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Versatile Modification for Highly Dispersive and Functionalized Mesoporous Silica Nanoparticles

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Highly dispersive and functionalized mesoporous silica nanoparticles (MSNs) 50–100 nm in diameter were formed by versatile surface modification through photopolymerization of organic molecules having vinyl groups. Hydrophilic polymers, hydrophobic chains, poly(*N*-isopropylacrylamide), and poly(*N*-vinylcarbazole) were easily attached to methacryl groups as a reactive site on the particle surface. We obtained MSNs having high dispersibility in various media and functionality, such as thermosensitivity and photoluminescence, using the facile technique.

Mesoporous silica has been of great interest because of many attractive features, such as narrow pore size distribution, large surface area, and well-defined surface properties. In particular, mesoporous silica nanoparticles (MSNs) are promising in bio-imaging,[1,2] drug delivery,[3] and low refractive index coatings[4] due to their large pore volume, high diffusivity, and high mobility. Miniaturization of mesoporous silica has been achieved by various procedures using nonionic surfactants,[5,6] chelating reagents,[7] and diluting precursor solution.[8] The size reduction of MSNs to less than 100 nm is required to obtain highly transparent colloids and films for optical usage.[4,9] Many efforts have been devoted to improve the dispersibility of MSNs by introduction of organic groups to the particle surface.[10–13] Bein et al. prepared highly dispersive MSNs with a diameter of 50–100 nm in water and ethanol by coverage of the surface with poly(ethylene glycol) (PEG) through delayed cocondensation.[10] Freire et al. synthesized hydrophobic MSNs 40–60 nm in diameter by cocondensation of tetraethyl orthosilicate (TEOS) and organosilane having fluorocarbon.[11] Recently, MSNs modified with poly(*N*-isopropylacrylamide) (PNIPAAM) were produced by radical polymerization.[12–14] The PNIPAAM-modified MSNs with a diameter of ca. 300 nm provided thermosensitive dynamic functions, such as temperature-dependent hydrodynamic diameter and release of an organic dye in water.[13] However, controlling the dispersibility and functionality of nanoparticles smaller than 100 nm is generally difficult. In the present work, highly dispersive and functionalized MSNs smaller than 100 nm were successfully obtained through a versatile surface-modification technique using photoreaction of vinyl groups.

In general, it is necessary to arrange optimized methods in order to prepare the organo-modified MSNs having a diameter smaller than 100 nm with different surface properties. Moreover, particular organosilanes have to be synthesized for the conventional cocondensation and grafting techniques to modify the particle surface. Here, we aimed at facile preparation of highly dispersive and functionalized MSNs in various media by a versatile surface modification method. Figure 1 shows a schematic illustration of the modification route for various organic molecules. First, we prepared MSNs having 3-methacryloxypropyl groups as a reactive site on their surface. Various kinds of organic molecules having vinyl groups were then attached at the reactive site under UV irradiation. Finally, we have successfully controlled the dispersibility and the hydrodynamic diameter of MSNs in hydrophilic and hydrophobic solvents by changing organic groups at the surface. The modified MSNs were easily functionalized by changing the organic groups and introduction of organic dyes to the micelle in the mesopores.[15] This versatile surface modification method is applicable to preparation of a wide variety of functionalized MSNs because a number of organic molecules having vinyl groups are commercially available.

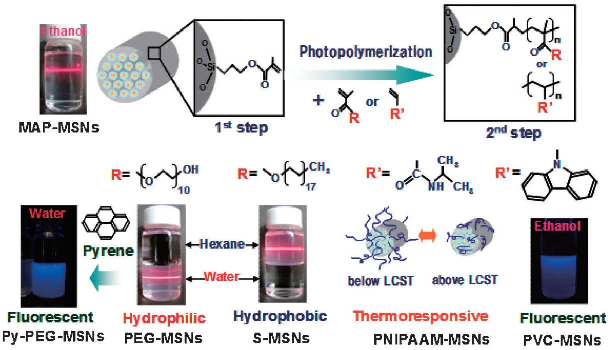

Figure 1. A schematic illustration of the modification route for various organic molecules and photographs of surface-modified MSNs dispersed in various media. The light scattering due to the dispersion of MSNs was observed with irradiation of a laser beam (690 nm).

The detailed method for preparation of MSNs was described in the previous reports.[6] In the present work, 3-methacryloxypropyltrimethoxysilane (MAPTMS) was used with TEOS as a silica source to create the reaction site on the particle surface. Cetyltrimethylammonium chloride (CTAC, 1.2 g, 3.76 mmol) and a triblock copolymer (Pluronic F127; $EO_{106}PO_{60}EO_{106}$, 2.4 g, 0.19 mmol) were mixed to a dilute hydrochloric acid (40 g, pH 2.0) at room temperature, and we then added TEOS (3.2 g, 15.4 mmol) and MAPTMS (0.96 g, 3.84 mmol) to the solution. The solution changed into a translucent sol by adding 4.0 g of 14.7 M ammonia water. Here, we obtained a sol containing MSNs that were modified with 3-methacryloxypropyl groups (MAP-MSNs). After addition of 40 mL of ethanol to 5 mL of the sol, the MAP-MSNs were separated by centrifugation (3000 rpm for 5 min) and redispersed in ethanol by ultrasonication. The triblock copolymer covering the particles was removed in this process. The MAP-MSNs dispersed in ethanol were separated by centrifugation (13500 rpm for 5 min).

