SYNTHETIC ROUTES TO SILICA-COATED GOLD NANORODS

BY

MEREDITH ELAINE RAGAN WALKER

THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Materials Science and Engineering in the Graduate College of the University of Illinois at Urbana-Champaign, 2012

Urbana, Illinois

Advisor:

Professor Catherine J. Murphy
ABSTRACT

The surface functionalization of gold nanorods has numerous applications for medical therapeutics, sensing, and other optoelectronic enhancement related phenomena. Surface chemistry of these particles can be altered by tuning the charge, chemical groups, and reactivity at the surface. Specifically, this thesis will focus on the synthesis of a silica coating on the surface of gold nanorods.

First, work pioneered by Liz-Marzán in silica coating of gold nanorods via mPEG-SH coated rods followed by a silane will be explored. Next, alternate routes involving modified Stöber methods will be examined. Finally, novel routes that include various silicate and silane coatings will be elucidated.

Silica coating of gold nanorods has received much attention due to its application in varying arenas such as SERS and therapeutics. Therefore, some initial results based on collaborations with the Gewirth group will be shown that validate and guide future efforts to coat these rods with silica.
I would first like to thank my research advisor, Professor Catherine J. Murphy, for her dedication, patience, and guidance throughout my time in her research group. I thank her for letting me join her research group after a rocky first year in graduate school. This thesis would not have been possible without the guidance of my research advisor.

I would also like to thank the Murphy research group, specifically, Sean Sivapalan, Jonathan Eller, Nardine Abadeer, Stefano Boulos, and Sam Lohse. Their guidance and help throughout my time here was very much appreciated. Finally, Dennis Butcher in the Gewirth group for running SERS experiments on my prepared gold nanorods.

A final acknowledgement to my husband, Brett Walker, for his support and patience throughout my studies here. I would also like to thank my family and friends for their constant support. Lastly, I would like to thank my dogs for getting me out of the lab every once in awhile for walks out in the sunshine.
# TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION TO GOLD-SILICA CORE-SHELL NANOMATERIALS ................................................................. 1

1.1 INTRODUCTION .......................................................................................................................................................... 1

1.2 THESIS SCOPE AND ORGANIZATION .................................................................................................................. 2

1.3 BACKGROUND ON GOLD NANOPARTICLES AND SILICA COATING ................................................................. 3

1.4 MATERIALS ............................................................................................................................................................... 11

1.5 INSTRUMENTATION ................................................................................................................................................ 11

1.6 SYNTHESIS OF NANOPARTICLES .......................................................................................................................... 13

   1.6.1 Synthesis of Citrate Seeds ................................................................................................................................. 13

   1.6.2 Synthesis of CTAB Seeds ................................................................................................................................. 16

   1.6.3 Short Rod Synthesis ........................................................................................................................................... 18

   1.6.4 Synthesis of 12 nm Citrate Capped Au Nanoparticles .................................................................................. 23

1.7 REFERENCES ......................................................................................................................................................... 26

CHAPTER 2 SILICA COATING OF GOLD NANORODS ....................................................................................................... 29

2.1 SILICA COATING OF NANOPARTICLES ................................................................................................................ 29

   2.1.1 Silica Coating of 12 nm Citrate Spheres ............................................................................................................. 29

   2.1.2 Unsuccessful Attempts at Silica Coating Rods ................................................................................................. 34

   2.1.3 Successful Attempts at Silica Coating Rods ................................................................................................. 55

2.2 CONCLUSIONS AND FUTURE WORK ..................................................................................................................... 75

2.3 REFERENCES ......................................................................................................................................................... 77
CHAPTER 1

INTRODUCTION TO GOLD-SILICA CORE-SHELL NANOMATERIALS

1.1 Introduction

As a class of materials, metallic nanoparticles are of interest for electrical, optical, and biomedical applications. Due to the ease of modification of metallic nanoparticle surfaces with varying functional groups, a number of varying coatings and shells can be applied post nanoparticle synthesis. These surface modifications can be used for a number of applications in sensing, medicine, and characterization. Along the vein of optical properties, surface enhanced Raman spectroscopy (SERS) is a technique that can especially benefit from the properties obtained via nanoscale metallic particles. Raman scattering is a technique that measures photon inelastic scattering and is useful in analyzing the composition of chemical species. SERS specifically focuses on this scattering by varying surface conditions that can amplify the typically weak signal from Raman scattering experiments (typically only 1 in 10 million photons participate in this inelastic scattering event). Specifically, gold nanoparticles and silica-coated gold nanoparticles can boost the signal received for SERS measurements by a factor of greater than $10^{10}$ resulting in the ability to resolve single molecule adsorption.
Also, due to tunable excitation wavelengths from both the diameter and length of these rods, these particles can be sensitized to certain wavelengths resulting in novel approaches to biomedical applications such as tumor targeting and other related objectives.

