An imine-based approach to prepare amine-functionalized Janus gold nanoparticles

Ang, Chung Yen; Nguyen, Kim Truc; Li, Menghuan; Zhao, Yanli; Wu, Shaojue; Tan, Si Yu

2015

Wu, S., Tan, S. Y., Ang, C. Y., Nguyen, K. T., Li, M., & Zhao, Y. (2015). An imine-based approach to prepare amine-functionalized Janus gold nanoparticles. *Chemical Communications*, 51(58), 11622-11625.

<https://hdl.handle.net/10356/98596>

<https://doi.org/10.1039/C5CC03582A>

© 2015 Royal Society of Chemistry. This is the author created version of a work that has been peer reviewed and accepted for publication by *Chemical Communications*, Royal Society of Chemistry. It incorporates referee's comments but changes resulting from the publishing process, such as copyediting, structural formatting, may not be reflected in this document. The published version is available at: [<http://dx.doi.org/10.1039/C5CC03582A>].

Downloaded on 26 Apr 2023 19:58:55 SGT

Cite this: DOI: 10.1039/c0xx00000x

www.rsc.org/xxxxxx

ARTICLE TYPE

An Imine-Based Approach to Prepare Amine-Functionalized Janus Gold Nanoparticles

Shaojue Wu,^a Si Yu Tan,^a Chung Yen Ang,^a Kim Truc Nguyen,^a Menghuan Li,^b Yanli Zhao^{*a,b}

Received (in XXX, XXX) Xth XXXXXXXXX 20XX, Accepted Xth XXXXXXXXX 20XX

DOI: 10.1039/b000000x

An imine-based approach was developed to prepare Janus gold nanoparticles (Janus AuNPs) having one patch of surface with amine functionality and the other with polyethylene glycol unit. This unique technique features covalent bonding as the force to immobilize AuNPs on the template, enabling a direct modification of AuNPs in both water and organic solvents. Colloidal clusters were then obtained *via* electrostatic assembly of these Janus AuNPs with citrate stabilized AuNPs or AgNPs.

Janus nanoparticles (Janus NPs) are NPs with their two sides of faces decorated with different chemical structures.^{1,2} This asymmetric character enables the construction of NP assemblies that are otherwise difficult to achieve using common three-dimensionally isotropic NPs. The most well known example of Janus NPs is Au/Ag NPs for the generation of hot spots for surface-enhanced Raman spectroscopy (SERS) applications, which can be readily fabricated in solution.³⁻⁷ Other structures, such as NP chains⁸ and core-satellite structures,^{5-7,9} have also been assembled with the use of Janus NPs. Janus NPs with one face hydrophilic and the other hydrophobic possess surfactant-like amphiphilic property, thus allowing for the assembly of cell membrane like structures, where the interstices between NPs enable chemical exchange across the membranes just like breathable skin.¹⁰ The surfactant-like property of such Janus NPs has also been attracted research attention on their interesting interactions with lipid bilayers of membranes.¹¹ For the studies involving Janus NPs, their preparation methods are usually the prerequisite. Herein, we report a novel method for convenient preparation of amine-functionalized Janus AuNPs based on the reversible property of imine bond. By using this method, both charged and hydrophobic AuNPs could be modified into Janus AuNPs in a direct manner.

There are several methods for the preparation of Janus NPs, mainly including spontaneous phase separation of ligand monolayers,¹² interfacial engineering,¹³ and protection-deprotection strategy based on solid substrates such as glass.^{3-5,7} Among them, the solid substrate technique appears to be a popular method. Briefly, the process begins with the adsorption of NPs onto the substrate surface. In this way, the surface of NPs in contact with the substrate is concealed, while the exposed surface is under chemical modification. Subsequently, NPs are released from the substrate, and the concealed surface is also

exposed for the second modification. The key point of this technique lies in that NPs must be adsorbed onto the substrate and the concealed surface of NPs should be readily modifiable after exposure to the second type of ligand. Therefore, strong noncovalent interactions such as electrostatic interaction^{3-5,7,14} are usually chosen for the immobilization and dissociation of NPs, while strong covalent bonding (e.g., thiol-Au bonding) may make the second modification difficult to proceed *via* ligand-exchange. Accordingly, the solid substrate technique is usually performed in water, and examples using organic solvent as a medium are rare.^{15,16} However, many inorganic NPs including metal semiconductors as well as metal and metal oxide NPs are synthesized in nonpolar organic solvents, and they remain hydrophobic after the synthesis process.^{17,18} In the case of AuNPs, while large-sized AuNPs (12-200 nm, normally negatively charged) are obtained *via* the reduction reaction performed in water,^{19,20} small-sized AuNPs (2-10nm, hydrophobic) are mainly synthesized in nonpolar solvents by Brust method²¹ or others.^{22,23} In order to modify these hydrophobic NPs using the solid substrate technique, NPs need to be coated with charged layers for the immobilization on the substrate surface *via* electrostatic interaction.¹⁴ In this regard, it would be highly beneficial if the solid substrate technique can be performed not only in water but also in organic solvents to asymmetrically modify NPs that are either charged or hydrophobic. To this end, strong covalent bonding (thiol-Au bonding) will be an ideal choice to anchor AuNPs onto the surface of solid substrates.

