One-step seed-mediated growth of 30–150 nm quasispherical gold nanoparticles with 2-mercaptosuccinic acid as a new reducing agent

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

2007 Nanotechnology 18 325607

(http://iopscience.iop.org/0957-4484/18/32/325607)

View the table of contents for this issue, or go to the journal homepage for more

Download details:
IP Address: 132.70.228.158
The article was downloaded on 17/10/2010 at 14:48

Please note that terms and conditions apply.
One-step seed-mediated growth of 30–150 nm quasispherical gold nanoparticles with 2-mercaptosuccinic acid as a new reducing agent

Jiali Niu, Tao Zhu and Zhongfan Liu

Center for Nanoscale Science and Technology (CNST), Beijing National Laboratory for Molecular Sciences (BNLMS), State Key Laboratory for Structural Chemistry of Unstable and Stable Species, Key Laboratory for the Physics and Chemistry of Nanodevices, College of Chemistry and Molecular Engineering, Peking University, Beijing 100871, People’s Republic of China

E-mail: zhutao@pku.edu.cn and zfliu@pku.edu.cn

Received 13 March 2007, in final form 11 May 2007
Published 13 July 2007
Online at stacks.iop.org/Nano/18/325607

Abstract

We report herein a modified approach to the seed-mediated synthesis of large-diameter quasispherical gold nanoparticles by using 2-mercaptosuccinic acid (MSA) as a reducing agent in aqueous solution at room temperature. Simply through a one-step seeding growth approach, gold nanoparticles in the size range 30–150 nm were prepared from 15 nm gold seeds under the particular [HAuCl₄]:[MSA] ratio of 1:0.6. Particle diameters could be controlled by varying the ratio of [HAuCl₄]:[seeds]. The resultant gold nanoparticles are quasispherical with narrow size distributions (relative standard deviation, RSD < 10%) and high yields; other nanostructures (nanorods, triangles, or hexagonal nanoplates) are rarely found, although they are frequently observed during the seeding growth when using hydroxylamine or ascorbic acid as reducing agents. The presence of MSA, which is not only a reducing agent but also a capping agent, is believed to make a great contribution to the isotropic growth of gold seeds and the formation of such monodisperse quasispherical particles.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Metal particles in the nanometre size regime have received great attention because of their morphology-dependent properties; therefore, the synthesis of size- and shape-controlled metal nanoparticles with high purity and monodispersity is of great importance in a wide range of applications in nanoscience and technology, such as nanoelectronic devices and biosensors [1–4]. In the last few decades, controlled synthesis of different types of metal nanostructures has been achieved, such as rods, wires, triangles, cubes, branched multipods, and so forth [2, 5–8].

There are mainly two approaches to the production of metal nanoparticles by wet chemical methods: direct synthesis or a seeding growth method. For gold nanoparticles, direct synthesis can be categorized in two ways [9]: the Frens method [10] and the Brust method [11]. The Frens method [10] utilizes citrate reduction of gold salts, producing nearly spherical gold nanoparticles in the size range from 12 to 20 nm with a relatively narrow size distribution (relative standard deviation, RSD ~10–16%); but large colloidal gold nanoparticles (diameters of 30–120 nm) produced in this way have a broad size distribution and tend to aggregate [10, 12]. The Brust method [11] utilizes borohydride reduction of gold salts in the presence of an alkanethiol capping agent to produce smaller gold clusters (1–5 nm) in nonaqueous solutions. However, through direct synthesis, it is difficult to get large-size gold nanoparticles with narrow size distribution.
Another common approach to controlling the morphology of nanoparticles is the seeding growth method. Hydroxylamine and ascorbic acid are common reducing agents used in seeding growth of gold nanoparticles [12–16]. The particle sizes can be manipulated by varying the ratios of [HAuCl₄]:[seeds]. In either one-step or step-by-step seeding growth of large-size spherical gold nanoparticles prepared by hydroxylamine or ascorbic acid, a certain percentage of nonspherical byproducts such as nanorods, triangles, and hexagonal nanoplates were frequently observed [12, 15, 16]. There is no efficient technique to absolutely separate the spherical particles from nonspherical ones, which would depress the yield of spherical gold nanoparticles [15, 17]. Some measures have been taken to promote this anisotropic growth for the synthesis of gold nanorods by using surfactants as templates [5, 18, 19]; but few methods have been discussed to suppress the anisotropic growth for obtaining spherical gold nanoparticles [20].