1.2 Thesis Scope and Organization

The aim of this work is to develop various methods to fabricate silica coatings for gold nanorods in aqueous solution. The systems developed are based on previously reported findings on silica coating of gold nanorods via vitrification from silicates of a thiol-terminated poly(ethylene glycol) capping layer. Also, other methods will be explored that involve replacing the cetyltrimethylammonium bromide (CTAB) layer with various amine-terminated polymers such as branched poly(ethylene imine) (PEI) and chitosan. Various methods of characterization will be demonstrated such as ultraviolet-visible (UV-Vis) spectroscopy, transmission electron microscopy (TEM), zeta potential, dynamic light scattering (DLS), X-ray Photoelectron Spectroscopy, as well as SERS data.

Chapter 1 details prior literature that navigates synthetic routes for gold nanoparticles (both spheres and rods) as well as silica coating of these particles. Chapter 2 reports experimental results when reproducing work in silica coating gold nanorods as well as aforementioned novel methods in producing silica coatings. The main conclusions are also presented in Chapter 2.
1.3 Background on Gold Nanoparticles and Silica Coating

Of all the unique properties that metallic nanoparticles possess, optical properties have been studied for a few decades at the nanoscale. These are a manifestation of new physics present, which reveal themselves in other ways such as unusually low melting temperatures as compared to their bulk counterparts [1]. While gold at even the micron scale has a melting temperature identical to the bulk material, once the diameter of these particles begins to decrease past the 100 nm range the melting temperature begins to relate linearly to the inverse particle diameter. These particles have been synthesized in a number of ways and due to the scope of this thesis only a few of these methods will be mentioned.

The optical properties of metallic nanoparticles also behave unusually as compared to their bulk counterparts. Due to the electron mobility of metals, light can interact with these surface electrons and create what are called plasmons. Briefly, plasmons result from the oscillation of surface electrons via incoming light. In bulk metals these effects are negligible due to the relatively low amount of surface electrons as compared to bulk metallic electrons. However, nanoparticles have a large portion of their electrons on the surface of the particle resulting in electron oscillations that absorb at various wavelengths of light depending on the size of the nanoparticle [2-5]. Macroscopically, this can result in a variety of effects including vibrant colors due to the absorption and scattering of various wavelengths [5]. On the nanoscale, these wavelength numbers can
yield a large amount of information about the structure and size of the nanoparticle itself (Figure 1).
Figure 1. Ultraviolet-visible spectrum showing the absorption spectra for spheres and rods of varying sizes [5].
For solution-based synthesis, gold precursors exist of both mono and trivalent salts with varying counterions. These salts have relatively low solubility compared to many other metallic salts in solution generally, which results in fairly dilute suspensions of nanoparticles when the salts are reduced. While numerous methods can be employed with relatively strong reducing agents such as borohydrides [6], amines can be used as both a reducing and capping agent for these solutions [7], [8]. Citrate ions serve a similar purpose as well [9]. Citrate ions provide a good segue into anisotropic gold particle synthesis and properties.

Anisotropic particles are interesting due to their controllable inhomogeneity along the length axis. The synthesis of these particles relies on the utilization of reagents that selectively cap certain facets in order to promote anisotropic growth. Citrate ions can perform this function at various temperatures and pH values for silver [9], [10]. However, anisotropic gold nanorods with controllable aspect ratios have proven relatively difficult to produce utilizing typical methods employed with copper and silver rods. Therefore, the seed-mediated, hexadecyltrimethylammonium bromide (CTAB) capped gold nanorod growth route is the predominate method to grow controllable aspect ratio rods. Anisotropic gold particles (for the purpose of this thesis gold nanorods and wires) are especially useful for diagnostic purposes because they can provide optical feedback at two wavelengths due to possessing two characteristic dimensions – length and diameter. This enhances optical sensitivity and provides useful information on the aspect ratio of the rod itself. The most commonly used
nanorod synthesis route was developed by the Murphy group using a seed mediated growth and CTAB capping agent [6], [11].

While gold nanorods provide excellent SERS substrates, they can aggregate. This causes “hotspots” which actually quenches the SERS signal. Silica coatings provide two distinct advantages. First, silica is relatively chemically inert meaning that it will not modify or interfere with surface adsorbents. Second, these coatings prevent the gold nanorods from coming in contact with one another and creating hotspots that result in a weakened signal. With a basic understanding of the properties, synthesis, and applications of nanoparticles, we can now move on to functionalizing these particles via silica coating. Silica coating of gold nanoparticles can be accomplished in several ways for spherical particles. The surface layer can be capped with a thiol-functionalized poly(ethylene glycol) (PEG) chain and directly functionalized with a silane such as an amino silane (3-aminopropyldimethoxysilane, APTMS) or other similar moieties. In the case of the PEG-capped particle, transference into ethanol precedes a simple Stöber reaction process whereby a silica cap of controllable thickness can be grown with tetraethylorthosilicate (TEOS) [13], [14] (Figure 2). For silane or siloxane routes, addition of silicic acid or a salt of silicic acid can grow the layers resulting in a conformal silica coating [15]. These coatings provide a significant red shift in the longitudinal surface plasmonic resonance resulting in improved heating efficiency when lased with an appropriate wavelength light source. However, these coatings can contain a SERS reporter
molecule that will not degrade or release upon heating with NIR light. Therefore, these particles are promising candidates for robust tumor targeting materials.
Figure 2. Schematic of Stöber synthesis with representative chemical structures [15].
While silica coatings on gold nanospheres proved to be fairly straightforward, this was not the case for gold nanorods. Gold nanorods are the material of choice for tumor targeting due to their unique plasmonic properties and absorption at NIR wavelengths. Silica coating would result in a robust particle that can withstand repeated use for oncological therapeutics. The most widely accepted method of achieving a conformal silica coating on these particles is replacing the CTAB bilayer with a PEG thiol chain. Once this modified thiol has absorbed on the surface of the particle the particles are then placed in ethanol and a modified Stöber process yields a uniform silica coating [13]. However, this process is often associated with low yields and is difficult to reproduce. The previously mentioned silane routes can also work with modification [16], [17].
1.4 Materials

