

Towards “designer” surfaces: functionalisation of self-assembled monolayer (SAM) on colloidal gold by alkene metathesis†‡

Debasis Samanta,^a Nicolas Faure,^b Francis Rondlez^b and Amitabha Sarkar^{§*a}^a Division of Organic Chemistry (Synthesis), National Chemical Laboratory, Pune-411 008, India^b Laboratoire Physico Chimie, Institut Curie, Paris 05, France. E-mail: oca@iacs.res.in

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A variety of groups like a Fischer carbene complex, an *N*-hydroxysuccinimide or a ferrocene derivative have been grafted by ruthenium-catalyzed cross-metathesis reaction with terminal alkene groups on monolayer-protected gold clusters as a mild and convenient strategy to anchor functional molecules.

Self-assembled monolayer (SAM) on flat or curved surfaces¹ has attracted a great deal of attention in recent years because surfaces modified with SAM can find diverse application in sensor devices,² catalysis,³ nanoelectronics,⁴ etc. In this context, SAMs on colloidal gold are especially attractive due to their ease of preparation *via* the thiol functional end of an organic molecule. The structure of the SAMs and the organic functional groups they contain can be investigated by both electron microscopy as well as conventional techniques of solution spectroscopy, *e.g.* IR, NMR, etc. Following the seminal work by Schiffrin and coworkers⁵ several groups have functionalised gold nanoparticles with organic, organometallic and biological molecules. One interesting example is attachment of oligonucleotide probes in the context of DNA biochips to recognize specific target DNA sequences through complementary hybridization.⁶ Use of carbohydrates for study of biological interactions,⁷ or ferrocene in developing redox-sensitive probes⁸ are some other interesting variations.

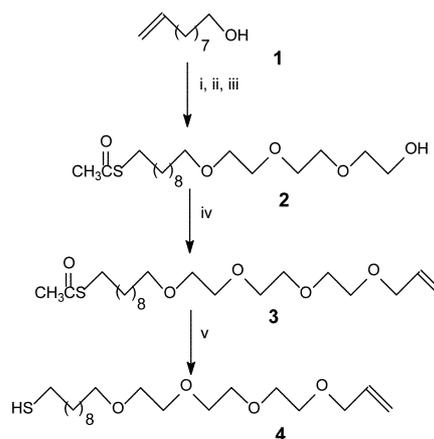
To create a functionalised SAM on a given surface one can use α,ω -difunctional chains where one functional end can be utilized for attachment on the surface while the other terminal functionality remains available for the desired application.⁹ Synthetic routes must necessarily be unique for each type of chain and synthetic challenges for such thiols can be formidable if the exposed terminus features a sensitive functional group. Alternatively, a less reactive, precursor functional group at the exposed terminus of a SAM can be transformed to a desired functionality by *in situ* chemical modification.¹⁰ In this case, reaction conditions are limited to those that do not damage the monolayer.

It was recognized that Ru-catalyzed alkene cross-metathesis reaction¹² offers a highly convenient strategy of grafting functional molecular segments to a SAM. It would only require that we prepare a ‘generic’ SAM with an accessible exposed alkene terminus. Alkene cross-metathesis could then be performed at ambient temperature to graft a wide range of functional groups in one step.

We report in this paper a clear-cut demonstration that metathesis reactions are feasible on monolayers assembled on colloidal gold particles. Cross-metathesis reaction indeed provided useful functionalities on surfaces, such as a Fischer carbene complex or an *N*-hydroxysuccinimide, as well as a redox-active ferrocene derivative. The first two functional groups readily react with amines to form stable covalent bonds

under mild condition in aqueous medium, and hence relevant for eventual anchoring of proteins *via* their ubiquitous amino function.¹³

A functional chain consisting of a C₁₀-hydrocarbon fragment, a triethylene glycol (TEG) spacer and allyl ether terminus was synthesized by a well-defined synthetic sequence as depicted in Scheme 1. The C₁₀-alkyl chain would permit the incorporation of this molecule in the standard n-octanethiol SAM while the TEG spacer would allow functional termini to protrude beyond the cluster of densely packed hydrocarbon chains for efficient reaction in solution phase.^{14,3b} Allylation of the alcohol by standard procedure of base/allyl bromide invariably produced a product with –OAc and *S*-allyl groups. The procedure finally adopted¹⁵ for step iv, on the other hand, gave a clean reaction and yielded the desired product. Products from each step were purified by column chromatography and characterized by ¹H and ¹³C NMR spectra and the final compound provided satisfactory elemental analysis. Initially, colloidal gold was capped with n-octanethiol by the Schiffrin procedure⁵ and then a mixed SAM was prepared by exposing the particles to a solution of the functional chain.¹⁶



Scheme 1 Synthesis of double bond terminated thiol molecule with TEG spacer. *Reagents and conditions:* i, Ph₃P–Br₂, DCM, rt, 12 h; ii, 50% NaOH, triethylene glycol, Δ , 24 h; iii, CH₃COSH, AIBN, MeOH, hv, 7 h; iv, [allyl alcohol and trichloroacetonitrile], triflic acid, DCM–cyclohexane, 18 h; v, MeOH–HCl, Δ , 4 h.

No significant change was observed in chemical shift values for the ¹H NMR signals before or after the functional thiol was assembled on gold, although there was expected line-broadening typical of a grafted monolayer. From the integration of methyl signal (0.90 ppm) and the signal due to –CH=CH₂ protons (5.81–6.01 ppm and 5.15–5.23 ppm) respectively, it is possible to estimate the loading of the functional chain as part of the monolayer components.^{14a} In our experiments, about 25% of the chains contained the TEG–O–allyl tether.

