Hierarchic Template Approach for Synthesis of Silica Nanocapsules with Tuned Shell Thickness

Masahiro Mashimo,[1,2] Qingmin Ji,*[2] Shinsuke Ishihara,[2] Hideki Sakai,[1]
Masahiko Abe,[1] Jonathan P. Hill,[2,3] and Katsuhiko Ariga*[2,3]

[1]*Department of Pure and Applied Chemistry, Tokyo University of Science, 2641 Yamazaki, Noda, Chiba 278-8510*
[2]*World Premier International (WPI) Research Center for Materials Nanoarchitectonics (MANA),*
National Institute for Materials Science (NIMS), 1-1 Namiki, Tsukuba, Ibaraki 305-0044
[3]*JST, CREST, 1-1 Namiki, Tsukuba, Ibaraki 305-0044*

(Received May 27, 2011; CL-110449; E-mail: JI.Qingmin@nims.go.jp)

Nanoporous silica capsules with mesosized diameter (ca. 60 nm) were prepared by using polystyrene (PS) beads and polyethyleneimine (PEI) as the hierarchic core and shell templates, respectively. The coverage of PEI on the PS beads enhanced the positive charge density on the template surface and favored the formation of well-separated hollow spheres with diameters smaller than 100 nm. By tuning the PEI shell template layer on the solid PS bead templates at different pH values, the shell thickness of the hollow silica sphere could also be controlled at the nanometer level in the range 3–12 nm.

Silica (SiO_2) capsules are promising materials with potential applications in drug delivery,[1–3] as novel microreactors,[4,5] catalysts,[6,7] sensors,[8] optical or electrochemical architectures,[9,10] etc. Their expansive hollow interiors make encapsulation of a variety of substances possible, and their permeable shells promote the facile transport of guest materials. Many templates have been used to prepare silica capsules (hollow spheres), such as emulsion droplets, nanoparticles, vesicles, and polymer spheres.[11–16] Polystyrene (PS) beads are attractive templates due to their low cost and availability in various monodisperse diameters. Caruso et al. used layer-by-layer (LbL) self-assembly of prefabricated SiO_2 nanoparticles and polymers on PS cores to fabricate hollow SiO_2 spheres.[11] There are also reports of the use of PS beads with amine- or zwitterion-functionalized surfaces for growth of silica shells.[17,18] However, most of the resulting SiO_2 capsules are larger than 100 nm in diameter and are not of monodisperse dimensions. Large sizes of the shells usually reduces the effectiveness of SiO_2 capsules in optical or biomedical applications because of low transparency and limited cell permeability.[19,20] On the other hand, dispersibility of SiO_2 capsules is also important for application although silica tends to aggregate during the sol–gel formation and calcination process. Despite the availability of many syntheses of SiO_2 capsules, facile methods for controlling the shell thickness, which is an important property for regulating guest release, are scarce and rarely effective.[21,22] For instance, shell thickness control due to variation of reaction solvent or quantity of silica precursors usually results in changes of the hollow dimensions or aggregated state of the spheres.

Here, we report the synthesis of mesoscopic SiO_2 capsules of monodisperse 60-nm diameter by using a hierarchic core and shell template method with PS beads and polyethyleneimine (PEI). The resulting SiO_2 capsules possess a homogenous size distribution, and this method also allows a tunable shell thickness from 3 to 12 nm depending on the PEI layer on the template surface. We have found that sole usage of amine-functionalized PS beads with diameters less than 100 nm as template does not yield a silica layer on the bead surfaces, which may be due to the reduction in surface positive charges upon decreasing the bead size. We thus considered preparing a shell layer possessing high cationic charge density on the PS bead to guarantee the formation of silica of sufficient thickness. PEI is a cationic polymer containing amine groups. Besides being widely used in therapeutic applications for enhancing the attachment of weakly anchoring cells, it has also been used as template for the synthesis of silica nanocomposites.[23] The PS–PEI hierarchic core and shell template strengthen the adsorption of the SiO_2 precursors. In addition, by tuning the PEI layer on the PS bead at different pH values, the shell thickness of the SiO_2 capsules can be easily controlled at the nanometer level.