Chloroauric acid (HAuCl₄ • 3H₂O), trisodium citrate, sodium borohydride (NaBH₄), silver nitrate, ascorbic acid, 3-aminopropyltrimethoxysilane (APTMS), anhydrous ethanol, 2 M ammonia in ethanol, and tetraethyl orthosilicate (TEOS) were obtained from Sigma-Aldrich and were used as received. Hexadecyltrimethylammonium bromide (CTAB), 99% was obtained from Sigma-Aldrich and used as received. Silicic acid, 99.9% was obtained from Sigma-Aldrich and used as received. Methoxyl poly(ethylene glycol) thiol (mPEG-SH), molecular weight 5000, was obtained from NanoCS. Sodium silicate solution, reagent grade (~10.6% Na₂O, ~26.5% SiO₂) was obtained from Sigma-Aldrich and used as received. All glassware used was cleaned prior to use by aqua-regia (3:1 v/v hydrochloric: nitric acid) and deionized water (Resistivity of 18 mΩ), which was also used for all experiments.

1.5 Instrumentation

UV-Vis spectroscopy was performed on a Varian model Cary 500 Scan UV-Vis-NIR spectrophotometer. Zeta potential and light scattering measurements were performed on a Brookhaven Zeta PALS instrument. Transmission electron microscopy (TEM) measurements were performed on a Hitachi H-8000 TEM instrument operating at an accelerating voltage of 200 kV. For TEM, the samples were prepared by drop casting 10 μL of the nanorod solution twice on a carbon coated copper grid and allowing the grid to air dry. X-ray Photoelectron Spectroscopy (XPS) was performed on a Kratos Axis ULTRA XPS with a
differentially pumped 1-5 KeV ion gun. XPS samples were drop cast onto a silicon wafer whose surface was passivated using Piranha solution, a mixture of sulfuric acid (H$_2$SO$_4$) and hydrogen peroxide (H$_2$O$_2$). The centrifuge used was a Thermo Scientific Sorvall Legend XI Centrifuge and all sample were spun in Corning centrifuge tubes. Raman spectra were collected using two-compartment, glass electrochemical cells [18] and SERS (see Figure 42) was obtained by using a HeNe laser (632.8 nm) as the excitation source [19] with a 45-degree angle of incidence. Radiation was collected with a Canon camera lens and a f/4 focusing lens. The diffraction grating contained 1200 grooves/mm and was projected to a cooled CCD (Andor) [20]. The acquisition time at each potential was 30 s with 0.05 V potential steps between acquisitions. Potential control was achieved using a CV-27 (BAS) with the gold surface as the working electrode, gold wire as the counter electrode, and a no-leak Ag/AgCl reference electrode (Cypress Systems). All potentials are reported versus the Ag/AgCl reference [21].
1.6 Synthesis of Nanoparticles

1.6.1 Synthesis of Citrate Seeds

Citrate capped gold nanoparticles, 4 nm in size, were synthesized by reducing the gold ions (III) to atomic gold atoms using a strong reducing agent, sodium borohydride, in the presence of citrate ions. A 20 mL batch was produced by first placing 500 µL of 0.01 M chloroauric acid in a 25 mL flask to which 19 mL of deionized water was added. Next, 500 µL of 0.01 M sodium citrate (prepared by dissolving 0.0294 g trisodium citrate in 10 mL water) was added and the solution was stirred using a stir bar and magnetic stir plate. To the stirring solution, 600 µL of 0.1 M freshly prepared ice-cold sodium borohydride was added to the flask. Stirring was stopped immediately upon the addition of the sodium borohydride. The flask was left undisturbed for 3 to 5 hours. The solution turned dark red after the sodium borohydride was added, further turned blackish, and finally turned back to red after 3 – 5 hours.

After this was successful, a scaled-up 200 mL batch was attempted by using: 5 mL 0.01 M HAuCl₄, 190 mL deionized water, 5 mL 0.01 M sodium citrate, and 6 mL 0.1 M NaBH₄. This scale up didn’t work, presumably because it took too long to add in the appropriate amount of sodium borohydride. A 50 mL batch was then prepared using: 1.25 mL 0.01 M HAuCl₄, 47.5 mL deionized water, 1.25 mL 0.01 M sodium citrate, and 1.5 mL 0.1 M NaBH₄. This was a successful scale-up and was confirmed by UV-Vis (Figure 3) and TEM (Figure 4).
Figure 3. Ultraviolet-visible spectrum of an aqueous solution of 4 nm citrate capped gold nanoparticles.
Figure 4. Transmission electron micrograph with a 20 nm scale bar of an aqueous solution of 4 nm citrate capped gold nanoparticles drop cast on a carbon coated copper TEM grid.
1.6.2 Synthesis of CTAB Seeds

