

Synthesis of double-shelled hollow silica sphere with single-shelled hollow silica sphere and cetyltrimethyl ammonium bromide as dual templates

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Published in *Micro & Nano Letters*; Received on 21st June 2016; Revised on 25th October 2016; Accepted on 31st October 2016

In this work, single-shelled hollow mesoporous silica nanoparticles (SHMSNs) were first fabricated via template method and surface-protected etching strategy with the aid of cetyltrimethyl ammonium bromide (CTAB). Then, double-shelled hollow mesoporous silica nanoparticles (DHMSNs) were successfully synthesised based on single-shelled hollow mesoporous silica. The etching procedure using sodium carbonate as etchant, the surface-protected etching time and the influence of CTAB were discussed in detail. Experimental results showed that a warm and effective etching process could be achieved at 39°C for 3 h with CTAB protection. The resulting SHMSNs and DHMSNs were characterised by transmission electron microscope, scanning electron microscope, and nitrogen adsorption–desorption isotherms. In addition, it was proved that SHMSNs and DHMSNs possessed a well-defined hollow structure and uniform size. It is believed that the nanostructure feature some implication for creating other hollow structures.

1. Introduction: In the past decades, a lot of significant researches have been devoted to the development of mesoporous silica nanoparticles (MSNs) [1–3] due to their superior performance such as low density, high specific surface areas, good load capacity, low toxicity, and well-modifiable mesoporous shell. Compared with MSNs, hollow MNSs (HMSNs) [4–6] possess higher load capacity and pore volume except above superiorities.

Generally, there are four classical methods for synthesising HMSNs, including traditional hard-templating [7–9], soft-templating [10, 11], sacrificial-templating [12], and self-templating methods [13]. The four synthesis methods could be well distinguished from each other according to their characteristics. Conventional hard-templating method could conduct narrow size distribution and wide range of size of particles. However, the synthesis processes are relatively complicated and the yields of products are also relatively low. For example, Zhao *et al.* [14] prepared HMSNs using hematite as hard template. Soft-templating (liquid or gaseous) method is certainly the most effective and common route for the synthesis of HMSNs. Oil-in-water, water-in-oil emulsion drops, various micelles, and gas bubbles are generally used for soft templates. Sacrificial-templating method is defined that template itself not only acts as template, but also as a reactant. Template simultaneously possesses several roles in whole synthetic processes. The resulting shape and size of particles are directly determined by template. Finally, self-templating method is normally achieved by one-step using Ostwald ripening mechanism in fabricating HMSNs. In comparison with other methods, avoiding tedious synthesis procedures and improving large-scale applications are the apparent superiorities of this method. In a word, the four methods could be widely utilised for synthesising HMSNs.

Here, single-shelled HMSNs (SHMSNs) are first synthesised by sol–gel process and selective etching strategy. Based on SHMSNs, we further fabricate DHMSNs with the same method and strategy. The schematic illustration of the synthesis of DHMSNs is shown in Fig. 1. Both SHMSNs and DHMSNs are uniform in size and possess a well-defined hollow structure. The special surface area and pore volume of SHMSNs and DHMSNs are 103.4 m² g⁻¹, 0.42 cm³ g⁻¹ and 152.3 m² g⁻¹, 0.24 cm³ g⁻¹, respectively. Compared with SHMSNs, DHMSNs possess a well-defined double-shelled hollow structure and bigger hollow space. This

characteristic enables more potential applications of the material, such as microreaction container, drug delivery system and so on.

2. Experimental

2.1. Chemicals: Tetraethoxysilane (TEOS), 3-aminopropyltriethoxy-silane (APTES), cetyltrimethyl ammonium bromide (CTAB), ammonium hydrate (NH₃·H₂O, 25–28 wt%), anhydrous sodium carbonate (Na₂CO₃), ethanol (C₂H₅OH), and ammonium nitrate (NH₄NO₃) were purchased from Sinopharm Chemical Reagent Nanjing Co., Ltd. All the reagents were used as received without any further purification.

