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Semisolid Phase Synthesis of Metal-complexed Organic Nanotubes

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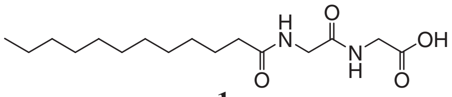
The first semisolid phase synthesis of organic nanotubes was achieved by mixing an aqueous solution of metal salt with an alcoholic dispersion of glycylglycine lipid. The dry 80–240 g of nanotubes are easily obtained within a few hours using 1 L of solvent.

Self-assembled nanofibers and nanotubes are expected to be promising nanomaterials using energy- and resource-saving bottom-up techniques.[1,2] In addition to hydrogen bonding, π–π stacking, electrostatic interaction, and hydrophobic interaction, coordination to metal cation is widely utilized for constructing a structural backborn and functionalities. Metal-complexed nanofibers have been frequently studied over last two decades.[3–7] On the contrary, investigation of metal-complexed nanotubes has been limited.[8,9] Strict directionality of the coordination bonds would be unfavorable for tubular morphology in comparison with other weak interactions.

We have reported the self-assembly of metal-complexed organic nanotubes (M-ONTs) using glycylglycine-containing fatty acid.[10] Since the glycylglycine residue is a powerful building block for tubular morphology, it can overcome the strict directionality of the coordination bonds.[11–13] The M-ONTs are instantly formed by mixing an aqueous solution of metal salt with that of peptide lipid. Although the M-ONTs are expected to be useful as catalysts, adsorbents, and templates for metal–organic hybrid nanotubes, low solubility of the lipids have prevented large scale synthesis.[14,15] Here, we report the first semisolid phase synthesis of M-ONTs. Mixing an aqueous solution of metal salt with an alcoholic dispersion of the lipid gave a highly concentrated dispersion of the M-ONTs. This novel synthesis improved the production efficiency 200–600 times in comparison with that of conventional self-assembly in solution.



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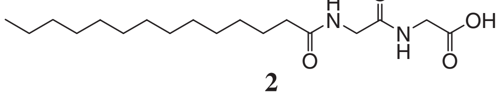

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Chart 1.

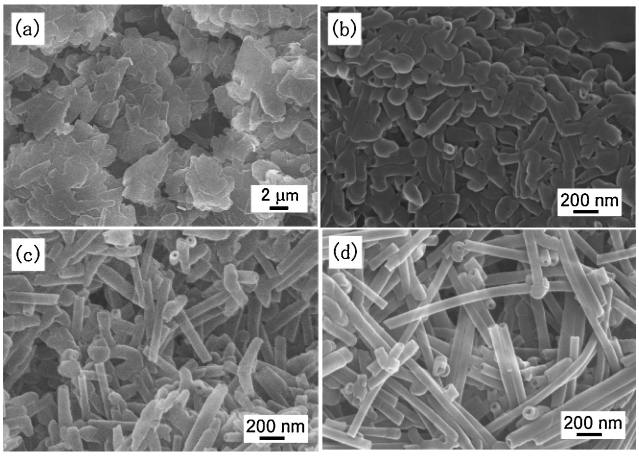

Figure 1. FE-SEM images of the (a) original plates before the addition, (b) 10 s, (c) 10 min, and (d) 3 h after the addition of zinc acetate.

We used peptide lipids **1** and **2** in this study (Chart 1), since they tend to form nanotubes easily and they also can be synthesized using inexpensive naturally occurring fatty acid.[10,13] After dry powder of the lipid **2** is dispersed in methanol (1.71 g, 5 mmol in 20 mL), an aqueous solution of $Zn(OAc)_2 \cdot 2H_2O$ (0.82 g, 3.75 mmol in 5 mL) is added. Since the solubility of **2** at 20 °C is less than 0.01 g in 20 mL of methanol, most lipid molecules exist as a solid. Figure 1 shows field-emission scanning electron microscopic (FE-SEM) images of morphology before and after mixing. Original dry powder of lipid **2** showed plate morphology (Figure 1a). These plates changed into globular or tube-like morphology just after mixing (Figure 1b). The globules gradually disappeared and short nanotubes gradually increased (Figure 1c). Finally, long nanotubes with short nanotubes as a minor component appeared after 3 h (Figure 1d). Average outer- and inner-diameters of the nanotubes are around 85 and 35 nm, respectively. The nanotube membranes consist of 4 bilayers. This suggests that metal complexation and morphological change will take place in the semisolid phase.

After 3 h, dry nanotubes are easily obtainable by filtration and drying in vacuo. The elemental analysis showed the existence of one Zn^{2+} cation with two lipid molecules. They also include no water or alcohol. FT-IR spectra of the dried nanotubes were different from the original plates (Figure S1).[16] In particular, disappearance of C=O stretching bands between 1700–1730 cm^{-1} indicated that Zn^{2+} cation formed a metal complex with COO^- of the lipids. A cation exchange between Zn^{2+} and H^+ of the COOH takes place rapidly. X-ray diffractions of the dry nanotubes also showed that metal complexation was complete within a few minutes.