The seeds were prepared by reducing the gold ions (III) to atomic gold atoms using a strong reducing agent, sodium borohydride, in the presence of CTAB (see Figure 5). In a 50 mL tube 9.75 mL 0.1 M CTAB stock solution and 250 µL of 0.01 M chloroauric acid were combined and stirred vigorously. 600 µL of 0.01 M freshly prepared ice-cold sodium borohydride was added to the flask. The solution was stirred for two minutes. Note: color should be tan at this point. The seed solution was not used for at least half an hour to ensure complete reaction of sodium borohydride.
Figure 5. Chemical structure of hexadecyltrimethylammonium bromide (CTAB).
1.6.3 Short Rod Synthesis

Short rods (less than 100 nm) were prepared using CTAB capped seeds. 9.5 mL of 0.1 M CTAB solution was placed into five 15 mL centrifuge tubes. 20, 40, 60, 80, and 100 µL of 0.01 M silver nitrate solution was added to each tube and inverted to mix the reagents. Different amounts of AgNO₃ yield different rod dimensions; increasing the amount of AgNO₃ will increase the aspect ratio and result in a red shift in the longitudinal plasmonic band on the UV-Vis spectra (Figure 6). 500 µL 0.01 M chloroauric acid was added to the tube and inverted to mix. A dark gold color appeared. 55 µL of freshly prepared 0.1 M ascorbic acid solution was added and the tube inverted to mix. The gold color disappeared immediately indicating the reduction of gold (III) to gold (I) (unlike sodium borohydride, ascorbic acid is a weak reducing agent and therefore will not reduce the gold ions to atomic gold). 15 µL CTAB capped seeds were added and the tube was gently mixed. The solution was allowed to sit overnight to let the rods grow; an experimental schematic is shown in Figure 7. The rods were purified via centrifugation for 20 minutes using 10,000 rpm then resuspended in deionized water. They were then centrifuged for 10 minutes using 10,000 rpm and also resuspended in deionized water. A picture showing the varying color of the nanoparticles is shown in Figure 8 and their respective UV-Vis spectra are shown in Figure 9.
Figure 6. Short rods via seed-mediated growth with increasing amounts of silver nitrate (AgNO₃) and increasing aspect ratios with their respective transmission electron micrographs and ultraviolet-visible spectrums [22].
9.5 mL 0.1 M CTAB
+ x uL 0.01 M AgNO₃
+ 500 uL 0.01 M HAuCl₄
+ 55 uL 0.1 M ascorbic acid
+ 15 uL CTAB seed

x = 20, 40, 60, 100 uL 0.01 M AgNO₃

Figure 7. Schematic of short rod (less than 100 nm) synthesis.
Figure 8. Photograph of aqueous solutions of short rods synthesized via seed-mediated growth with increasing amounts of silver nitrate from left to right.
Figure 9. Normalized ultraviolet-visible spectrum for short rods synthesized via seed-mediated growth with increasing amounts of 0.01 M silver nitrate from 20 µL to 100 µL.
1.6.4 Synthesis of 12 nm Citrate Capped Au Nanoparticles

To a 200 mL Erlenmeyer flask, 2.5 mL of 0.01 M HAuCl$_4$ and 97.5 mL deionized water was added. The solution was then heated to a gentle, rolling boil while being stirred with a stir bar on a magnetic hot plate. When the gold solution started to boil, 3 mL of 1% sodium citrate (0.1 g in 10 mL deionized water) was added in one swift motion. The solution was boiled for at least 30 minutes. The color changed slowly to a deep red. If necessary, additional citrate (about 1 mL) was added after the solution stopped changing color. If added, the solution was boiled for another 30 minutes to help passivate the surface of the formed particles and keep the nanoparticles more stable over a longer period of time.

The heat was turned off and the red colored gold nanoparticle solution was allowed to cool while stirring and an experimental schematic is shown in Figure 10. After the solution had cooled to room temperature, deionized water was added to make the total volume 100 mL (or the desired concentration). The next day the solution was split into two 50 mL centrifuge tubes and centrifuged at 11,000 RPM for 30 minutes. The supernatant was discarded and the pellets were diluted to 40 mL with deionized water, UV-Vis data is shown in Figure 11 (Note: Make sure the solution does not boil to dryness. Add boiling deionized water if necessary).
Figure 10. Experimental schematic for the synthesis of 12 nm citrate capped spheres.
Figure 11. Ultraviolet-visible spectrum of an aqueous solution of 12 nm citrate capped gold nanospheres.
1.7 References