2.2. Synthesis of SHMSNs by surface-protected etching: 40 ml of deionised water and 10 ml of anhydrous ethanol mixed absolutely with 0.084 g of CTAB until no bubbles existed, followed by 0.5 ml of NH₃·H₂O (25–28 wt%). Then, 0.25 g of TEOS and 0.25 g of APTES was orderly added for forming hybrid core. After 15 min, 0.3 g of TEOS was dropwise added for structuring outside shell. With violent mechanical stir for 4 h at room temperature, the white precipitate was collected by filtration, washing three times with water and ethanol. Then, the collected white precipitate was dispersed in 50 ml deionised water containing 1.06 g of Na₂CO₃ and 0.015 g of CTAB by ultrasonic concussion. After continuous stir for 3 h at 39°C, the CTAB-protected etching process was achieved. Then, the collected precipitate went through reflux for 2 h in 50 ml of 3 mg ml⁻¹ ethanol solution of ammonium nitrate. SHMSNs were obtained by filtration, washing with ethanol, and dried at 60°C under vacuum overnight.

2.3. Synthesis of DHMSNs by surface-protected etching: 0.05 g of as-prepared SHMSNs was dispersed in 40 ml of deionised water and 10 ml of anhydrous ethanol, followed by addition of 0.042 g of CTAB. 0.5 ml of NH₃·H₂O (25–28 wt%) was added to adjust pH for the subsequent reaction. Then, 0.15 g of TEOS and 0.15 g of APTES were added in sequence. After 15 min, 0.2 g of TEOS was quickly added into the mixture. The reaction was completed with stirring for 4 h under ambient temperature. The white precipitate was obtained by filtration and transferred into a reaction vessel containing 50 ml of water, 0.75 g of Na₂CO₃, and 0.015 g of CTAB. After the same etching and the reflux process above, the

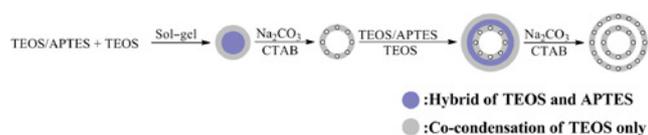


Fig. 1 Schematic illustration of the synthesis of DHMSNs

resulting DHMSNs were obtained by filtration, repeated washing with ethanol, and drying overnight in a vacuum oven.

3. Characterisation: The observation of the hollow structure of the as-synthesised nanoparticles was performed on a JEM-2100 TEM (transmission electron microscope), operating at 200 kV. Scanning electron microscope (SEM) measurement was achieved by using an ultra plus electron microscope. The specific surface area, pore volume, and pore size distribution of the obtained nanoparticles were characterised by nitrogen adsorption–desorption method with an ASAP 2020 M analyser at 77 K, prior to that all samples were calcinated at 550°C for 6 h and degassed at 180°C for 12 h.

4. Results and discussion: SEM and TEM images of SHMSNs are shown in Figs. 2*a* and *b*. As can be seen, SHMSNs have a well-defined hollow structure. In addition, SHMSNs also exhibit superior performance in shape and size distribution. The average diameter of SHMSNs is of about 130 nm with a 24 nm shell. Figs. 2*c–g* show SEM images of two layers coated SHMSNs after etching at 39°C for 0 h (*c*), 0.5 h (*d*), 1 h (*e*), 2 h (*f*), 3 h (*g*) to produce DHMSNs without CTAB protecting. Solid nanospheres were observed and gradually became rough on the surface after etching for 1 h. Further etching for 2 h, the middle hybrid layer was etched absolutely. The internal layer was also partly etched. The surface of DHMSNs became more rough. After etching for 3 h, the etching of internal layer is also achieved. However, the outermost layer was etched to some extent and resulted in a broken shell. The arrow inset in Fig. 2*g* indicates a broken outer shell, a more clear photograph was given in Fig. 2*h*. It is easy to discover that the nanoparticle possesses an integrated internal shell and damaged outer shell. In contrast, DHMSNs have a smooth and unbroken outer shell under the protection of CTAB (Fig. 2*i*). The corresponding TEM image is shown in Fig. 2*j*. Apparently, DHMSNs possess a well-defined double-shelled hollow structure. The average diameter of DHMSNs is of around 220 nm. The relevant thickness of outmost shell is of around 22 nm.

