View Article Online / Journal Homepage / Table of Contents for this issue

# ChemComm

This article is part of the

## Surface Enhanced Raman Spectroscopy web themed issue

Guest editors: Professors Duncan Graham,
Zhongqun Tian and Richard Van Duyne

All articles in this issue will be gathered together online at
www.rsc.org/sers.

ChemComm

Dynamic Article Links

Cite this: *Chem. Commun.*, 2011, **47**, 4415–4417

www.rsc.org/chemcomm

COMMUNICATION

# Rationally designed SERS active silica coated silver nanoparticles†‡

**Louise Rocks, Karen Faulds and Duncan Graham***

***Received 2nd December 2010, Accepted 22nd February 2011***
**DOI: 10.1039/c0cc05338d**

**A reproducible method for the successful silica coating of silver nanoparticles is reported. A selection of tri-functional reporter molecules were designed to allow controlled synthesis of silica shelled, dye coded, SERS active silver nanoparticles.**

Surface enhanced Raman scattering (SERS) has been employed in the development and improvement of numerous biological detection systems.[1,2] The output consists of narrow spectral bands highlighting the multiplexing capabilities of this technique.[3] One approach that can be exploited to improve the sensitivity of this technique is to make use of the resonance contribution from a dye molecule which has an electronic transition close to the excitation frequency. This is known as surface enhanced resonance Raman scattering (SERRS). Sensitivity of this detection system is excellent and in some cases can rival that of fluorescence.[4,5]

Metallic nanoparticles, especially the coinage metals, have proven to be useful substrates for SE(R)RS analysis. Decreasing the size of the particles to the nanometre range results in significant absorption in the UV/visible range which can influence the optical properties in both near and far field.[6]

The vast majority of biological cellular SE(R)RS analysis has utilised gold nanoparticles, due to the biocompatible nature of the material, their mobility and versatility.[7] Whilst the SERS enhancement of silver nanoparticles is typically greater than that observed with gold analogues,[8] there has been some concern regarding the cytotoxic properties of silver and as such their biocompatibility.[9] The requirement for aqueous compatible nanoparticles for use within a biological environment has led to the development of core-shell systems to isolate the inner metal core from the outer biological environment. The use of nanoparticle cores, both metallic and semi-conductor, functionalised with polyethylene glycol (PEG) shells has been shown to be widely applicable to cellular analysis.[10,11] Similarly, silica is being used increasingly for the shelling of nanoparticles to provide a robust substrate with consistent surface chemistry.

The silica shell is considered to "physically sequester" the nanoparticle core allowing exploitation of the optical, electrical, and catalytic properties of the core.[12] Silica growth can be achieved using Stöber synthesis.[13] This involves ammonium hydroxide-catalysed hydrolysis and condensation of alkoxysilanes in low molecular-weight alcohols. The main limitation to the silica coating of metallic nanostructures is the inherent vitreophobic nature of noble metals. The relative chemical instability of silver, in comparison to gold, poses an additional obstacle in the silica coating of silver nanoparticles. Ammonium hydroxide readily oxidises silver to form soluble complex ions resulting in the formation of excess core-free silica particles.[14] Furthermore, transferring metallic nanoparticles into an alcohol/water solution, as per the Stöber method, may result in multiple silver cores within the silica shell due to the reduction in dielectric constant. For this reason vitreophilising agents, namely mercapto and amino functionalised silane coupling agents, have been employed to facilitate the silica-coating of both silver and gold nanoparticles.[12,15] Self assembled monolayer coverage of the silane coupling agents enhances the stability of the core in the harsh conditions necessary for silica growth and provides a vitreophilic surface for the growth of a silica shell *via* alkoxysilane condensation.

Raman reporter molecules such as fluorescein isothiocyante have previously been incorporated into the silica coated nanoparticles to produce SERS active probes for biological applications.[16] These methods often employ mixed monolayer coverage of Raman active molecules and vitreophilising precursors. Competition for surface binding of the aforementioned molecules can result in reduced reproducibility of SERS signal, since the amount of reporter molecules per nanoparticle may not be homogenous. Successful silica encapsulation of gold nanospheres has been achieved *via* covalent attachment of silane precursors to complete monolayers of Raman reporters[17] and also monolayer coverage of terminal alkoxysilane Raman reporters.[18] Similarly, a resonant molecule capable of providing a vitreophillic surface should provide a suitable precursor for silver/ silica core/shell nanotags with increased sensitivity.