CHAPTER 2

SILICA COATING OF GOLD NANORODS

2.1 Silica Coating of Nanoparticles

2.1.1 Silica Coating of 12 nm Citrate Spheres

A stock solution of 100 mM 3-aminopropyltrimethoxysilane (APTMS) was made with 179 µL of APTMS in 10 mL of deionized water. 100 µL of the 100 mM APTMS solution was added to 10 mL of deionized water to yield 1mM APTMS solution. 0.4 mL of 1mM APTMS solution was added dropwise to 50 mL of the 12 nm citrate spheres previously described (see Section 1.6.4, called Solution A). The reaction was allowed to proceed for 15 minutes while being stirred on a magnetic stir plate with a stir bar. A 0.54wt% solution of 40 µL of sodium silicate in 10 mL of deionized water was prepared (pH ~ 10.5). 3.2 mL of the 0.54 wt% sodium silicate solution was added to the APTMS/citrate nanoparticle solution (Solution A) to give Solution B. Solution B was placed in a 90°C water bath; an experimental schematic is shown in Figure 12 [1]. 10 mL of Solution B was removed from the flask after 1, 3, 17, 20, and 24 hours and 8.5 mL of it was placed in a 15 mL centrifuge tube. Each aliquot was centrifuged once at 5,000 RPM for 15 minutes. The supernatant was discarded and the pellet was resuspended up to 8.5 mL with deionized water. The aliquots were then
centrifuged a second time at 5,000 RPM for 15 minutes. The supernatant was discarded; the pellet was resuspended up to 2 mL with deionized water. 10 µL were put on a TEM grid to dry prior to centrifugation. From the TEM images (Figure 13 and Figure 14), there was no presence of a silica coating.
Figure 12. Experimental schematic for silica coating 12 nm citrate caped nanoparticles.
Figure 13. Transmission electron micrograph with a 200 nm scale bar of an aqueous solution (17 hour aliquot) of 12 nm citrate capped gold nanoparticles drop cast on a carbon coated copper TEM grid.
Figure 14. Transmission electron micrograph with a 200 nm scale bar of an aqueous solution (24 hour aliquot) of 12 nm citrate capped gold nanoparticles drop cast on a carbon coated copper TEM grid.
2.1.2 Unsuccessful Attempts at Silica Coating Rods

1. mPEG-SH & TEOS

Short Rod Synthesis

A 200 mL batch of short rods were made using 190 mL 0.1 M CTAB stock solution, 1200 µL 0.01 M AgNO₃, 10 mL 0.01 HAuCl₄, 1,100 µL 0.1 M ascorbic acid, and 240 µL CTAB seeds, an experimental schematic is shown in Figure 15. The rods were centrifuged twice at 11,000 RPM for 20 minutes each time discarding the supernatant. The pellets were combined and diluted up to 40 mL using deionized water. The zeta potential was measured to be +36.4 ± 3.92 mV. The next day the rods were concentrated down by centrifugation at 11,000 RPM for 30 minutes. The supernatant was discarded, the pellet was diluted to 2 mL with deionized water, and a UV-Vis spectrum was obtained (Figure 16).
Figure 15. Experimental schematic for synthesizing CTAB short rods via seed-mediated growth.

190 mL 0.1 M CTAB
+ 1200 uL 0.01 M AgNO$_3$

+ 10 mL 0.01 M H$_2$AuCl$_4$

+ 1100 uL 0.1 M ascorbic acid

+ 240 uL CTAB seed
Figure 16. Ultraviolet-visible spectrum of an aqueous solution of a 200 mL batch of short rods.
**mPEG-SH Coating**

0.165 g of methoxyl poly(ethylene glycol) thiol (mPEG-SH) with a molecular weight of 5000, structure shown in Figure 17, was dissolved in 8.25 mL of deionized water and sonicated for 15 minutes. 2 mL of the mPEG-SH solution was added to 1 mL of the aforementioned synthesized short rods dropwise and was vortex stirred after every 5-10 drops. The sample was then placed on the shaker (Belly Dancer model) for 2 hours. After 2 hours, the sample was added to a 10,000 molecular weight cutoff (MWCO) 3 mL sample volume dialysis cassette for ~20 hours against 4 L of deionized water, with the water having been changed once. A schematic showing the surface chemistry for coating the CTAB rods with mPEG-SH is shown in Figure 20. This experiment could not proceed to silica coating using TEOS as planned due to aggregation and an unsuccessful attempt to mPEG-SH coat the rods, which can be verified via UV-Vis (Figure 18).
Figure 17. Chemical structure of methoxyl poly(ethylene glycol) thiol (mPEG-SH).
Figure 18. Ultraviolet-visible spectrum of an aqueous solution of CTAB short rods after mPEG-SH coating, indicating the sample aggregated due to an unsuccessful mPEG-SH coating.
2. mPEG–SH & Silicic Acid

Short Rod Synthesis

Four 100 mL batches of short rods were made. Each batch contained 95 mL 0.1 M CTAB, 5 mL 0.01 M HAuCl₄, 550 µL 0.1 M ascorbic acid, and 150 µL CTAB seed. Two batches named A & B contained 400 µL 0.01 M AgNO₃ and two batches named C and D contained 600 µL 0.01 M AgNO₃, see Figure 19 for an experimental schematic. Each batch was divided into 4 large centrifuge tubes with 25 mL in each tube. Batches A and B were centrifuged at 11,000 RPM for 25 minutes and then again at 11,000 RPM for 15 minutes. The supernatant was collected and centrifuged at 11,000 RPM for 30 minutes. The pellets were combined and diluted to 25 mL with deionized water. Batches C and D were centrifuged at 11,000 RPM for 25 minutes and again at 10,000 RPM for 30 minutes. The supernatant was collected and centrifuged at 10,000 RPM for 20 minutes. The pellets were combined and diluted to 25 mL with deionized water. All four batches of rods were then cleaned a second time at 10,000 RPM for 30 minutes. The supernatant was discarded and the pellets from each batch (4 pellets for each batch) were all combined and diluted with deionized water up to 25 mL. UV-Vis and zeta potential were then run; see Figure 22 and Figure 23 for “A rods” and Figure 24 and Figure 25 for “C rods”.