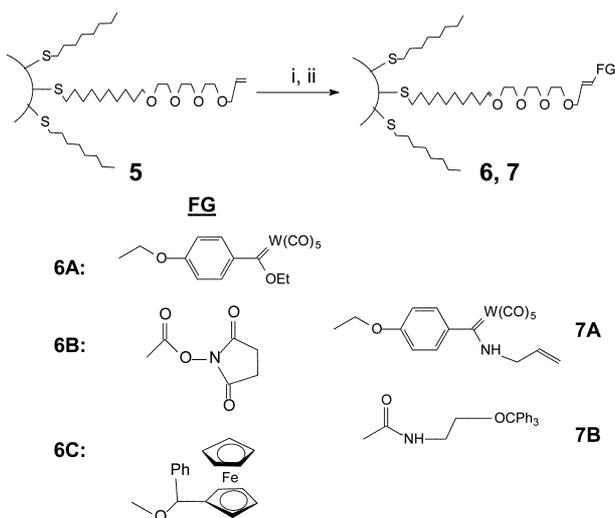
Next, we proceeded to graft a Fischer carbene complex and an *N*-hydroxysuccinimide function on the alkene terminus of the SAM described above by cross-metathesis reaction. Cross-metathesis between the functionalised gold nanoparticles and alkene-tethered organic and organometallic molecules was

† Electronic supplementary information (ESI) available: experimental data and Figs S1–S14. See <http://www.rsc.org/suppdata/cc/b3/b300833a/>

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§ Present address: Department of Organic Chemistry, Indian Association for the Cultivation of Science, Kolkata-700032, India.

carried out in anhydrous dichloromethane in which the colloidal gold easily dispersed, at ambient temperature in the presence of a catalytic amount of $\text{Cl}_2(\text{Pcy}_3)_2\text{Ru}=\text{CH}-\text{Ph}$ (5–10 mol% with respect to alkene) for 10–12 h (Scheme 2).



Scheme 2 Cross-metathesis reaction followed by aminolysis on gold colloids. *Reagents and conditions:* i, $\text{CH}_2=\text{CH}-\text{FG}$ 1, $\text{Cl}_2(\text{Pcy}_3)_2\text{Ru}=\text{CH}-\text{Ph}$ (cat.), CH_2Cl_2 , 12 h; ii, RNH_2 , CH_2Cl_2 , 5 h.

Incorporation of the Fischer carbene moiety (**6A**) on the SAM was evident from the IR spectra of gold nanoparticles (Fig. S12[†]) as well as from the change in proton NMR spectral pattern in the alkene region (terminal alkene *vis-à-vis* internal alkene) and appearance of new aromatic proton signals. We also succeeded in grafting a fragment containing *N*-hydroxysuccinimide (NHS) functionality (**6B**) to gold nanoparticles using a similar procedure. The gold particles can be dried and re-dispersed in dichloromethane several times while the NMR spectra remain unchanged, indicating that the monolayer is not degraded during such operations.

The Fischer carbene function in **6A** readily underwent aminolysis with allylamine to provide **7A**, attested by the shift of typical IR absorptions of the CO group.

The –NHS group was replaced by an amide function on treatment with tritylated ethanalamine. The aromatic proton signals of the – OCPh_3 group in the NMR spectrum confirmed the formation of modified chain **7B** from **6B**. Also there was a significant change in the IR spectrum of the product: peaks due to NHS carbonyls (1740 , 1791 and 1816 cm^{-1}) were replaced by amide absorption (1635 cm^{-1}). Thus, usual techniques of solution spectroscopy were found adequate to monitor formation of new bonds on the surface of colloidal gold particles. Success of these experiments further strengthens the possibility of attachment of proteins *via* their pendant amino groups such as those present in lysine side chains.¹³ The results presented here provide an interesting example where one organometallic catalyst effects a covalent linking of a gold particle with another organometallic reactive functionality.

A ferrocene derivative was similarly appended to the functional chain (**6C**) by metathesis. Electrochemical measurements established the presence of linkage between ferrocene and the monolayer.^{7a} The single peak at 0.417 mV in a differential pulse voltammogram confirmed that only one type of species was present. This example indicates that it should be possible to covalently attach a wide range of molecules relevant for application as sensor devices to surfaces by alkene metathesis.

In summary, we have illustrated that organometallic chemistry, specifically the chemistry of metal–carbon double bond, can be purposefully utilized to functionalise surfaces. A Fischer

carbene complex was grafted to a preformed mixed SAM on gold nanoparticles by Ru-catalysed cross-metathesis. The process is mild, convenient and compatible with a large number of sensitive functional groups. A reactive NHS-activator, similarly grafted on the surface, leads to facile amide bond formation on reaction with amines. Such chemistry should permit anchoring of biological molecules and macromolecules by their ubiquitous amine functions. Adaptation of this strategy for decorating different kinds of surfaces by attachment of proteins, amino-tethered DNA or oligonucleotide or charged functional groups or sensor probes is currently being pursued in our laboratories.

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Notes and references

† *Typical procedure:* About 25 mg of gold cluster was dispersed in dry dichloromethane, and *ca.* 10 molar equivalent of alkene and 5–10 mol% of Ru-catalyst was added to it. The dispersion was stirred for 12 h under argon, and then for 5 min in air. It was then passed through a small pad of alumina. Evaporation of the solvent followed by washing the residue thrice with acetonitrile afforded gold clusters with functional appendage.

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