A series of tri-functional linkers based on benzotriazole dyes were synthesised for conjugation to the surface of silver nanoparticles (Fig. 1).[19] Benzotriazole dyes have previously been synthesised and designed specifically to complex directly to the surface of silver nanoparticles through the benzotriazole moiety.[20] Alkoxy silane functionality can be introduced to the dyes (Dye 1) to provide a vitreophillic surface. Thus, they can

---

*Centre for Molecular Nanometrology, WestCHEM, Department of Pure and Applied Chemistry, University of Strathclyde, 295 Cathedral Street, Glasgow, UK. E-mail: duncan.graham@strath.ac.uk; Tel: +44 1415484701*

† This article is part of a ChemComm web-based themed issue on Surface Enhanced Raman Spectroscopy.

‡ Electronic supplementary information (ESI) available: SEM images, UV-visible experimental procedures. See DOI: 10.1039/c0cc05338d

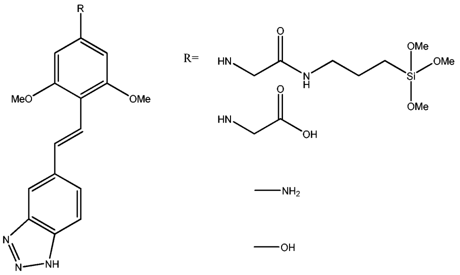

**Fig. 1** Tri-functional benzotriazole dyes designed as precursors for silica encapsulation of silver nanoparticles.

be considered to act as precursors for the development of an integrated network of siloxane linkages *via* the Stöber method.

Silver nanoparticles (AgNP) were synthesised according to the previously published method by Fabrinkos *et al.*[21] Dye 1 was added to colloidal suspensions to a final concentration of 1 × $10^{-7}$ M. Silica coating was achieved using a modified Stöber method (see supporting information‡). Due to the oxidizing capabilities of ammonium hydroxide, a more sterically hindered amine base, triethylamine, was used as a catalyst. Previous work has indicated that even one methyl substitute on ammonium hydroxide is enough to reduce the rate of oxidation of silver nanoparticles.[22] Tetraethyl orthosilicate (TEOS) was introduced to the nanoparticle–precursor conjugates in small aliquots over a three hour period until a final concentration of 5.4 mM was achieved. Continuous agitation of the samples was employed throughout the shelling process. Silica coating was successful using the alkoxysilyl functional Dye 1, however the formation of multiple silver cores was evident (ESI, Fig. S1‡).

Dyes 2–4 also possess functional groups capable of undergoing condensation with TEOS. These dyes were added to colloidal suspensions of AgNP to a final concentration of 1 × $10^{-7}$ M prior to silica coating *via* the outlined modified Stöber method (see supporting information‡). The resulting AgNP@$SiO_2$ (core@shell) "nanotags" were washed and analysed by UV visible spectroscopy (Fig. 2a and b). The data was normalised to take into account the variation in nanoparticle concentration within the samples. Conjugates prepared from Dye 2 did not exhibit significant aggregation of the AgNP. Dampening of the surface plasmon and increased absorbance at longer wavelengths were observed in the nanotags prepared from Dyes 1 and 3. This suggests aggregation of the nanoparticle cores has occurred. Nanotags prepared using Dye 4 exhibited minimal agglomeration of the nanoparticle cores.

The SE(R)RS properties of the four tri-functional precursors were investigated, post-silica coating of the silver nanoparticles, using 3 excitation wavelengths (Fig. 2c). The intensity of the peak at 1615 $cm^{-1}$ was standardized against cyclohexane intensity at 800 $cm^{-1}$. No significant peaks were observed from any of the samples using 785 nm excitation.

The SERS enhancement was found to be greater for the nanotags synthesised from Dyes 1 and 3 (with alkoxysilyl and amino functionality) which is most likely due to formation of multiple cores within the sample. In the case of Dye 1, this is most likely due to premature siloxane bridging between adjacent nanoparticle-dye conjugates in the alkaline alcohol solution prior to addition of TEOS. Dye 3 was observed to induce aggregation of nanoparticles in an aqueous environment prior to silica coating (ESI, Fig. S2‡). This is most likely a result of electrostatic interactions between the protonated primary amine of Dye 3 with the bare silver nanoparticles. The UV visible data illustrated in Fig. 2a and b indicates Dyes 2 and 4, with carboxyl and hydroxyl functionality, respectively, have increased reproducibility with respect to monodispersity of the nanotags.

SEM images of Ag@$SiO_2$ nanotags synthesised from Dyes 2–4 illustrate that shelling of the silver nanoparticles was successful using the tri-functional precursors (ESI, Fig. S3‡). The samples synthesised from Dye 3 exhibited numerous nanoparticle cores within the silica shell. The nanotags synthesised from Dyes 2 and 4 showed evidence of monomers and smaller aggregates within shells. This is in agreement with the data observed in Fig. 2. All four rationally designed dyes are capable of initiating silica shelling of silver nanoparticles, however Dyes 2 and 4 produce nanotags with reduced polydispersity. The SERS intensity of nanotags synthesised from Dye 2 is approximately twice that observed from the Dye 4 analogues. Thus the carboxyl functionalised benzotriazole dye is determined to be the optimal dye for silica coating of silver nanoparticles. Similarly, non resonant Raman reporters with terminal carboxyl groups should prove to be equally effective precursors.