40
Figure 19. Batch A and C short rod experimental schematic.

Batch A

95 mL 0.1 M CTAB + 400 uL 0.01 M AgNO₃ + 5 mL 0.01 M HAuCl₄ + 550 uL 0.1 M ascorbic acid + 150 uL CTAB seed

Batch C

95 mL 0.1 M CTAB + 600 uL 0.01 M AgNO₃ + 5 mL 0.01 M HAuCl₄ + 550 uL 0.1 M ascorbic acid + 150 uL CTAB seed
**Attempt 1:**

**mPEG-SH Coating**

5 mL of “A” and “C” rods were diluted to 15 mL with deionized water in a 50 mL centrifuge tube. Two solutions of 0.027 g of mPEG-SH (MW 5000) in 5 mL of water was made and sonicated for 1 minute. The mPEG-SH solution was added to each tube of rods dropwise while stirring on a magnetic stir plate with a stir bar. The tubes were then placed on a shaker (Belly Dancer model) for 2 hours at setting 5. After two hours, they were centrifuged at 8,000 RPM for 20 minutes. The supernatants were removed and centrifuged at 8,000 RPM for 20 minutes. The pellets were combined and anhydrous ethanol was added up to 10 mL [2]. A schematic showing the surface chemistry for coating the CTAB rods with mPEG-SH is shown in Figure 20.
Figure 20. Schematic showing the surface chemistry for coating CTAB rods with mPEG-SH.

\[ \text{CTAB bilayer} \]
Silica Coating with Silicic Acid

0.8 mM silicic acid (structure shown in Figure 21) solution was made by adding 0.0625 g of silicic acid in 10 mL of anhydrous ethanol then taking 100 µL of the aforementioned solution and diluting it to 10 mL with anhydrous ethanol. To the mPEG-SH coated rods, 3.04 mL of deionized water, 0.688 mL of 2 M ammonia in ethanol, and 0.288 mL of 0.8 mM silicic acid solution was added and stirred with a magnetic stir plate and stir bar for 3 hours. After 3 hours the samples were centrifuged at 8,000 RPM for 20 minutes. The supernatants were removed and centrifuged at 8,000 RPM for 20 minutes. The pellets were combined and diluted to 6.5 mL with deionized water. UV-Vis spectra and zeta potential data is shown in Figure 22 and Figure 23 for “A rods” and in Figure 24 and Figure 25 for “C rods”. Dynamic light scattering (DLS) measurements were reported as follows: the shorter aspect ratio “A rods” had an effective diameter of 169.2 nm with a standard error of 1.0 nm, the larger aspect ratio “C rods” had an effective diameter of 33.7 nm with a standard error of 0.3 nm.
Figure 21. Chemical structure of silicic acid.
Figure 22. Ultraviolet-visible spectrum of an aqueous solution of bare smaller aspect ratio “A rods”, mPEG-SH coated rods, and silicic acid attempt 1 rods.
Figure 23. Zeta potential with error bars of bare smaller aspect ratio “A” rods”, mPEG-SH coated rods, and silicic acid coating attempt 1 rods.
Figure 24. Ultraviolet-visible spectrum of an aqueous solution of bare larger aspect ratio “C rods”, mPEG-SH coated rods, and silicic acid attempt 1 rods.
Figure 25. Zeta potential with error bars of bare larger aspect ratio “C” rods”, mPEG-SH coated rods, and silicic acid coating attempt 1 rods.
**Attempt 2:**

**mPEG-SH coating**

5 mL of A and C rods were diluted to 10 mL with deionized water in 50 mL Erlenmeyer flask. The mPEG-SH solution was made as described in Attempt 1 except the solution was gently stirred on the belly dancer for 3 hours at setting 6.5 [2]. The rods were centrifuged the same as in Attempt 1. The pellets were combined and diluted to 2 mL with anhydrous ethanol. The pH was measured and for sample of rods A the pH was approximately equal to 7.2 and for the sample of rods C was approximately equal to 6.2. A schematic showing the surface chemistry for coating the CTAB rods with mPEG-SH is shown in Figure 20. UV-Vis spectra and zeta potential values were then obtained as shown in Figure 26 and Figure 27 for “A rods” and Figure 28 and Figure 29 for “C rods”.