In the seeding method, the growth of seeds can be considered as a competition between the surface-assisted chemical reduction and the simultaneous ligand capping on the particle surfaces [20–22]. So the final shape of the grown nanoparticles would be influenced by introducing factors that may regulate the relative rates of reduction and the rates of capping on the different facets of seeds [21, 22]. Therefore, in order to promote the isotropic growth of seeds to obtain large-size nearly spherical gold nanoparticles, here we introduced 2-mercaptosuccinic acid (MSA) into the seeding growth system based on the consideration of its molecular features: as a dicarboxylic compound that may serve as a reducing agent, and as a mercapto derivative that can act as a capping agent [21, 23] at the same time. Taking advantages of the above-mentioned features of MSA, by carefully controlling the experimental parameters, 30–150 nm gold nanoparticles were prepared from 15 nm gold seeds simply through a one-step seed-mediated process. Transmission and scanning electron microscopy (TEM and SEM) results indicated that the gold nanoparticles grown are quasispherical, with uniform sizes and narrow size distributions (RSD ~ 5–8%); nonspherical gold nanoparticles were almost completely suppressed. These results are very significant in gold nanoparticle synthesis because no methods previously mentioned could produce nearly spherical particles with such high purity and monodispersity only by a one-step seeding growth process, which can also provide hints for further understanding the kinetic and thermodynamic behaviours during seeding growth and establishing new strategies for shape-controlled preparation.

2. Experimental details

2.1. Materials and instruments

Hydrogen tetrachloroaurate trihydrate (HAuCl₄·3H₂O) was purchased from Sigma, and other reactants were obtained from Acros. 2-mercaptosuccinic acid (MSA) was purchased in its acid form, whereas it was used in its disodium salt form by NaOH neutralization. In what follows, the term ‘MSA solution’ means this kind of neutralized solution. Deionized (DI) water was obtained using a Milli-Q system. The ultraviolet–visible (UV–vis) absorption spectra of the samples were measured using a Jasco V-550 UV–vis spectrophotometer. Transmission electron microscopy (TEM) and high-resolution TEM (HRTEM) images were acquired with JEOL JEM-200CX and Tecnai F30 electron microscopes, operated at 160 kV and 300 kV, respectively. The size distribution was measured from several TEM images by counting more than 150 nanoparticles. Scanning electron microscopy (SEM) characterization was performed on a Hitachi S4800 electron microscope, operated at 10 kV.

2.2. Preparation of the gold seeds

The gold seeds were synthesized according to the Frens method [10]. An aqueous solution containing 50 ml of 2.5 × 10⁻⁴ M HAuCl₄ was heated to boiling with stirring; then 1.75 ml 1% (wt/v) aqueous sodium citrate was added at once. The colour of the mixed solution changed to wine red in several minutes, indicating the formation of gold nanoparticles. The boiling and stirring were continued for 30 min. The seed solution was cooled to room temperature and used directly for the further experiments. This method produced gold nanoparticles with a mean diameter of 15.3±1.5 nm according to TEM images. The concentration of gold seeds was estimated as ~1.4 × 10¹⁵ particles l⁻¹, assuming all the added HAuCl₄ was consumed to form 15.3 nm spherical particles.

2.3. Growth of the gold seeds

A set of experiments was performed to study the influence of [HAuCl₄]:[MSA] ratios on the gold nanoparticle morphology. To each of five 25 ml conical flasks (labelled A1, A2, A3, A4, and A5, respectively), 10 ml of the growth solution was added, which contained 0.60 ml gold seed solution and 0.16 ml 5 × 10⁻³ M HAuCl₄, so that the [HAuCl₄]:[seeds] ratios remained constant. Then, different volumes of 0.01 M MSA solution (16, 32, 48, 64, and 80 μl) were added under stirring, making the [HAuCl₄]:[MSA] ratios 1:0.2, 1:0.4, 1:0.6, 1:0.8, and 1:1, respectively. The colour of the reaction mixtures turned from pink to purple in several minutes, indicating the growth of gold seeds. In these five samples, the predicted diameters of resultant particles were all calculated as 28 nm.