Scheme 1 Schematic process to prepare amine-functionalized Janus AuNPs *via* an imine-mediated protection-deprotection strategy.

In this work, we relied on silica nanoparticles (SiO₂NPs) as the

solid substrate for the immobilization of AuNPs. These SiO₂NPs were grafted with a layer of lipoyl ligands containing imine bond as the linkage (Scheme 1, and the synthetic process is illustrated in Scheme S1 of ESI). To achieve this, SiO₂NPs were firstly functionalized with azide by reacting pristine SiO₂NPs with 3-azidopropyltrimethoxysilane. The successful grafting on SiO₂NPs was confirmed by the presence of infrared vibration band of the azido group at 2108 cm⁻¹ (Fig. S1a in ESI). Thereafter, benzaldehyde was introduced to the silica surface by Cu(I) catalyzed click reaction between azide and alkyne. After the reaction, the azido vibration band disappeared (Fig. S1b in ESI), thus confirming the success of the click reaction. Amine containing lipoyl ligand (lipoic-TriEG-amine, Scheme 1) was then conjugated onto the silica surface *via* the formation of imine bond by simply mixing the ligand with benzaldehyde grafted SiO₂NPs in dimethylformamide (DMF). The successful conjugation was confirmed by X-ray photoelectron spectroscopy (XPS), which showed 97.2% reaction efficiency (Fig. S2a in ESI). To further confirm that the conjugation of the lipoyl groups onto SiO₂NPs was bridged by imine bond, the as-prepared functionalized SiO₂NPs were placed in acidic HCl aqueous solution and stirred for a few hours. The, the obtained SiO₂NPs were washed several times with water and ethanol followed by drying before the characterization by XPS. The XPS results showed the disappearance of the sulfur element, whereas the nitrogen element still remained on SiO₂NPs (Fig. S2b in ESI). These observations provide concrete evidence that the linkage between SiO₂NPs and the lipoyl functionality was imine bond, which can be hydrolyzed in acidic aqueous condition.²⁴

Fig. 1 (a,c,e) TEM images of AuNPs adsorbed on SiO₂NPs and (b,d,f) free single AuNPs released from SiO₂NPs after etching in 2% HF aqueous solution. Citrate stabilized AuNPs with a size of (a,b) 40 nm and (c,d) 14 nm, and dodecylamine stabilized AuNPs with a size of (e,f) 3.6 nm were used respectively for the preparation of Janus NPs.

With the use of lipoyl-containing SiO₂NPs as a substrate, amine-partially-functionalized Janus AuNPs were prepared *via* the protection-deprotection strategy (Scheme 1). Asymmetrical modification of 40nm citrate stabilized AuNPs was first carried out in water. In this case, SiO₂NPs dispersed in DMF were mixed with citrate stabilized AuNPs in water under vigorous stirring. Transmission electron microscopy (TEM) image (Fig. 1a) shows that these AuNPs were successfully adsorbed onto silica surface in a discrete fashion. In this step, the surface of AuNPs in contact