The synthesis of SiO_2 capsules through the hierarchic template approach is illustrated in Figure 1. Carboxylate (–COOH)-functionalized PS beads (PS–COOH) of 60-nm diameter (2.5 wt % solution, 50 μL) and an aqueous solution of PEI ($10 g L^{-1}$, 200 μL) were mixed in 1 mL of H_2O. The resulting mixture was adjusted to the appropriate pH using HNO_3(aq). Hydrolyzed tetramethylorthosilicate (TMOS) solution (40 μL), which had been obtained by vigorously mixing TMOS (148 μL) with HCl(aq) (0.01 M, 1 mL) for 20 min, was added to the template suspension and stirred overnight. The
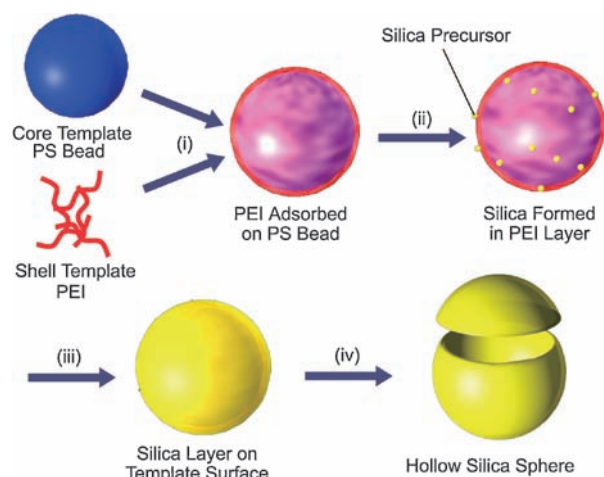

Figure 1. Schematic illustration for the formation of the silica capsules through a hierarchic core and shell template approach. (i) Mixing under different pH values; (ii) add silica precursors; (iii) stirring overnight; (iv) calcination at 600 °C.
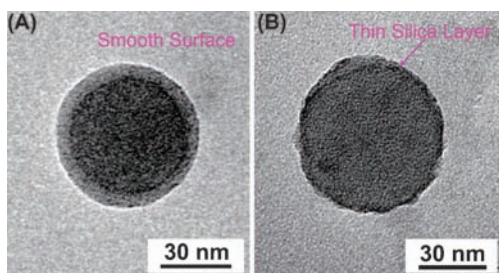
Figure 2. TEM images of (A) PS–PEI template prepared by mixing of PS–COOH bead and PEI solution at pH 7, (B) thin silica layer formed on PS–PEI template which prepared by mixing of PS–COOH bead and PEI solution at pH 4.
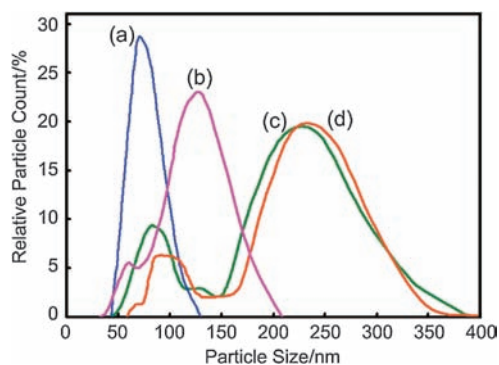

Figure 3. DLS size distribution profiles of (a) PS–COOH beads, PS–PEI beads prepared by mixing of PS–COOH beads and PEI solution at (b) pH 5, (c) pH 7, and (d) pH 8.

reaction solution was then purified several times by centrifugation followed by water redispersion and finally freeze-dried under vacuum. The template was removed by calcination at 600 °C for 4 h.