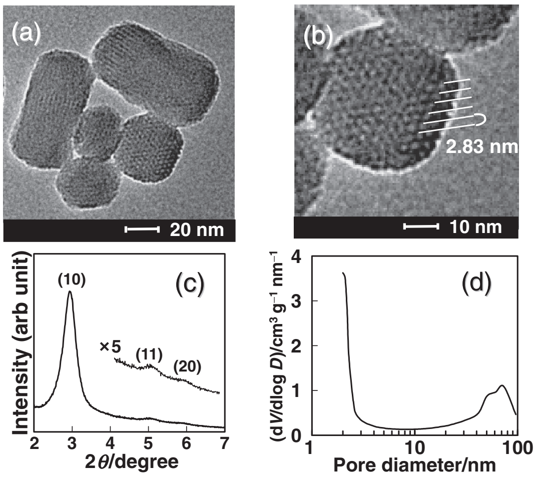

Figure 2. (a, b) Transmission electron micrographs of MAP-MSNs and (c) XRD pattern and (d) pore-size distribution of MAP-MSNs calcined at 673 K.

Modifying reagents having vinyl groups, such as poly(ethylene glycol) (PEG, $n = 8$–12) methacrylate (1.2 g), stearyl methacrylate (1.2 g), *N*-isopropylacrylamide (NIPAAM) (1.0 g), and 9-vinylcarbazole (VC) (0.1 g), and benzyl dimethyl ketal (0.05 g, 0.2 mmol) as a photopolymerization initiator were added into 20 mL of ethanol containing ca. 0.1 g of MAP-MSNs. The ethanolic dispersion was stirred for 3 h under UV (365 nm) irradiation to induce photopolymerization. We then obtained PEG-modified MSNs (PEG-MSNs), stearyl group-modified MSNs (S-MSNs), PNIPAAM-modified MSNs (PNIPAAM-MSNs), and PVC-modified MSNs (PVC-MSNs). The modified MSNs were purified by two cycles of centrifugation and dispersion in ethanol. The unfixed polymers were removed through this washing process. Pyrene (10.6 mg) was successfully introduced into PEG-MSNs by addition of the dye molecules to the initial solution of hydrochloric acid and the surfactants.

As shown in transmission electron microscopy (TEM) images obtained using a FEI TECNAI F20 (Figures 2a and 2b), MAP-MSNs had a diameter of 50–100 nm and the ordered mesostructure. The hexagonal arrangement of the mesopores was confirmed from TEM images (Figure 2b) and three XRD peaks assigned to (10), (11), and (20) planes which were recorded on a Bruker D8 Advance system (Figure 2c). The *d* spacing of (10) estimated from XRD pattern was 2.98 nm. The pore-size distribution of MAP-MSNs after calcination at 673 K for 3 h is shown in Figure 2d. The pore diameter less than 2 nm and the specific surface area of 1218 m^2 g^{-1} were estimated with the BJH and BET methods, respectively, from nitrogen adsorption–desorption isotherm (Figure S1[18]) obtained at 77 K with a Micromeritics TriStar 3000. Pores around 70 nm in Figure 2d are ascribed to the interparticle spacing of MSNs.

Figure 3 shows FT-IR spectra of organo-modified MSNs, which were obtained using a Bruker ALPHA. The absence of the specific peaks at 841 (–CH$_2$– groups) and 2878 cm^{-1} (C–H stretch of PEO segments) indicates the removal of F127 around the MSNs. Two characteristic peaks at 1722 (C=O stretch) and 1641 cm^{-1} (C=C stretch) for MAP-MSNs suggest the presence of methacrylate groups. Since the content of organic compounds was estimated to be 28 wt% from thermogravimetric analysis using a Seiko EXSTAR 6000, most of methacrylate groups originating from MAPTMS were fixed in the particles. Hoffmann et al. reported that the organic groups are localized on the surface of mesoporous silica prepared through the cocondensation process of TEOS and organosilanes.[16] Thus, the reaction sites were inferred to be located on the surface. We observed a decrease in the stretching mode of C=C for PEG-MSNs. Additional absorption peaks at 1655 and 1560 cm^{-1} for PNIPAAM-MSNs are attributed to the secondary amide C=O stretching and N–H in-plane stretching, respectively.[13] These results indicate the introduction of PEG chains and PNIPAAM on MSNs succeeded through the photopolymerization of PEG methacrylate and NIPAAM. The intensity of the stretching modes for the –CH$_2$– groups at 2928 and 2857 cm^{-1} for S-MSNs is larger than those for MAP-MSNs. Two characteristic peaks at 730 and 755 cm^{-1} for PVC-MSNs are attributed to the stretchings of aromatic groups in carbazole. Therefore, specifically modified MSNs were obtained with successful modification with long alkyl chains of stearyl groups and poly(vinylcarbazole).