with SiO₂NPs was decorated with imine units. After complete adsorption of AuNPs on SiO₂NPs in solution to obtain the SiO₂@AuNPs hybrid, the external surface of AuNPs was passivated with a PEGylated lipoyl ligand (lipoic-mPEG₇₅₀, Scheme 1). The SiO₂@AuNPs hybrid was then purified *via* typical centrifugation-washing process. Thereafter, the imine linkage between silica and AuNPs was hydrolyzed in HF aqueous solution (ca. 2%, pH = ~1), where silica substrates were etched completely. Finally, the released Janus AuNPs (Fig. 1b) containing both lipoic-TriEG-amine and lipoic-mPEG₇₅₀ ligands were stably dispersed in HF aqueous solution, and were purified by the centrifugation-washing process and dialysis. After etching SiO₂NPs, some free lipoic-TriEG-amine ligands might be released into solution. Since the two faces of Janus AuNPs were already modified with two types of lipoic ligands respectively, these free ligands cannot easily spoil the obtained Janus AuNPs. The positive zeta-potential (30.4 mV) of as-prepared Janus AuNPs, in contrast to the negative zeta-potential (-33.6 mV) of citrate stabilized AuNPs, proves the generation of amine functionalities on Janus AuNPs. By using this method, these lipoic-TriEG-amine functionalities were decorated specifically on one patch of the AuNP surface, while the rest of surface was passivated by lipoic-mPEG₇₅₀. Smaller citrate stabilized AuNPs (14 nm in diameter) were also asymmetrically modified using the same procedure (Fig. 1c,d). Experimentally, small 14 nm AuNPs could be captured by SiO₂NPs more readily as compared to the large 40 nm AuNPs.

Fig. 2 TEM images of NP clusters assembled from Janus AuNPs with citrate stabilized NPs. (a-c) Clusters assembled from 40 nm Janus AuNPs with 14 nm citrate stabilized AuNPs; (d-f) clusters assembled from 14 nm Janus AuNPs with 14 nm citrate stabilized AuNPs; (g,h) core-satellites assembled from 14 nm Janus AuNPs with citrate stabilized AgNPs (about 56 nm in size); (i) core-satellites assembled from 3.6 nm Janus AuNPs with citrate stabilized AgNPs (about 56 nm in size). Insets are illustrations of the NP arrangements within clusters. Blue color represents the surface of AuNPs modified with amine units.

In order to show the versatility of this technique in the preparation of Janus NPs, we also demonstrated the applicability of this technique in organic solvents such as DMF and toluene for direct asymmetric modification of hydrophobic NPs. For this purpose, dodecylamine stabilized AuNPs (3.6 nm in size) were adsorbed onto SiO₂NPs upon mixing in DMF or toluene (Fig. 1e). After the external face of AuNPs was passivated by lipoic-mPEG₇₅₀, the SiO₂@AuNPs hybrid was purified by the centrifugation-washing process. The obtained SiO₂@AuNPs hybrid became dispersible in water, indicating successful passivation by lipoic-mPEG₇₅₀. After hydrolysis and etching in acidic HF aqueous solution, the released AuNPs (Fig. 1f) could be stably dispersed in water and purified by dialysis. This study confirms the successful modification of hydrophobic AuNPs with both lipoic-TriEG-amine and lipoic-mPEG₇₅₀ ligands. Thus, it was concluded that the imine-based solid substrate method could be extended for direct asymmetric modification of hydrophobic NPs in organic medium, an added advantage to the solid substrate methods reported in literature.

Fig. 3 (a) UV-vis spectra of as-prepared 40 nm Janus AuNPs, 14 nm citrate stabilized AuNPs, and clusters assembled from these two types of AuNPs; (b) UV-vis spectra of as-prepared 14 nm Janus AuNPs, 14 nm citrate stabilized AuNPs, and clusters assembled from these two types of AuNPs; (c) UV-vis spectra of as-prepared 14 nm Janus AuNPs, 56 nm citrate stabilized AgNPs, and core-satellites assembled from these two types of NPs; (d) UV-vis spectra of as-prepared 3.6 nm Janus AuNPs, 56 nm citrate stabilized AgNPs, and core-satellites assembled from these two types of NPs. Water was used as the solvent for all the samples.