A series of gold nanoparticles with diameters in the range of 30–150 nm was prepared through the one-step seed-mediated process at a particular [HAuCl₄]:[MSA] ratio of 1:0.6. Five 100 ml conical flasks (labelled B1, B2, B3, B4, and B5, respectively) were taken. To these flasks were added 0.80 ml 5 × 10⁻³ M HAuCl₄ and different amounts (3.0, 0.48, 0.12, 0.05, and 0.02 ml) of 15.3 nm gold seed solution, then the mixtures were diluted to 50 ml. Next, 0.24 ml 0.01 M MSA solution was added to each flask under rigorous stirring. With the above recipes, the calculated mean diameters of the resultant particles were 28, 50, 78, 105, and 142 nm, respectively. Usually, gold colloids prepared by this approach were stable for months. Sedimentation was occasionally found, especially in samples with larger particles, while the precipitate could be easily redispersed with a gentle shake; and the mean diameters of gold nanoparticles could be well maintained.

A contrast experiment was carried out to compare the effects of different reducing agents on the morphology of the resultant gold nanoparticles. In each of two 25 ml conical flasks (labelled C1 and C2), 10 ml aqueous growth solution containing 0.16 ml 5 × 10⁻³ M HAuCl₄ and 24 μl 15.3 nm gold seed solution was prepared. Next, 85 μl 0.015 M NH₂OH
solution was added to flask C1; 48 µl 0.01 M MSA solution was added to flask C2 under stirring. The calculated final diameters of these two samples were both 78 nm.

3. Results and discussion

For the seeding growth method, the reducing agent should be carefully selected so that the reduction of metal ions could only happen on seed surfaces without new nucleations. It has been reported that MSA could reduce gold(III) salt under certain conditions in the synthesis of Au(I)-MSA complexes [24], gold clusters [25], and nanowires [26]; however, MSA serving as a reducing agent in the seeding growth method has not been mentioned before. Thus it is needed to make sure that MSA is a suitable reducing agent for the seeding method. Figure 1(a) shows the optical spectra of the HAuCl4/MSA (1:1) solution upon mixing and after 30 min. There is no surface plasmon band present, indicating that MSA could not reduce HAuCl4 to Au(0) in the absence of gold seeds under our experimental conditions. Figure 1(b) shows the visible spectra of the growing gold nanoparticles at different stages. The intensities of the absorption peaks become higher with time, implying that the reduction of HAuCl4 by MSA occurs in the presence of gold seeds and that the seeds are growing to become larger particles. After ~60 min, there are no further obvious changes of the spectra, suggesting that the reaction is finished by that time. Recognizing the fact that the reduction of HAuCl4 by MSA happened only in the presence of gold seeds, it was concluded that MSA could serve as an appropriate reducing agent for seeding growth, similar to NH2OH or ascorbic acid [12, 14].

3.1. Influence of the [HAuCl4]:[MSA] ratios on gold nanoparticle morphology

Figure 2 illustrates typical transmission electron microscopy (TEM) images of gold seeds (a) and the grown nanoparticles prepared with increasing amounts of MSA (images (b)–(f) for samples A1–A5, respectively). In figure 2(a), the gold seeds are spherical and uniform nanoparticles with a mean diameter of 15.3 ± 1.5 nm. From figures 2(b) to (f), it is obvious that the amounts of MSA are very crucial for the final morphology of the grown gold nanoparticles. When lower concentrations of MSA were used ([HAuCl4]:[MSA] = 1:0.2 or 1:0.4), as shown in figures 2(b) and (c), nanoparticles with irregular shapes could be always observed and their size distributions were wide (RSD ∼ 15%; see table 1). Then on increasing the concentration of MSA, when [HAuCl4]:[MSA] = 1:0.6, as shown in figure 2(d), the nanoparticles were all spherical with uniform sizes, and few particles were in nonspherical shapes. When much higher concentrations of MSA were used ([HAuCl4]:[MSA] = 1:0.8 or 1:1), as shown in figures 2(e) and (f), a large number of small gold clusters existed and a kind of unique ‘core–shell’ nanostructure could be observed. The inset in figure 2(f) shows the high-magnification TEM image of an individual ‘core–shell’ nanostructure: one large gold nanoparticle (~30 nm) as the core and smaller clusters (~3 nm) as the shell. HRTEM images and energy-dispersive x-ray (EDX) results proved these small clusters were indeed gold clusters; their existence suggested that, when the amount of MSA was in excess, besides the growth process on the preformed seeds surfaces, the additional nucleation process might come forth as well. Being byproducts, these small clusters would definitely consume some amount of HAuCl4 and depress the yield of expected larger ones.