Figure 2A shows the core–shell morphology of a particle of PS–COOH beads which was coated with PEI at pH 7. The PS–PEI core–shell template has a diameter around 60 nm and possesses a smooth surface. It is difficult to distinguish the PS–COOH beads from the PS–PEI beads by transmission electron microscopy (TEM) observation. However, we could clearly observe the changes due to PEI adsorption on the PS–COOH beads using dynamic light scattering (DLS). As shown in Figure 3a, the size distribution profile of PS–COOH bead dispersion indicates a well-dispersed state with an average particle size around 69 nm. The slight difference in size (60 nm) from that observed by TEM is probably due to a layer of hydrogen-bonded water molecules on the PS–COOH surface and slight swelling of hydrophilic chains in PS–COOH beads. The scattering profile for PS–PEI beads prepared at pH 5 shows a main peak centered at 129 nm with a small shoulder at 59 nm (Figure 3b). The main peak at 129 nm is likely due to aggregation of 2 or 3 PEI–PS beads. The shoulder peak, which indicates a similar size to PS–COOH bead, suggests incomplete coverage of PEI on the PS–COOH surface under these conditions. At pH 5, fewer –COOH groups of the PS–COOH beads are dissociated as –COO⁻ ions. The weakened surface charges may induce partial aggregation of the PS–COOH beads and the poorer adsorption of PEI on the surface. The size

distribution profiles of the PS–PEI beads prepared at pH 7 and 8 show clearly two scattering peaks. At pH 7, the two peaks are located at 81 and 223 nm, while at pH 8 they are found at 96 and 256 nm (Figures 3c and 3d). The particle distribution in the small diameter range should be due to isolated PS–PEI beads with those of larger size indicating 2 or 3 aggregated PS–PEI beads. At pH greater than 7, –COOH is completely dissociated to –COO⁻ ions in the PS–COOH beads, enabling enhanced adsorption of positive PEI molecules at the surface. The pK_a of the primary amine groups in PEI is 8.6. Although the amine groups in PEI will be positively charged in the pH range 7–8, the charge density will gradually decrease with increasing pH value. These charge changes affect the adsorbed amount of PEI on PS–COOH surface under weakly alkaline conditions. The DLS results indicate that a thicker PEI layer was adsorbed on the PS–COOH surface at pH 8 than at pH 7. It should be noted that the PS–PEI beads become less well-dispersed and begin to form agglomerates at pH >8. The decreasing positive charge density of PEI molecules leads to a reduction of the repulsion forces between neighboring beads.

Of the PS–PEI beads prepared at various pH values, those formed at pH 7–8 could be used as the core–shell templates to form hollow SiO_2 capsules. TMOS was hydrolyzed in hydrochloric acid yielding silicic acid as the SiO_2 precursor. Negatively charged silicic acid is adsorbed on the positively charged PEI layer then undegoes condensation to form the polymeric SiO_2 layer. Therefore, the coverage of PEI directly affects the completeness of formation of SiO_2 layer on the template surface. PS–PEI beads prepared at low pH values (pH 4–6), where there is incomplete coverage by the PEI layer, were poorly formed due to the partial formation of a very thin SiO_2 layer on the template surface (Figure 2B). These thin SiO_2 layers are too structurally weak to maintain spherical morphology during the calcination process yielding a collapsed or deformed yet still hollow morphology (Figure 4A). When using PS–PEI beads at pH 7–8 as the templates, we successfully obtained SiO_2 capsules with inner diameters of 60 ± 8 nm (Figures 4B and 4C). In particular, SiO_2 capsules obtained using PS–PEI templates prepared at pH 7.0, 7.2, 7.4, 7.6, 7.8, and 8.0 gave average shell thicknesses of 3.3 ± 0.5, 3.4 ± 0.3, 5.8 ± 0.7, 7.8 ± 0.3, 9 ± 0.7, and 12.2 ± 0.8 nm, respectively (Figure 5), clearly indicating the shell thickness controllability using this method. These dry SiO_2 capsules look similar to loose cotton and are easily resuspended in water. The BET surface area of the hollow SiO_2 capsules with 60-nm diameter and 12-nm shell thickness was $264 \, m^2 \, g^{-1}$. The BJH pore size distribution is around 2.4 nm. Although the condensation of SiO_2 precursors is affected by the pH values of their preparation, the condensation rate becomes saturated in the pH range of 7–8.[24] Considering the trend in the thickness of the PEI layer on the PS–COOH surface within this pH region, it is likely that variation of the PEI layer thickness is responsible for the SiO_2 formation on the template surface. The denser amine scaffold provided by the thicker PEI layer facilitates the condensation of SiO_2 precursor acting like a weak surface catalyst, thus promoting the formation of a thicker SiO_2 layer. This feature enables modulation of the shell thickness of the SiO_2 capsule between 3 and 12 nm.