In addition to the obtained results showing the successful conjugation of two different lipoyl ligands onto Janus AuNPs, asymmetric distribution of these two types of ligands on NP surface was also confirmed through the formation of colloidal clusters. When citrate stabilized AuNPs (negatively charged) were mixed with the as-prepared amine functionalized Janus AuNPs (positively charged), they assembled together through electrostatic interaction. Thus, upon mixing 40 nm Janus AuNPs with 14 nm citrate stabilized AuNPs, it was observed that the smaller AuNPs bound to the larger Janus NPs in a side-specific manner, forming dimers or other cluster structures (Fig. 2a-c and Fig. S3 in ESI). This side-specific binding is consistent with the regioselective modification of 40 nm AuNPs.⁶ UV-vis spectrum of the obtained cluster shows enhanced absorption in the range above 600 nm (Fig. 3a), which confirms the assembly of these two types of AuNPs in solution phase. Based on the measurement from Fig. 2c, the percentage of the spherical area on single 40 nm Janus AuNP contacting 14 nm citrate stabilized AuNPs was estimated to be ca. 22%, which is in agreement with the fact that only a small patch of AuNP surface was coupled with SiO₂@AuNPs and then modified with amine groups during the preparation (Fig. 1a). In the case of 14 nm Janus AuNPs, upon mixing with 14 nm citrate stabilized AuNPs, we observed the formation of discrete clusters including dimers, trimers, and tetramers (Fig. 2d-f and Fig. S4 in ESI). Similarly, UV-vis spectrum of the obtained clusters exhibits enhanced absorption in the range above 600 nm (Fig. 3b). We also mixed 14 nm Janus AuNPs with citrate stabilized AgNPs (about 56 nm in size). The formation of discrete core-satellite structures with AgNPs as cores and Janus AuNPs as satellites was observed from TEM (Fig. 2g,h) and scanning electron microscopy (SEM, Fig. S5 in ESI) images. The bimetallic structures were also confirmed by energy-dispersive X-ray spectroscopy (EDX, Fig. S6 in ESI). In this case, we observed a red shift in the plasmonic resonance band of AgNPs from original 415 nm to 433 nm, and also a red

shift in the plasmonic band of Janus AuNPs from original 525 nm to 569 nm (Fig. 3c). The as-prepared 3.6 nm Janus AuNPs were also assembled with citrate stabilized AgNPs (about 56 nm in size) to form the core-satellite structures (Fig. 2i). The spectral change (Fig. 3d) of 3.6 nm Janus AuNPs/AgNPs core-satellite structures is similar to that of 14 nm Janus AuNPs/AgNPs (Fig. 3c), but is of smaller magnitude, presumably due to the smaller size of 3.6 nm Janus AuNPs used. Taken together, the assembly of three types of Janus AuNPs with citrate stabilized NPs all led to the formation of discrete and regular cluster superstructures. As it is well known that the assembly of two types of regular NPs with opposite charges usually results in the formation of random and irregular aggregates (e.g., Fig. S7 in ESI), the formation of regular colloidal clusters proves the successful preparation and application of these Janus AuNPs.

In conclusion, we have prepared amine functionalized Janus AuNPs by taking advantage of reversible formation and dissociation nature of imine bond. The Janus structure of as-prepared AuNPs has been demonstrated through the formation of discrete nanoclusters. Different from common solid substrate technique where the immobilization of NPs is purely to sterically protect one side of NPs from chemical modification, in the approach developed here, the immobilization of NPs is coupled to the introduction of target chemical functionality (amine bond in this case) onto the NP surface, the principle of which is similar to the “solid-state grafting-to” strategy.^{15,16} Compared to the reported solid substrate method where electrostatic attraction is commonly chosen as a force to immobilize NPs in aqueous solution,^{3-5,7} the approach demonstrated in this work uses reversible covalent bond to immobilize NPs, which enables direct modification of NPs in diverse media. This is an advantage of the present approach especially when the modification of hydrophobic NPs by hydrophobic ligands is desired.

Furthermore, imine bond is a type of dynamic covalent bond that can be formed and cleaved reversibly in response to a specific stimuli.²⁵ We expect that the strategy reported here can be applicable to other types of dynamic covalent bonds, such as furan-maleimide cycloaddition, boronic esters, and hydrazones,²⁶ so as to impart NPs with other functionalities. On the other hand, the lipoyl group used here can be replaced with other anchoring groups (such as thiols or catechols) for the preparation of Janus NPs. In addition, the number of amine groups modified on a patch of NP surface can be adjusted by simply changing the grafting density of the lipoic-TriEG-amine ligand on SiO₂NPs. Thus, it might be possible to obtain Janus NPs having only a few or even only one amine group attached on a patch of surface. Such kind of Janus NPs would be useful to generate special hot spots for the application of surface enhanced Raman scattering.^{27,28}

This work is supported by the National Research Foundation (NRF), Prime Minister’s Office, Singapore under its NRF Fellowship (NRF2009NRF-RF001-015) and Campus for Research Excellence and Technological Enterprise (CREATE) Programme–Singapore Peking University Research Centre for a Sustainable Low-Carbon Future, as well as the NTU-A*Star Silicon Technologies Centre of Excellence under the program grant No. 112 351 0003.