To fully etch and obtain double-shelled hollow structure, etching time of 3 h is an appropriate choice inferred from Figs. 2*c–g*. Combining Fig. 2*g* with Fig. 2*i*, we concluded that CTAB could well protect silica surface from etching under alkaline environment. In addition, the comparison in diameter and shell thickness is also significant. The interesting thing is that the diameter of SHMSNs in DHMSNs is of about 113 nm and the corresponding thickness is of about 15 nm. By comparison, the decrease in diameter is 17 and 9 nm for shell thickness. The decrease of diameter is almost twice the decrease of shell thickness. It means that SHMSNs underwent a second etching during the surface-protected etching process. The outer shell on SHMSNs was partly etched without CTAB protecting.

Nitrogen adsorption–desorption isotherms and corresponding pore size distribution of SHMSNs and DHMSNs are shown in Fig. 3. According to the definition of IUPAC, the curve shown in Fig. 3*a* belongs to the typical IV isotherm. Under relative low pressure of below 0.4, monolayer nitrogen is deposited on the surface of SHMSNs. Special surface area is calculated based on the total area of the monolayer nitrogen using the model of Brunauer–Emmett–Teller (BET). The capillary condensation of nitrogen in mesopores and hollow core occurs at relative pressure of 0.4–0.6 and 0.9–1.0, correspondingly. The pore size distribution of SHMSNs (Fig. 3*b*) is obtained by Barrett–Joyner–Halenda (BJH) method from the

adsorption branch of the nitrogen isotherms. The maximum value at 2.1 nm clearly proves the existence of mesoporous. The maxima on the broken curve may be a good explanation for the cavities of nanoparticles. Likewise, the curve shown in Fig. 3*c* is classified as the typical IV isotherm with a wide hysteresis loop once the relative pressure above 0.1 and a sharp increase in nitrogen uptake at high relative pressure of 0.9. The corresponding pore size distribution of DHMSNs is exhibited in Fig. 3*d*. Apparently, the maximum at 2.5 nm standing for mesoporous is obviously stronger than the maximum at 10 nm

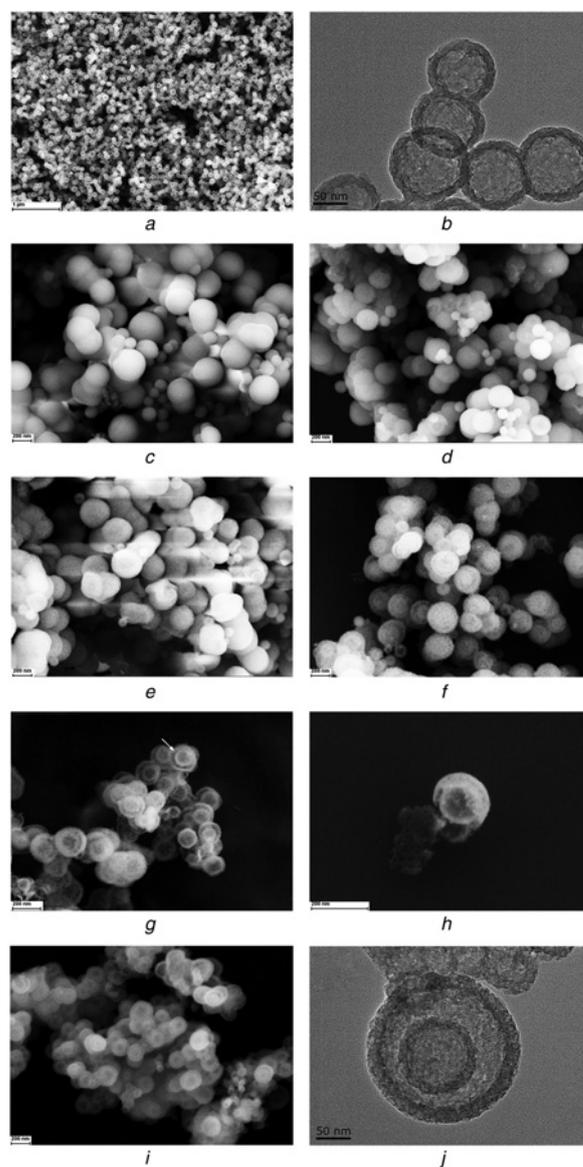


Fig. 2 Electron microscopy observation of preparation process of HMSNs
Electron microscopy images of SHMSNs after surface-protected etching at 39°C for 3 h
a SEM image
b TEM image
SEM images of DHMSNs after etching at 39°C for different time without CTAB protection
c 0 h
d 0.5 h
e 1 h
f 2 h
g 3 h
h 3 h, a clear view of broken DHMSN in *g*
Electron microscopy images of DHMSNs after surface-protected etching at 39°C for 3 h
i SEM image
j TEM image