**Silica coating using silicic acid**

A new stock solution of 0.8 mM silicic acid was made by adding 0.0625 g of silicic acid to 1 L of anhydrous ethanol. To each of the 2 mL samples of concentrated mPEG-SH coated rods, 0.995 mL anhydrous ethanol, 0.76 mL deionized water, 0.173 mL 2 M ammonia in ethanol, and 0.072 mL of 0.8 mM silicic acid was added and stirred on a magnetic stir plate with a stir bar for 5 hours. After 5 hours, the samples were centrifuged as in Attempt 1. The pellets were combined and diluted with deionized water to 1.5 mL.
Figure 26. Ultraviolet-visible spectrum of an aqueous solution of bare smaller aspect ratio “A rods”, mPEG-SH coated rods, and silicic acid attempt 2 rods.
Figure 27. Zeta potential with error bars of bare smaller aspect ratio “A” rods”, mPEG-SH coated rods, and silicic acid coating attempt 2 rods.
Figure 28. Ultraviolet-visible spectrum of an aqueous solution of bare larger aspect ratio “C rods”, mPEG-SH coated rods, and silicic acid attempt 2 rods.
Figure 29. Zeta potential with error bars of bare larger aspect ratio “C” rods, mPEG-SH coated rods, and silicic acid coating attempt 2 rods.
2.1.3 Successful Attempts at Silica Coating Rods

Coating using mPEG-SH & TEOS

Short Rod Synthesis

Short rods were made using 380 mL 0.1 M CTAB stock solution, 4 mL 0.01 M AgNO₃, 20 mL 0.01 HAuCl₄, 2.2 mL 0.01 M ascorbic acid, and 400 µL CTAB seeds. The rods were centrifuged twice at 12,000 RCF for 10 minutes each time discarding the supernatant. The pellets were combined and diluted up to 500 mL using deionized water. The zeta potential was measured to be +15.05 ± 1.95 mV and DLS measured the particle size to be 36.9 ± 0.6 nm. The next day the rods were concentrated down by centrifugation at 14,000 RCF for 10 minutes. The supernatant was discarded, the pellet was diluted to 1 mL with deionized water, a UV-Vis spectrum was obtained (Figure 39) and the zeta potential was measured (Figure 40).

mPEG-SH coating – Step 1

0.5 mL of concentrated CTAB rods were placed in a 10 mL centrifuge tube. A solution of 0.0335 g of mPEG-SH (MW 5000) was dissolved in 1 mL of water via sonication for 5 minutes. The mPEG-SH solution was added to the tube of rods dropwise while stirring on a magnetic stir plate with a stir bar. The tube was then placed on a shaker (Belly Dancer model) for 3 hours at mid-speed, setting 6 [2]. After three hours, the rods were centrifuged at 14,000 RCF for 5 minutes and the supernatant was discarded. The pellet was diluted to 2 mL and lyophilized.
overnight, after which anhydrous ethanol was added to the dried rods up to 1 mL. A UV-Vis spectra and zeta potential measurement is shown in Figure 39 and Figure 40. A schematic showing the surface chemistry for coating the CTAB rods with mPEG-SH is shown in Figure 20.

To test the quality and presence of the mPEG-SH coating, x-ray photoelectron spectroscopy (XPS) was performed. As a baseline, bare CTAB short rods were measured and the data is shown in Figure 30 and Figure 31. Figure 30 shows the N 1s scan of the CTAB rods and the peak indicates the presence of nitrogen in the sample. Figure 31 shows the S 2s scan of the CTAB rods which shows no discernable peaks indicating no sulfur present in the sample. Next, the mPEG-SH coated rods were measured and the data is shown in Figure 32 and Figure 33. Figure 32 shows the N 1s scan of the mPEG-SH coated rods and the peak indicates some nitrogen (but less than CTAB rods) is present in the sample. This makes sense because the mPEG-SH coating would be blocking the nitrogen from being fully detected in the scan. Figure 33 shows the S 2s scan of the mPEG-SH coated rods and indicates the presence of sulfur in the sample due to the mPEG-SH coating. Finally as a proof of concept and to further verify that our silica coating is present, silica coated rods were measured and the data is shown in Figure 34 and Figure 35. Figure 34 shows the N 1s scan of the silica coated rods and the lack of discernable peaks indicate no nitrogen is present due to the silica coating. Figure 35 shows the S 2s scan of the silica coated rods,
which also contains no discernable peaks indicating no sulfur is present due to the silica coating.
Figure 30. X-ray photoelectron spectrum at 400 eV of CTAB rods showing the N 1s peaks, proving the presence of nitrogen in the sample.
Figure 31. X-ray photoelectron spectrum at 230 eV of CTAB rods showing the S 2s peaks, showing no presence of sulfur in the sample.
Figure 32. X-ray photoelectron spectrum at 400 eV of mPEG-SH coated rods showing the N 1s peaks, showing some nitrogen (but less than CTAB rods) in the sample.
Figure 33. X-ray photoelecton spectrum at 230 eV of mPEG-SH coated rods showing the S 2s peaks, showing some presence of sulfur in the sample due to the mPEG-SH coating.
Figure 34. X-ray photoelectron spectrum at 400 eV of silica coated rods showing the N 1s peaks, showing no presence of nitrogen in the sample (due to the silica coating).
Figure 35. X-ray photoelectron spectrum at 230 eV of silica coated rods showing the S 2s peaks, showing no presence of sulfur in the sample (due to the silica coating).
Silica coating – Step 2