Earlier work in this field has employed mixed monolayers of vitreophilising precursors and dye molecules to synthesise SE(R)RS active nanotags. We have demonstrated that certain dyes can act as both a resonant molecule for SERRS and a precursor for the silica shelling of silver nanoparticles.

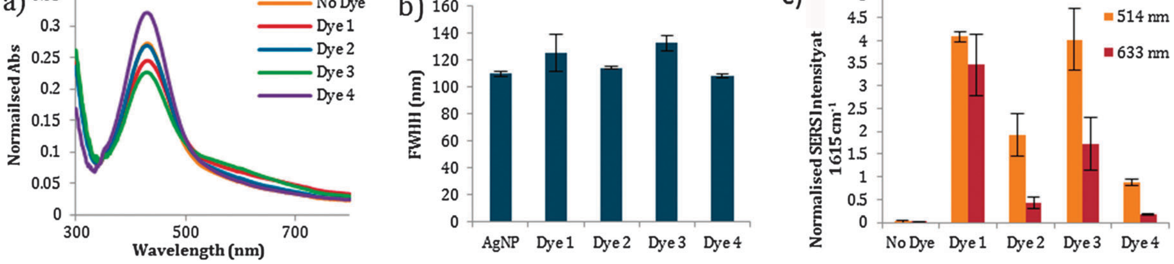

**Fig. 2** A comparison of the (a) UV visible (b) full width at half height measurements and (c) SERRS spectra observed at 2 wavelengths from nanotags synthesised using the 4 benzotriazole dyes identified in Fig. 1. Spectra are the average of triplicate samples (the error bars are ±1 standard deviation).

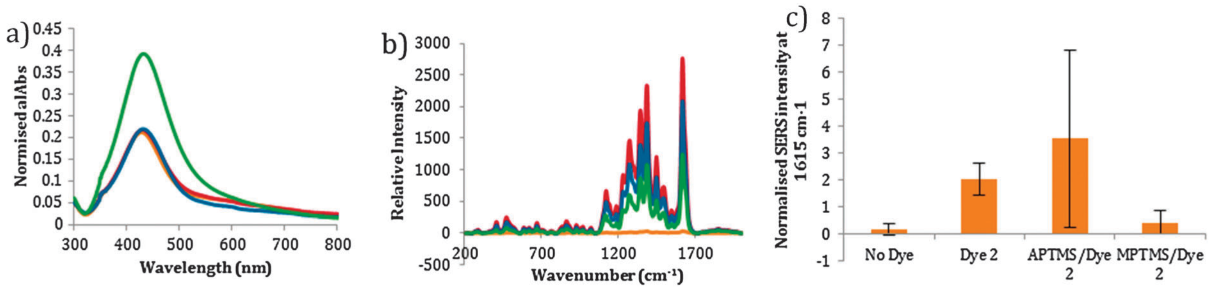

**Fig. 3** A comparison of the (a) UV visible and (b) SERRS spectra observed (514 nm excitation) from AgNP (yellow), nanotags synthesised from full monolayer of Dye 2 (red), mixed monolayer APTMS/Dye 2 (blue) and mixed monolayer MPTMS/Dye 2 (green). Spectra are an average of triplicate samples.

To highlight the increased reproducibility of the SERS enhancement of nanotags synthesised from monolayers of the rationally designed dyes in comparison to mixed monolayers, vitreophilising precursors 3-aminopropyl trimethoxysilane (APTMS) and 3-mercaptopropyl trimethoxysilane (MPTMS) were added to the silver colloidal suspension to a final concentration of $1 \times 10^{-6}$ M. The samples were agitated for a period of 0, 15 or 60 min prior to addition of Dye 2 to a final concentration of $1 \times 10^{-7}$ M.

Irreversible aggregation of the silver nanoparticles was induced in samples incubated with the silane precursors for 15 and 60 min (ESI, Fig. S4a and b‡). Addition of Dye 2 simultaneously with the silane precursors did not induce significant aggregation of the silver nanoparticles, however variation between sample replicates was significantly increased (ESI, Fig. S4c‡). Raman measurements were also obtained from all conjugates pre-silica coating at 514 nm excitation (ESI, Fig. S5‡). The significant variation in SERS intensity observed in the samples incubated with APTMS/MPTMS for a period of 15 or 60 min can largely be attributed to the aggregation as observed in the UV visible spectra. When APTMS and Dye 2 were added simultaneously, the SERS intensity was 2.75 times greater than in the absence of a silane precursor. However, the relative standard deviation of the sample replicates increased from 14.6% to 62.7%. When MPTMS and Dye 2 were added simultaneously, the preferential binding of sulfur to the silver surface results in minimal binding of Dye 2 and thus the SERS intensity was depleted.