In conclusion, we present a new strategy for preparation of uniform SiO_2 capsules (<100 nm) by using PEI-coated PS–COOH beads as the core–shell template. The adsorption of PEI
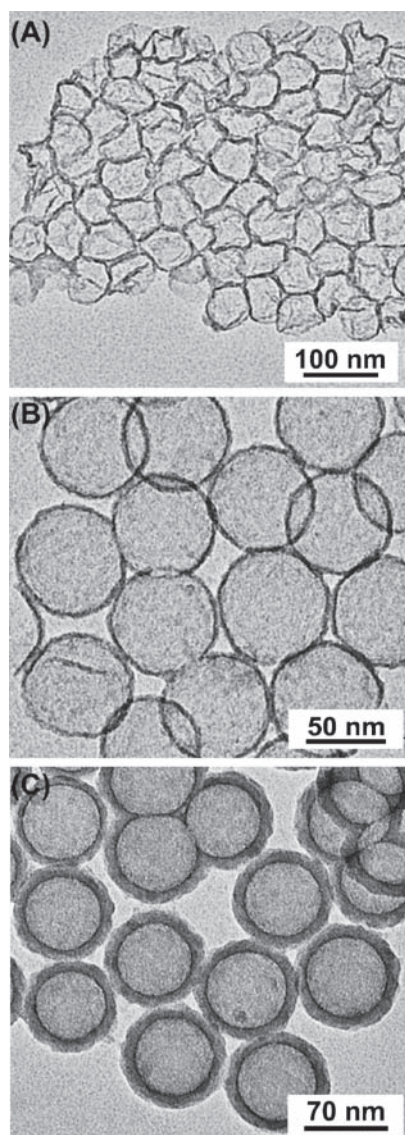
Figure 4. TEM images of SiO$_2$ capsules from PS–PEI template bead prepared by mixing of PS–COOH beads and PEI solution at (A) pH 5, (B) pH 7, and (C) pH 8.
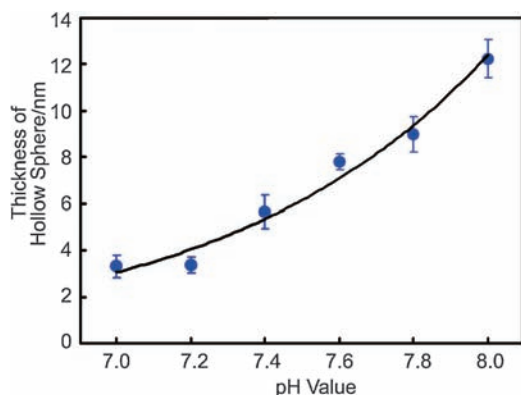

Figure 5. Relationship for the thickness of the SiO$_2$ capsules with pH values used for the preparation of PS–PEI templates.

on the template facilitates regulation of the formation of SiO$_2$ in the PEI layer and allows control to be exerted over the shell thickness of the hollow SiO$_2$ capsules. The SiO$_2$ capsules possess homogeneous, well dispersible, and less than 100 nm diameter characteristics, which are promising to improve their application as novel drug carriers, catalyst supports antireflection coating materials, etc. This synthesis at near neutral pH conditions would also make an interesting model for the formation of silica biomaterials.

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