pathway (see footnotes of Tables 1 and 2). Surprisingly, internal alkynes **21** and **22** are completely unreactive, while dimethyl acetylenedicarboxylate (**20**) did not yield neither cycloadduct nor hydrosilylation product, but slowly reduced within 24 h to dimethyl maleate (~90%) and dimethyl succinate (~10%). It is possible that the reduction proceeds through a gold-catalyzed hydrogenation[18] by the hydrogen gas produced from the slow oxidative hydrolysis of TMDS, as the reaction was performed within an open air flask. It is premature to comment on the reactivity trend and the substituent effects, especially for the case of internal alkynes, as the reaction mechanism (see below) is currently unclear.

Substituted 2,5-dihydro-1,2,5-oxadisiloles[19] is a class of compounds whose chemistry is essentially unexplored. For instance, they could be interesting candidates for Pd-catalyzed cross coupling reactions. Their known close analogues are the arene fused benzobisoxadisiloles,[20] which are used as synthetic equivalents (precursors) of benzynes.[21] Some of them were found to be powerful musk odorants.[22]

From the mechanistic point of view, we do not want to speculate at this stage what is the active catalytic species (Au^0, Au^I or Au^{III}). For clarity we indicate those species as [Au]. One possible rationalization (working hypothesis) for the observed oxidative cycloaddition pathway may be invoked through a modification of the Crabtree-Ojima[23] mechanism, as shown in Scheme 2. Thus, silylmetalation in the insertion to the alkyne step, followed by an intramolecular elimination of H_2 and [Au] will lead to the cycloadducts. Apart of this postulation, several other mechanistic options[24] are currently under consideration.

In conclusion, we present herein an extremely simple methodology for the oxidative cycloaddition of an 1,3-dihydro-1,3-disiloxane to alkynes catalyzed by supported gold nanoparticles. This reaction could be seen as the sila-analogue of click chemistry. Further work is in progress to examine the generality of this reaction with other siloxanes, to uncover the mechanistic details, as well as to explore the chemistry of substituted 2,5-dihydro-1,2,5-oxadisiloles, especially in Pd-catalyzed cross coupling reactions.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information. Spectroscopic data of all products (^1H, ^{13}C NMR and HRMS). This material is available free of charge via the Internet at http://pubs.acs.org.

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(17) Typical procedure for the [Au]-catalyzed oxidative cycloaddition: To a vial containing 0.38 mL (3.0 mmol) of *p*-tolylacetylene (**1**), 0.53 mL (3.0 mmol) of 1,1,3,3-tetramethyldisiloxane (TMDS), and 5 mL of dry dichloromethane were added 150 mg [Au]/TiO_2 (~0.25% mol in Au). An evolution of hydrogen gas immediately occurred. After 30 min the reaction was complete (TLC, GC-MS). The slurry was filtered with the aid of 5 mL dichloromethane through a short pad of silica gel (under a low pressure) to withhold the solid catalyst. The filtrate was evaporated under vacuum to afford 715 mg of addition product **1a** (96% yield, >99% pure).

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