A solution of tetraethyl orthosilicate (structure shown in Figure 36) was made by combining 264 µL with 10 mL of anhydrous ethanol. To silica coat the mPEG-SH coated rods, 120 µL of ammonia hydroxide, 1.33 mL deionized water, 100 µL of the aforementioned TEOS solution, and 372 µL of the mPEG-SH coated rods dissolved in anhydrous ethanol were all combined in a 20 mL scintillation vial with a stir bar and stirred for 2 hours on a magnetic stir plate [2]. After two hours, 0.75 mL was placed in each of two microcentrifuge tubes and centrifuged for 20 minutes at 5,000 RCF. The supernatant was discarded and the pellet was resuspended to 1.5 mL of water. UV-Vis (Figure 39), zeta potential (Figure 40), and TEM (Figure 41) were then obtained. A schematic of the entire process for coating of the CTAB rods with mPEG-SH followed by a thin layer of silica using TEOS in anhydrous ethanol, ammonia hydroxide, and water is shown in Figure 37 and an example reaction demonstrating the hydrolysis of TEOS to SiO$_2$ catalyzed by ammonium hydroxide is shown in Figure 38. The instrumental setup for the Raman spectroscopy experiments performed by the Gewirth group at the University of Illinois is shown in Figure 42.

The surface enhanced Raman spectroscopy (SERS) plot (Figure 43) indicates that during the first reduction/oxidation cycle, there are no peaks characteristic of pyridine being detected. Once that first cycle has taken place, peaks from pyridine (1000-1040 cm$^{-1}$, and 1485 cm$^{-1}$ most prominently) are observed because those molecules can adsorb to the gold beneath the shell. This
indicates some level of damage to the silica shell or perhaps some removal passivating species on the gold nanorods. Similarly, in the cyclic voltammogram (Figure 44), there is evidence of gold being exposed to solution. Bare particles will feature a gold stripping peak after being exposed to positive potentials. This is the reduction of generated oxides from the high potential. This is in the cathodic (bottom) scan usually between 0.6 and 0.8 V. When the shell is intact, there is no (or very little) gold exposed, meaning no gold stripping peak. The nanorods feature this peak in all scans, indicating some level of exposure from the beginning, even though this is not necessarily picked up by the SERS that was described earlier.
Figure 36. Chemical structure of tetraethyl orthosilicate (TEOS).
Figure 37. Schematic of stepwise coating of CTAB rods with mPEG-SH followed by a thin layer of silica using TEOS in anhydrous ethanol, ammonia hydroxide, and water.
Figure 38. Reaction demonstrating the hydrolysis of TEOS to SIO$_2$ catalyzed by ammonium hydroxide.
Figure 39. Ultraviolet-visible spectrum for CTAB rods, mPEG-SH coated rods, and silica coated rods.
Figure 40. Zeta potential with error bars of CTAB rods, mPEG-SH coated rods, and silica coated rods.
Figure 41. Transmission electron micrograph with a 5 nm scale bar of silica coated gold nanorods, silica shell approx. 1 nm thick.
Figure 42. Instrumental setup for Raman spectroscopy experiments performed in the Gewirth group at the University of Illinois at Urbana-Champaign.
Figure 43. Surface enhanced Raman spectroscopy graph of silica coated gold nanorods on glassy carbon in 0.1 M potassium chlorate and 1 mM pyridine.
Figure 44. Cyclic voltammogram of silica coated gold nanorods on glassy carbon in 0.5 M sulfuric acid.
2.2 Conclusions and Future Work

The procedure described by Liz-Marzán was successfully reproduced and more thoroughly analyzed. Particularly, the presence of an mPEG-SH coating was confirmed via XPS on CTAB-capped gold nanorods. Chromium-coated substrates are needed to analyze the presence of a silica coating on the rods due to the silicon on the substrates typically used for XPS measurements, however. Also, these rods were then successfully coated with a thin shell of silica, which was confirmed using TEM and SERS. This shell degraded upon exposure to an oxidation potential. A thicker shell is required in order to keep the particles stable under these conditions.

In order to more easily fabricate a shell around the gold nanoparticle, several synthetic routes offer promise as alternatives to those outlined by Liz-Marzán. I propose attempting an adaptation of Liz-Marzán’s work using 600-700 molecular weight PEG and TEOS at 90°C [3]. Primary amine groups are well known vitrification agents, especially in biological application such as diatoms where primary amines are the nucleation sites for silica growth. With this mechanism in mind, I propose displacing the CTAB coating with the polyanion PAA and subsequently coating the surface with branched PEI. Branched PEI is a polycation with numerous primary amine groups, which could serve as nucleation sites for the growth of a silica shell [4]. Chitosan is a derivative of the naturally occurring polymer chitin. Chitin is an acetylated poly(glucoseamine) material that...
is found in the shells of insects and crustaceans. Chitosan is fully deacetylated resulting in the exposure of primary amine groups along the backbone of the polymer. Furthermore, this polymer is biologically benign and can be used in vivo due to its ability to be metabolized. By functionalizing this polymer with a thiol group, chitosan can be successfully coated onto gold nanorods as shown in prior work by Wang [5]. I propose utilizing this method and subsequently coating the chitosan coated rods with silicic acid in order to get a conformal coating of silica.
2.3 References