By maintaining the amounts of gold seeds and added HAuCl4 constant, the target mean diameters of these five samples (A1–A5) were all calculated as 28 nm (see table 1 for the formula [12, 27]). The measured mean diameters of particles in figures 2(b)–(f) were 30.7 ± 4.6 nm, 30.4 ± 3.8 nm, 28.5 ± 2.4 nm, 27.5 ± 2.5 nm, and 26.9 ± 2.0 nm, respectively (for samples A4 and A5, just the sizes of ‘core’ particles were counted). They were roughly close to the calculated value, suggesting that the added HAuCl4 had been almost completely reduced by MSA and that growth only occurred on seed surfaces. It also means that the amount of MSA was enough to completely reduce all added HAuCl4 to Au(0) even at the [HAuCl4]:[MSA] ratio as low as 1:0.2, although we still do not know the exact stoichiometric relation of the reduction at present [25, 28].

Therefore, neither much lower or higher concentrations of MSA are of benefit for the growth of high-yield uniform spherical gold nanoparticles, and there must be an appropriate [HAuCl4]:[MSA] ratio within the range from 1:0.4 to 1:0.8. We did not make further efforts to optimize the [HAuCl4]:[MSA] ratio in this range, simply taking 1:0.6 as a favourable value in the following experiments. This is acceptable because, as shown in figure 2(d), at this ratio, neither nanoparticles in irregular shapes nor small gold clusters appeared; and the measured mean diameter (28.5 nm) was well matched to the predicted value (28 nm).
Figure 2. TEM images of gold seeds (a) and the grown nanoparticles prepared with different amounts of MSA ((b)–(f)). Images (b)–(f) correspond to samples A1–A5, and the molar ratios of [HAuCl₄]:[MSA] are 1:0.2, 1:0.4, 1:0.6, 1:0.8, and 1:1, respectively. The inset in (f) shows the high-magnification TEM image of an individual ‘core–shell’ gold nanostructure (scale bar = 5 nm).

Table 1. Data for gold seeds and the grown nanoparticles (samples A1–A5 correspond to TEM images in figure 2(b)–(f); samples B1–B5 correspond to TEM images in figures 3(a)–(e)).

<table>
<thead>
<tr>
<th>Sample</th>
<th>[HAuCl₄]:[MSA]</th>
<th>[HAuCl₄]:[seeds]</th>
<th>Calculated particle size (nm)</th>
<th>Measured particle size (nm)</th>
<th>Size distribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>seeds</td>
<td>—</td>
<td>—</td>
<td>15.3±1.5</td>
<td>9.9</td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>1:0.2</td>
<td>16:3</td>
<td>28</td>
<td>30.7±4.6</td>
<td>15</td>
</tr>
<tr>
<td>A2</td>
<td>1:0.4</td>
<td>16:3</td>
<td>28</td>
<td>30.4±3.8</td>
<td>13</td>
</tr>
<tr>
<td>A3</td>
<td>1:0.6</td>
<td>16:3</td>
<td>28</td>
<td>28.5±2.4</td>
<td>8.4</td>
</tr>
<tr>
<td>A4</td>
<td>1:0.8</td>
<td>16:3</td>
<td>28</td>
<td>27.5±2.5</td>
<td>9.1</td>
</tr>
<tr>
<td>A5</td>
<td>1:1</td>
<td>16:3</td>
<td>28</td>
<td>26.9±2.0</td>
<td>7.4</td>
</tr>
<tr>
<td>B1</td>
<td>1:0.6</td>
<td>100:3</td>
<td>50</td>
<td>49.5±3.3</td>
<td>6.6</td>
</tr>
<tr>
<td>B2</td>
<td>1:0.6</td>
<td>400:3</td>
<td>78</td>
<td>77.6±4.1</td>
<td>5.3</td>
</tr>
<tr>
<td>B3</td>
<td>1:0.6</td>
<td>960:3</td>
<td>105</td>
<td>105.0±5.3</td>
<td>5.0</td>
</tr>
<tr>
<td>B4</td>
<td>1:0.6</td>
<td>2400:3</td>
<td>142</td>
<td>142.7±9.9</td>
<td>6.9</td>
</tr>
<tr>
<td>B5</td>
<td>1:0.6</td>
<td>16:3</td>
<td>28</td>
<td>28.5±2.4</td>
<td>8.4</td>
</tr>
</tbody>
</table>

a [HAuCl₄] and [seeds] mean the metal concentrations of added HAuCl₄ and the seed solutions.