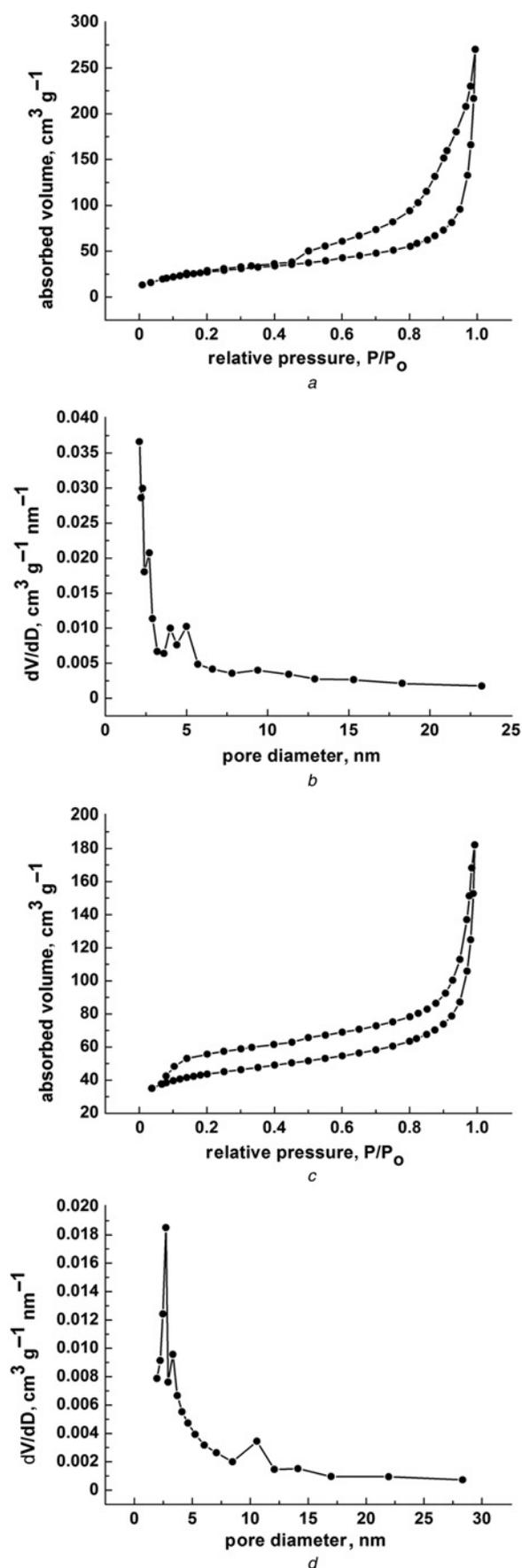


Fig. 3 Nitrogen adsorption results of HMSNs
 a Nitrogen adsorption–desorption isotherms of SHMSNs
 b BJH pore size distribution of SHMSNs
 c Nitrogen adsorption–desorption isotherms of DHMSNs
 d BJH pore size distribution of DHMSNs

representing cavities of nanoparticles. The BET surface area and BJH pore volume are $103.4 \text{ m}^2 \text{ g}^{-1}$ and $0.42 \text{ cm}^3 \text{ g}^{-1}$ for SHMSNs and $152.3 \text{ m}^2 \text{ g}^{-1}$ and $0.24 \text{ cm}^3 \text{ g}^{-1}$ for DHMSNs. In comparison, DHMSNs possess a higher BET surface area and smaller pore volume for its double-shelled structure. What's more, the cavities of DHMSNs ($\sim 10 \text{ nm}$) are bigger than SHMSNs ($\sim 5 \text{ nm}$) due to the bigger size.

To investigate the application potential of HMSNs in drug delivery, ibuprofen, an analgesic drug was loaded in SHMSNs and DHMSNs, the drug loading content (DLC) was 23.7 and 30.4%, respectively. This suggests that the HMSNs we synthesised showed very high drug loading capacity, and DHMSNs have a better DLC than SHMSNs.