Notes and references

- ^aDivision of Chemistry and Biological Chemistry, School of Physical and Mathematical Sciences, Nanyang Technological University, 21 Nanyang Link, Singapore 637371. E-mail: zhaoyanli@ntu.edu.sg; Tel: +65 6316 8792
- ^bSchool of Materials Science and Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798.
- † Electronic Supplementary Information (ESI) available: Additional synthesis and characterization data. See DOI: 10.1039/b000000x/
1. A. Walther and A. H. E. Müller, *Chem. Rev.*, 2013, **113**, 5194-5261.
2. M. Lattuada and T. A. Hatton, *Nano Today*, 2011, **6**, 286-308.
3. R. Sardar, T. B. Heap and J. S. Shumaker-Parry, *J. Am. Chem. Soc.*, 2007, **129**, 5356-5357.
4. L. Guo, Y. Xu, A. R. Ferhan, G. Chen and D.-H. Kim, *J. Am. Chem. Soc.*, 2013, **135**, 12338-12345.
5. Y. Hu and Y. Sun, *J. Am. Chem. Soc.*, 2013, **135**, 2213-2221.
6. L. H. Tan, H. Xing, H. Chen and Y. Lu, *J. Am. Chem. Soc.*, 2013, **135**, 17675-17678.
7. Z. Li, E. Cheng, W. Huang, T. Zhang, Z. Yang, D. Liu and Z. Tang, *J. Am. Chem. Soc.*, 2011, **133**, 15284-15287.
8. R. Sardar and J. S. Shumaker-Parry, *Nano Lett.*, 2008, **8**, 731-736.
9. S. Pal, J. Sharma, H. Yan and Y. Liu, *Chem. Commun.*, 2009, 6059-6061.
10. P.-G. de Gennes, *Angew. Chem., Int. Ed. Engl.*, 1992, **31**, 842-845.
11. A. Alexeev, W. E. Uspal and A. C. Balazs, *ACS Nano*, 2008, **2**, 1117-1122.
12. T. Chen, M. Yang, X. Wang, L. H. Tan and H. Chen, *J. Am. Chem. Soc.*, 2008, **130**, 11858-11859.
13. S. Pradhan, L. Xu and S. Chen, *Adv. Funct. Mater.*, 2007, **17**, 2385-2392.
14. M. Lattuada and T. A. Hatton, *J. Am. Chem. Soc.*, 2007, **129**, 12878-12889.
15. C.-P. Chak, S. Xuan, P. M. Mendes, J. C. Yu, C. H. K. Cheng and K. C.-F. Leung, *ACS Nano*, 2009, **3**, 2129-2138.
16. B. Wang, B. Li, B. Zhao and C. Y. Li, *J. Am. Chem. Soc.*, 2008, **130**, 11594-11595.
17. X. Peng and J. Thessing, in *Semiconductor Nanocrystals and Silicate Nanoparticles*, eds. X. Peng and D. M. P. Mingos, Springer Berlin Heidelberg, 2005, **118**, 79-119.
18. J. Yang, E. H. Sargent, S. O. Kelley and J. Y. Ying, *Nat. Mater.*, 2009, **8**, 683-689.
19. N. R. Jana, L. Gearheart and C. J. Murphy, *Langmuir*, 2001, **17**, 6782-6786.
20. S. D. Perrault and W. C. W. Chan, *J. Am. Chem. Soc.*, 2009, **131**, 17042-17043.
21. M. Brust, M. Walker, D. Bethell, D. J. Schiffrin and R. Whyman, *J. Chem. Soc., Chem. Commun.*, 1994, 801-802.
22. N. R. Jana and X. Peng, *J. Am. Chem. Soc.*, 2003, **125**, 14280-14281.
23. N. Zheng, J. Fan and G. D. Stucky, *J. Am. Chem. Soc.*, 2006, **128**, 6550-6551.
24. M. E. Belowich and J. F. Stoddart, *Chem. Soc. Rev.*, 2012, **41**, 2003-2024.
25. S. J. Rowan, S. J. Cantrill, G. R. L. Cousins, J. K. M. Sanders and J. F. Stoddart, *Angew. Chem., Int. Ed.*, 2002, **41**, 898-952.
26. A. W. Jackson and D. A. Fulton, *Polym. Chem.*, 2013, **4**, 31-45.
27. M. M. Maye, D. Nykypanchuk, M. Cuisinier, D. van der Lelie and O. Gang, *Nat. Mater.*, 2009, **8**, 388-391.
28. D.-K. Lim, K.-S. Jeon, H. M. Kim, J.-M. Nam and Y. D. Suh, *Nat. Mater.*, 2010, **9**, 60-67.

TOC Figure

5

An imine-based approach was developed to prepare Janus gold nanoparticles having one patch of surface with amine functionality and the other with polyethylene glycol unit.