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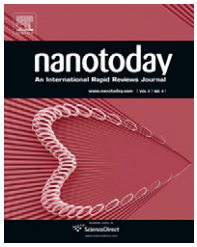

REVIEW

Synthesis and biomedical applications of hollow nanostructures

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Summary Hollow nanostructures have attracted tremendous attention from researchers in various disciplines because their high surface to volume ratio and large pore volume are highly desirable for many technological applications including drug delivery system. Several colloidal synthetic methods have been used to synthesize various hollow nanostructures. These synthetic approaches are mainly categorized into four main classes according to how the hollow structure is formed: the Kirkendall effect, chemical etching, galvanic replacement, and template-mediated approach. The large pores inside the hollow nanostructures can encapsulate and release various drugs and biomolecules, while the surface of the nanostructure can be functionalized for drug targeting or bio-labeling. These features make the hollow nanostructures a unique and promising candidate as multifunctional drug delivery vehicles. This review article covers recent progress concerning the synthesis of hollow nanostructures with their sizes smaller than 200 nm and their biomedical applications including specific targeting, imaging, and controlled release of therapeutics for simultaneous diagnosis and therapy.

For the last decade, hollow nanostructures with a controlled pore volume and shell thickness have emerged as an important class of nanomaterials [1—4]. These hollow nanostructures have much higher surface to volume ratio compared to the solid counterparts with the same sizes, which would be beneficial for applications including catalysis, energy storage and conversion, and biomedicine [1].

The most popular method to synthesize the hollow nanostructures is template-mediated approaches [5]. By coating the surface of the template particles with desired materials and removing the template by a post-treatment, various hollow particles can be easily obtained. Silica particles and polymer beads are widely used hard template materials. There are various methods to coat materials on these hard templates: layer-by-layer assembly [6,7], chemical deposition [8,9], adsorption [10—12], casting [13], and atomic layer deposition [14]. Various soft templates have been also employed for the synthesis of hollow nanostructures, including microemulsions formed in a two-phase solution [15,16], gas bubbles in liquid [17,18], and micelles (or vesicles) assembled by surfactants or supramolecules [19,20]. Recently, Lou and co-workers comprehensively reviewed the synthesis and applications of hollow micro- and nanos-

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Table 1 Synthetic strategies for the hollow nanomaterials.

Applied methods	Hollow materials	Initial materials (templates)	Shape	Ref.
Nanoscale-Kirkendall effect	Co_3S_4, Co_9S_8, CoSe	Co	Sphere	[21,33]
	Pt—CoO	Pt—Co	Yolk—shell	[21]
	Fe_3O_4	Fe—Fe_3O_4	Sphere	[34]
	γ-Fe_2O_3	Fe	Sphere	[35,44]
	$ZnAl_2O_4$	ZnO—Al_2O_3	Tube	[36,37]
	$CoSe_2$, Co_3S_4, CoTe	Co	Necklace	[38]
	Ni_2P, Co_2P	Ni, Co	Sphere	[39,40]
	CeO_2—ZrO_2	CeO_2—ZrO_2	Sphere, box	[41]
	FePt—CoS_2	FePt—Co	Yolk—shell	[98]
	FePt—Fe_2O_3	FePt—Fe_2O_3	Yolk—shell	[99]
	Au—Fe_2O_3	Au—Fe_2O_3	Yolk—shell	[42]
	Pt—Cu	Pt—Cu	Core—shell	[45]
	$Cu_{2-x}Se$	Cu_2O	Sphere	[46]
	CuO	Cu	Tube	[47]
	Ag—Ag_2Se, Ag_2Se	Ag	Sphere, tube	[48,49]
	PbS, Pb—PbS, Pb—Ag	Pb	Sphere	[50]
	CdS	Cd	Sphere	[43]
	Co_3S_4	$Co(CO_3)_{0.35}Cl_{0.20}(OH)_{1.10}$	Tube	[51]
	ZnS	ZnO	Sphere	[52]
	ZnO	Zn	Sphere	[53]
Chemical etching	Fe	Fe	Box, frame	[54]
	Fe-phosphide	Fe_3O_4, α-Fe_2O_3	Sphere, box	[22]
	Mn-phosphide	MnO	Sphere, multi-pods	[22]
	Mn—Fe-phosphide	$MnFe_2O_4$	Sphere	[22]
	ZnO, Au—ZnO, Pt—ZnO, Au—Pt—ZnO	ZnO	Sphere	[57]
	Co	Co	Box, frame	[55]
	Pd	Pd	Box, frame	[56]
	Cu_2O	Cu_2O	Dodecahedral, frame	[58]
Galvanic replacement	Au	Ag	Box, cage, triangular ring, prism-shaped box, tubes, multiple-walled shell or tube	[3,4,62—68]
	Pd—Ag, Pt—Ag	Ag	Box, frame	[69]
	Au, Ag, Pt, AuPt, CoPt	Co	Sphere	[70—75]
	AuPt,	Co	Necklace	[71]
	Au, Pt, Pd	Co	Necklace	[76]
Nanotemplate	α-Fe_2O_3, Fe_3O_4	β-FeOOH	Capsule	[23]
	α-Fe_2O_3	Silica	Sphere	[77]
	Silica	Fe_3O_4	Sphere	[78]
	α-FeOOH	Organics	Tube	[80]
	Co	CoO	Parallelepiped	[81]