b The expected size can be calculated from the following theoretical equation (the calculation assumes growth occurs only on metal seeds to give larger spherical particles):

\[ r = r_s \left( \frac{[M_a] + [M_s]}{[M_s]} \right)^{1/3} \]

where \( r_s \) and \( r \) indicate the particle radius for seeds and the grown particles, and \([M_a]\) and \([M_s]\) indicate metal concentrations in seeds and added HAuCl₄ solutions, respectively.

3.2. Synthesis of 30–150 nm quasispherical gold nanoparticles

By maintaining the [HAuCl₄]:[MSA] ratio at 1:0.6, five sets of quasispherical gold nanoparticles with predicted mean diameters of 28, 50, 78, 105, and 142 nm were synthesized through such a one-step seeding growth method. The final particle diameters can be controlled by varying the ratio of added gold salts to gold seeds: the higher the [HAuCl₄]:[seeds] ratio, the larger resultant gold nanoparticles [12].

Figure 3 shows TEM images of the synthesized gold nanoparticles with increasing diameters (images (a)–(e) for samples B1–B5): the gold nanoparticles were nearly spherical with uniform sizes; byproducts such as nanorods, triangles, and small clusters could be hardly found. Measured mean diameters for samples B1–B5 are 28.5±2.4 nm, 49.5±3.3 nm, 77.6±4.1 nm, 105.0±5.3 nm, and 142.7±9.9 nm, respectively. They all matched well with the calculated values (table 1), once again providing support for the notion that all the added gold salts were translated into gold atoms grown on the seed surfaces, and that additional nucleation was completely suppressed.

The insets in figures 3(c)–(e) are corresponding SEM images of gold nanoparticles. There are obvious faceted structures on the particle surfaces, and the surfaces are all smooth, clearly indicating that the grown gold nanoparticles
Figure 3. Representative TEM images of quasispherical gold nanoparticles with increasing diameters prepared under a proper [HAuCl₄]:[MSA] molar ratio of 1:0.6. Images (a)–(e) correspond to samples B1–B5: (a) 28.5 nm, (b) 49.5 nm, (c) 77.6 nm, (d) 105 nm, (e) 143 nm. The insets in images 2(c)–(e) are corresponding SEM images.

in our system are indeed single particles with quasispherical and polyhedral morphology, and not compact aggregates of smaller units [29]. In addition, it was found that the size distributions of these five samples (RSD ∼ 5–8%) were well preserved after growth, and even better than that of gold seeds (RSD ∼ 10%), implying that the seeds have been growing almost simultaneously and isotropically in our system. The coherence between the measured and calculated diameters as well as the narrow size distributions suggested that all the seeds grew nearly homogeneously; therefore, the yields of these quasispherical particles can be estimated as nearly 100%.

Figure 4 shows the absorption spectra of grown gold nanoparticles with different diameters corresponding to the TEM images in figure 3. Curves a–c correspond to samples B1–B3, measured from the original solutions; curves d and e are for samples B4 and B5, measured from the concentrated solutions. From the curves a to c, with particle diameters increasing from 28 to 78 nm, the absorption peak is noticeably red-shifted from 525 to 557 nm. When the diameter is increased to 105 nm (d), there is also an obvious red-shift to 581 nm and obvious band broadening, still with a single band. On increasing the diameter further to 143 nm (e), a shoulder peak appears at lower wavelengths (∼550 nm); the main peak red-shifts to 633 nm and broadens further. These results are consistent with the reports of Pérez-Juste and Liz-Marzán [17]. As the particle sizes increase, scattering effects become more relevant, and the absorption peak will be red-shifted and broadened when the particle sizes are above 100 nm, dephasing starts to occur and new plasmon modes can be accommodated within the particle surface [1, 17].