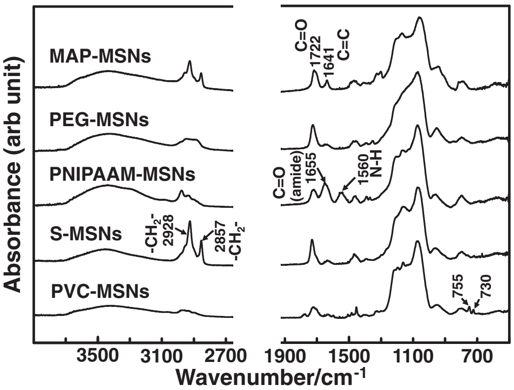

Figure 3. FT-IR spectra of organo-modified MSNs.

As shown in Figure 1, MAP-MSNs, PEG-MSNs, and S-MSNs formed transparent MSN sols in ethanol, water, and hexane, respectively. Figure 4 shows particle-size distribution of the organo-modified MSNs in various media measured by dynamic light scattering (DLS) with a Horiba LB-550. Unmodified MSNs aggregated in water, ethanol, and hexane. On the other hand, MAP-MSNs showed high dispersibility in ethanol, indicating that MSNs were covered with methacryloxypropyl groups originating from MAPTMS (Figure 4a). The hydrodynamic diameter was larger than the particle size observed in TEM images due to the presence of the organic groups on the surface. The hydrodynamic diameter increased with the modification with PEG and PNIPAAM because the length of the modifiers was larger than that of methacryloxypropyl groups. Although MAP-MSNs were not dispersed in water, PEG-MSNs and PNIPAAM-MSNs were not aggregated for six months in water (Figure 4b).

Figure 4b indicates that the hydrodynamic diameter of PNIPAAM-MSNs changed with temperature. The conformation of the thermosensitive polymer changes from the swollen, hydrophilic state to the shrunken, hydrophobic state above lower critical solution temperature (LCST 30–35 °C) in water.[17] The diameter at a high temperature is almost the same as that estimated from the TEM image. It means that the polymer chains completely shrank on the particle surface. On the other hand, the

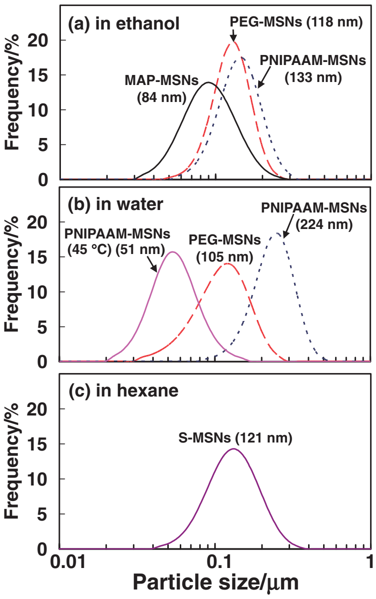

Figure 4. Particle-size distributions of the organo-modified MSNs dispersed at 24 °C [(a) in ethanol, (b) in water, and (c) in hexane]. Numbers after the sample names indicate the modal diameter.

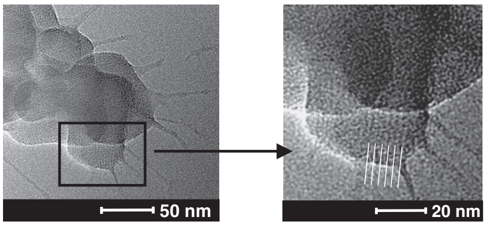

Figure 5. Transmission electron micrographs of PNIPAAM-MSNs.

diameter of PNIPAAM-MSNs in water (224 nm) at 24 °C was larger than that in ethanol (133 nm). Thus, the polymer chains are highly stretched in water by hydration. The stretched chains of PNIPAAM on the MSN were observed in the TEM image (Figure 5). We also confirmed the presence of the cylindrical mesopores after the modification in the enlarged micrograph.

Blue fluorescence (Figure 1) was observed from pyrene-doped PEG-MSNs (Py-PEG-MSNs) in water and PVC-MSNs in ethanol under illumination of a black light (365 nm). The stably dispersed MSNs emitted the blue fluorescence originating from the pyrene monomers entrapped inside the nanochannels and poly(vinylcarbazole) covering the surface. The fluorescence spectra of the functionalized MSNs are shown in Figure S2.[18]

In summary, highly dispersive and functionalized MSNs smaller than 100 nm were successfully obtained through a versatile surface-modification technique using photoreaction of vinyl groups. These MSNs showed high dispersibility in polar and nonpolar solvents without aggregation. Organic fluorescent dye molecules were introduced in the highly dispersive MSNs. Thermoresponsive MSNs were also prepared by modifying with PNIPAAM. The modified MSNs are a promising material for applications in bioimaging and drug delivery.

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