In the previous method, it is necessary to dissolve the lipids by adding sodium hydroxide for deprotonation of the terminal carboxyl groups. However, the strong hydrogen-bond networks between the glycylglycine residues lower the solubility of the lipids. Less than 0.4 g of the M-ONT was obtainable using 1 L of aqueous solution with this method. In the new method, the

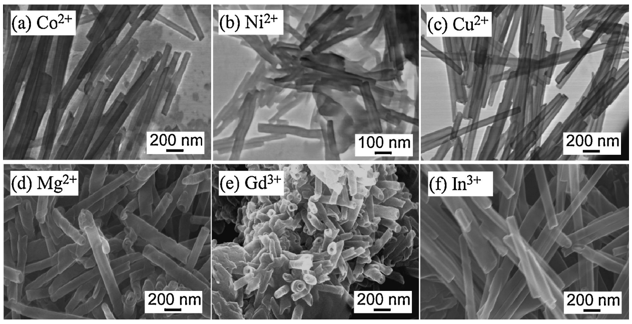

Figure 2. STEM images of M-ONTs from (a) Co^{2+}, (b) Ni^{2+}, and (c) Cu^{2+}. FE-SEM images of M-ONTs from (d) Mg^{2+}, (e) Gd^{3+}, and (f) In^{3+}.

solubility of the lipids is negligible. After the dry powders of the lipids are just dispersed in alcohol with stirring, aqueous solutions of metal salts are added to the dispersion. Concentration of the M-ONT dispersions will be increased by the saturated concentration of metal salts in water. In the zinc acetate case, about 80 g of Zn^{2+}-ONT is obtainable using 1 L of methanol–water mixture.

This first semisolid phase synthesis of the M-ONTs will increase the possibility of first industrial application of the nanotubes. However, the mechanism and conditions for the nanotube formation are considerably complicated. Although Zn^{2+}-ONTs obtained from methanol–water mixture were stable in the dispersion for 1 week (Figure S2a), Zn^{2+}-ONTs obtained from ethanol–water mixture changed into long plates even after 1 day (Figure S2b).[16] Zn^{2+}-ONTs seem to be kinetically and thermodynamically stable in methanol–water mixture, but kinetically stable in ethanol–water mixture. In addition, the change of a counter anion from acetate to nitrate, the decrease of metal/lipid ratio from 1:0.75 to 1:0.5, and the exchange of methanol/water ratio from 1:4 to 4:1 dramatically reduce the nanotube/plate ratio to less than 50%. Many kinetically or thermodynamically meta-stable structures will exist for the metal complex of the peptide lipids. Specific conditions are necessary for M-ONTs formation.

Now, we have succeeded in finding the conditions for Cu^{2+}-, Ni^{2+}-, Co^{2+}-, Gd^{3+}-, Mg^{2+}-, and In^{3+}-ONTs. Although the ratio of nanotube/plate is less than 50%, Ag^{+}-, Fe^{3+}-, Eu^{3+}-, and Cd^{2+}-ONTs are also obtainable. Figure 2 shows scanning transmission electron microscopic (STEM) and FE-SEM images of the M-ONTs. The conditions are roughly divided into two types (Table 1). The first is for Zn^{2+}, Co^{2+}, Mg^{2+}, In^{3+}, and Gd^{3+}, and the second is for Cu^{2+} and Ni^{2+}. The first type M-ONTs are produced in alcohol-rich dispersions, and alkali-like NEt_3 is not necessary. In contrast, the second type M-ONTs are produced in water-rich dispersions and alkali is necessary. In case of $GdCl_3$, water content will be large owing to the low solubility of metal salts, and alkali will be necessary to help the cation exchange. Maximum yield (ca. 240 g L^{-1}) was achieved with Cu^{2+}- and Ni^{2+}-ONTs. Appropriate conditions for any metal cation should exist, since we are able to obtain M-ONTs from alkali-earth-, general transition-, IIIb-, and rare-earth-metals.

In summary, we demonstrated the first semisolid phase synthesis of metal-complexed organic nanotubes. Mixing an aqueous solution of metal salt with an alcoholic dispersion of the peptide lipid produced the dry 80–240 g of nanotubes within a few hours using 1 L of solvents. Metal coordination and morphological change took place at appropriate conditions rapidly just after mixing. Obtained nanotubes will be applied as self-templates for metal nanoparticle embedded organic nanotubes.[14,15] We have been also investigating catalytic activity of the M-ONTs for oxidation of various kinds of organic compounds.[17]

Table 1. Conditions and diameters for M-ONTs

Metal salt	Lipid	Solvent	Alkali	Diameter[a] /nm
$Zn(OAc)_2$	**2**	$MeOH:H_2O = 4:1$	—	$\approx 85 \pm 15$
$CoCl_2$	**2**	$EtOH:H_2O = 4:1$	—	$\approx 85 \pm 10$
$MgCl_2$	**2**	$MeOH:H_2O = 10:1$	—	$\approx 70 \pm 10$
$InCl_3$	**2**	$MeOH:H_2O = 10:1$	—	$\approx 90 \pm 25$
$GdCl_3$	**2**	$MeOH:H_2O = 4:1$	1equiv NEt_3	$\approx 80 \pm 10$
$Cu(OAc)_2$	**2**	$EtOH:H_2O = 1:4$	1equiv NEt_3	$\approx 100 \pm 20$
$NiCl_2$	**1**	$EtOH:H_2O = 1:4$	1equiv NEt_3	$\approx 40 \pm 10$

[a] Average outer diameters and their standard deviations.

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16 Figures S1 and S2 are shown in Supporting Information. Supporting Information is available electronically on the CSJ-Journal Web site, http://www.csj.jp/journals/chem.-lett/index.html.
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