3.3. Roles of MSA in seed growth procedure

Although both MSA and NH₂OH are similar mild reducing agents for HAuCl₄ reduction in the seeding growth, MSA may behave differently because of the stronger affinity to the gold surface due to its mercapto groups [11, 21, 23]. Figure 5 shows TEM images of the samples obtained by the two reducing agents in the one-step seeding growth method (a: NH₂OH; b: MSA). The expected diameters were both 78 nm. It is evident that the yield of spherical gold nanoparticles was much higher in the MSA reduction system than that in the NH₂OH system, further suggesting that MSA is a more appropriate reducing agent for seeding growth, at least from the point of view that it can help to effectively suppress anisotropic growth. We assume that MSA might also act as a capping agent at the same time, which would make it responsible for the inhibition of anisotropic growth so as to promote the homogeneous growth of gold seeds.
As mentioned above, the morphologies of the grown nanoparticles were dependent on the [HAuCl₄]:[MSA] ratios, implying that the seeding growth process was sensitive to the concentration of MSA in the growth solutions. MSA plays two cooperative roles in our system. On the one hand, as a reducing agent, it could reduce HAuCl₄ to gold atoms on seed surfaces and make the seeds grow larger; the reduction rate would increase with the concentration of MSA. On the other hand, as a capping agent, adsorption of MSA on gold seeds would counteract the adsorption of AuCl₄⁻ and retard the growth of seeds; its capping ability would also depend on the concentration of MSA. So the final morphology of the grown particles would be determined by the competition between the growth of seeds and the capping on seed surfaces [22, 30], which could be controlled by varying the [HAuCl₄]:[MSA] ratios.

When the concentration of MSA was low, for instance, [HAuCl₄]:[MSA] = 1:0.2 or 1:0.4, although the absolute amount of MSA was enough to reduce all the added gold salts, at the late stage of seeding growth, the instantaneous concentration of MSA would become lower and lower as it consumed by HAuCl₄. Therefore, as a capping agent, it might be insufficient to protect growing seeds from the selective adsorption of AuCl₄⁻ on different facets, leading to resultant gold nanoparticles with imperfect morphologies and wide size distributions (such as seen in figures 2(b) and (c)).

On increasing the concentration of MSA, besides the amount that is consumed by HAuCl₄, the remainder was still enough to compete with AuCl₄⁻ in the adsorption on seed surfaces, making it still act as a capping agent even at the late stage of seeding growth. When the concentration of MSA was too high, for instance, [HAuCl₄]:[MSA] = 1:0.8 or 1:1, at the late stage of seeding growth, with gold seeds growing larger and the amount of HAuCl₄ getting less, the amount of MSA would become much too excessive and tend to dominate the adsorption layer on seed surfaces, leading to the retarding of subsequent growth on seeds. Meanwhile, the excess of MSA in solution may also induce an additional nucleation process in the vicinity of the grown particles [16, 31], resulting in the solutions being rich with very small clusters. Because both the large particles and small clusters were capped with MSA molecules, the interaction between carboxyls of MSA might lead to the formation of such special ‘core–shell’ nanostructures (such as figures 2(e) and (f)).

Based on the above discussion, once the capping and the growth become balanced under an optimized condition, uniform gold nanoparticles could be achieved. Our results have proved this point: quasispherical gold particles with narrow size distributions were successfully synthesized with a favourable [HAuCl₄]:[MSA] ratio of 1:0.6.

4. Conclusions

We have developed a seed-mediated approach for the preparation of large-size gold nanoparticles in the range 30–150 nm with narrow size distributions (RSD ~ 5–8%) and high yields by using 2-mercaptosuccinic acid (MSA) as a novel reducing agent. The particle diameters can be manipulated by varying the ratio of [HAuCl₄]:[seeds]. Under the particular condition ([HAuCl₄]:[MSA] = 1:0.6), such a one-step seeding method is quite effective in obtaining large quasispherical gold nanoparticles, without any nonspherical particles being present. The character of MSA both as a mild reducing agent and a capping agent is believed to promote the isotropic growth of seeds and the formation of these large-size gold nanoparticles. There is no doubt that even larger (> 150 nm) quasispherical gold particles can be achieved through this method. The optical properties of these monodisperse larger spheres can make them good candidates for the construction of highly efficient photonic structures [17, 32, 33].

Acknowledgments

We are grateful for the financial support from the National Natural Science Foundation of China (Grants Nos 50521201 and 20473004) and the SRF project for ROCS, Ministry of Education, China.

References