5. Conclusions: In summary, DHMSNs were successfully fabricated by sol–gel process using SHMSNs and CTAB as dual templates. After a series of comparison experiments, it was found that the best etching time is 3 h with the protection of CTAB during a warm and effective etching process. After etching process, both SHMSNs and DHMSNs have a good shape and well-defined hollow structure as shown in SEM and TEM observation. It is believed that the synthesis method in this Letter could be a good reference for synthesising other hollow structures.

6. Acknowledgment: This work was supported by the National High-tech Research and Development Project (863 Project, 2013AA032205), Industry Project of Jiangsu Science-technology Support Plan (BE2013840), Science and Technology Development Program of Suzhou (ZXY201412).

7 References

- [1] Pan Y., Wu H., Lee L., *ET AL.*: 'Cyanide- and carboxylate-functionalized cubic mesoporous silicas SBA-1: synthesis, characterization and reactivity of organic functional groups', *Micropor. Mesopor. Mater.*, 2009, **123**, (1-3), pp. 78–90
- [2] Che S., Liu Z., Ohsuna T., *ET AL.*: 'Synthesis and characterization of chiral mesoporous silica', *Nature*, 2004, **429**, (6989), pp. 281–284
- [3] Zhao D.Y., Huo Q.S., Feng J.L., *ET AL.*: 'Nonionic triblock and star diblock copolymer and oligomeric surfactant syntheses of highly ordered, hydrothermally stable, mesoporous silica structures', *J. Am. Chem. Soc.*, 1998, **120**, (24), pp. 6024–6036
- [4] Chen H., Yan Z., Li B., *ET AL.*: 'Manipulation of mesoporous silica hollow spheres by control of silica precursors', *Mater. Lett.*, 2013, **112**, pp. 78–80
- [5] Yin L., Shen Z., Niu J., *ET AL.*: 'Synthesis of hollow sphere-like mesoporous silica with reformer naphtha as a swelling agent', *Mater. Lett.*, 2009, **63**, (26), pp. 2212–2214
- [6] Caruso F., Caruso R.A., Mohwald H.: 'Nanoengineering of inorganic and hybrid hollow spheres by colloidal templating', *Science*, 1998, **282**, (5391), pp. 1111–1114
- [7] Castillo S.I.R., Ouhajji S., Fokker S., *ET AL.*: 'Silica cubes with tunable coating thickness and porosity: from hematite filled silica boxes to hollow silica bubbles', *Micropor. Mesopor. Mater.*, 2014, **195**, pp. 75–86
- [8] Wan H., Long Y., Xu H., *ET AL.*: 'New strategy to prepare hollow silica microspheres with tunable holes on the shell wall', *Langmuir*, 2014, **30**, (3), pp. 683–686
- [9] Jiao Y., Guo J., Shen S., *ET AL.*: 'Synthesis of discrete and dispersible hollow mesoporous silica nanoparticles with tailored shell thickness for controlled drug release', *J. Mater. Chem.*, 2012, **22**, (34), pp. 17636–17643
- [10] Li Y., Bastakoti B.P., Imura M., *ET AL.*: 'Dual soft-template system based on colloidal chemistry for the synthesis of hollow mesoporous silica nanoparticles', *Chem. Eur. J.*, 2015, **21**, (17), pp. 6375–6380
- [11] Wu X., Xu D.: 'Soft template synthesis of yolk/silica shell particles', *Adv. Mater.*, 2010, **22**, (13), pp. 1516–1520
- [12] Alvarez S., Fuertes A.B.: 'Synthesis of macro/mesoporous silica and carbon monoliths by using a commercial polyurethane foam as sacrificial template', *Mater. Lett.*, 2007, **61**, (11-12), pp. 2378–2381
- [13] Yoo B.U., Han M.H., Nersisyan H.H., *ET AL.*: 'Self-templated synthesis of hollow silica microspheres using Na_2SiO_3 precursor', *Micropor. Mesopor. Mater.*, 2014, **190**, pp. 139–145
- [14] Zhao W., Lang M., Li Y., *ET AL.*: 'Fabrication of uniform hollow mesoporous silica spheres and ellipsoids of tunable size through a facile hard-templating route', *J. Mater. Chem.*, 2009, **19**, (18), pp. 2778–2783