The resulting AgNP@$SiO_2$ "nanotags" were washed and analysed by UV visible and Raman spectroscopy (Fig. 3). While the greatest enhancement is observed from nanotags prepared from an APTMS/Dye 2 mixed monolayer, the relative standard deviation of the SERS intensity is 3 times greater than in the absence of a silane precursor (92.5% *cf.* 28.3%). Samples prepared using a mixed monolayer coverage of dye and MPTMS had reduced SERS intensity but increased variation in SERS intensity at 1615 $cm^{-1}$ when compared to samples prepared in the absence of a silane precursor (102.1% *cf.* 28.3%).

Four tri-functional molecules have been synthesised to stabilise a silver nanoparticle core, act as a Raman reporter and provide a suitable precursor for an integrated network of silica polymers *via* Stöber condensation. The use of a silane precursor was found to be unnecessary, however use of a suitable site of growth for the silica greatly enhanced the reproducibility of both the synthesis and the SERS. This has resulted in the synthesis of reproducible SERS active silver/silica, core/shell nanotags which will find use in a wide range of applications where gold has previously been used but offering the alternative optical properties of silver.

## Notes and references

1 D. Graham and K. Faulds, *Chem. Soc. Rev.*, 2008, **37**, 1042.
2 X. Han, B. Zhao and Y. Ozaki, *Anal. Bioanal. Chem.*, 2009, **394**, 1719.
3 K. Faulds, F. McKenzie, W. E. Smith and D. Graham, *Angew. Chem.*, 2007, **119**, 1861.
4 G. Sabatte, R. Keir, M. Lawlor, M. Black, D. Graham and W. E. Smith, *Anal. Chem.*, 2008, **80**, 2351.
5 K. Faulds, R. P. Barbagallo, J. T. Keer, W. E. Smith and D. Graham, *Analyst*, 2004, **129**, 567.
6 M. Quinten, *Z. Phys. D: At., Mol. Clusters*, 1995, **35**, 217.
7 J. Kneipp, H. Kneipp, M. McLaughlin, D. Brown and K. Kneipp, *Nano Lett.*, 2006, **6**, 2225.
8 R. J. Stokes, A. Macaskill, P. J. Lundahl, W. E. Smith, K. Faulds and D. Graham, *Small*, 2007, **3**, 1593.
9 P. V. AshaRani, G. Low Kah Mun, M. P. Hande and S. Valiyaveettil, *ACS Nano*, 2008, **3**, 279.
10 X. H. Gao, Y. Y. Cui, R. M. Levenson, L. W. K. Chung and S. M. Nie, *Nat. Biotechnol.*, 2004, **22**, 969.
11 X. M. Qian, X. H. Peng, D. O. Ansari, Q. Yin-Goen, G. Z. Chen, D. M. Shin, L. Yang, A. N. Young, M. D. Wang and S. M. Nie, *Nat. Biotechnol.*, 2008, **26**, 83.
12 S. P. Mulvaney, M. D. Musick, C. D. Keating and M. J. Natan, *Langmuir*, 2003, **19**, 4784.
13 W. Stöber, A. Fink and E. Bohn, *J. Colloid Interface Sci.*, 1968, **26**, 62.
14 T. Ung, L. M. Liz-Marzan and P. Mulvaney, *Langmuir*, 1998, **14**, 3740.
15 L. M. LizMarzan, M. Giersig and P. Mulvaney, *Langmuir*, 1996, **12**, 4329.
16 X. Liu, M. Knauer, N. P. Ivleva, R. Niessner and C. Haisch, *Anal. Chem.*, 2009, **82**, 441.
17 B. Küstner, M. Gellner, M. Schütz, F. Schöppler, A. Marx, P. Ströbel, P. Adam, C. Schmuck and S. Schlücker, *Angew. Chem., Int. Ed.*, 2009, **48**, 1950.
18 M. Schütz, B. Küstner, M. Bauer, C. Schmuck and S. Schlücker, *Small*, 2010, **6**, 733.
19 G. McAnally, C. McLaughlin, R. Brown, D. C. Robson, K. Faulds, D. R. Tackley, W. E. Smith and D. Graham, *Analyst*, 2002, **127**, 838.
20 D. Graham, G. McAnally, J. C. Jones and W. Ewen Smith, *Chem. Commun.*, 1998, 1187.
21 V. Fabrikanos, S. Athanassiou and K. Leiser, *Z. Naturforsch. B: Chem. Sci.*, 1963, **18**, 612.
22 Y. Kobayashi, H. Katakami, E. Mine, D. Nagao, M. Konno and L. M. Liz-Marzan, *J. Colloid Interface Sci.*, 2005, **283**, 392.