

[*Supporting Information*]

Soft-Matter Nanotubes: A Platform for Diverse Functions and Applications

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Table S1. Summary of properties, functions, applications, and main action fields of LNT materials.

Property, Function, and Application		Action Field				SMNT	ref
		Interior	Wall Membrane	Exterior	Whole of Nanostructure and Ensemble of Nanotubes		
chemical	• embedding		• 8-anilinonaphthalene-1-sulfonate, Zn-phthalocyanine			LNT	131
	• encapsulation and chiral induction	• polythiophene and boronic acid				LNT	114
	• release	• enforced release of fullerene				LNT	244
	• separation	• chiral separation of Ser, Thr, Cys, Tyr, and enkephalin analogues				LNT	115
	• recognition and sensing			• chiral amine detection		LNT	62
	• catalyst	• oxidation with <i>tert</i> -butyl hydroperoxide or hydrogen peroxide		• oxidation with <i>tert</i> -butyl hydroperoxide or hydrogen peroxide		LNT	118,119
	• template and scaffold			• Au NPs on LNT surface		LNT	149
		• sample -fixation matrix for TEM CT analysis for ferritin, DNA-binding protein from starved cell				LNT	116,117
	• hydrogel formation				• multi-walled nanotube hydrogel	LNT	167
	• organogel formation				• pH-responsive hydrogelation	LNT	165
physical	• light harvesting	• light-harvesting antenna	• light-harvesting antenna		• hydrogelation of bundled nanotubes	LNT	378
		• enhancement of photocatalytic activity of Re (I) complex	• enhancement of photocatalytic activity of Re (I) complex		• nanotube organogel in absolute alcohol	LNT	169
			• chirality and energy transfer, and amplification of CPL		• nanotube organogel in DMSO, DMF and so on	LNT	62,170
	• mechanical reinforcement				• nanotube organogel emitting a fluorescence	LNT	61
	• stiffness, rigidity, and elasticity					LNT	61
biological	• positioning and alignment					LNT	168
	• protein refolding and solubilization		• artificial chaperone for lysozyme, GFP, & CS		• nanotube-based fiber mat	LNT	425,426
	• nanopipette and nanochannel	• nanopipette device (50-nm inner diameters)			• Young's Modulus	LNT	167
					• high-frequency AC electric field	LNT	467-470
						LNT	201
						LNT	37
						LNT	73,532
					• nanotube network	LNT	204

Table S1. (continued-1) Summary of properties, functions, applications, and main action fields of LNT materials.

Property, Function, and Application		Action Field				SMNT	ref
		Interior	Wall Membrane	Exterior	Whole of Nanostructure and Ensemble of Nanotubes		
biological	• nanopipette and nanochannel				• shear flow-induced nanotubulation	LNT	206
medical	• supramolecular channel reactor • antimicrobial activity • photothermal therapeutic agent • PEGylated nanotube	• cell-to-cell bacterial communication • controlled polymerization of imine • dumbbell-like PDA nanofiber fabricated by using an LNT lumen as a template	• Ag-embedded nanotube	• helically coiled PDA nanofiber fabricated by using an LNT outer surface as a template • prevention of aggregation by PEGylation		LNT LNT LNT LNT	545 554 563 157

Table S2. Summary of properties, functions, applications, and main action fields of BANT materials.

Property, Function, and Application		Action Field				SMNT	ref			
		Interior	Wall Membrane	Exterior	Whole of Nanostructure and Ensemble of Nanotubes					
chemical	• release	• GFP	• moisture-sensitive transformation from tube to sheet			BANT	40			
	• transportation	• encapsulation and transportation (GFP, ferritin) • dye diffusion (SRB, Nile Red, hydrated Nile Red)				BANT	238			
	• separation	• hydrophobic amino acids (Leu, Met, Val, Ile, and Ala), three angiotensin analogues				BANT	38,40			
	• recognition and sensing	• Mukaiyama aldol RXN ^a , Diels-Alder RXN	• chiral sensing of amino acids, naked eye detection		• ConA detection	BANT	259,265			
	• catalyst					BANT	276			
	• template and scaffold		• Mukaiyama aldol RXN ^a , Diels-Alder RXN • surfactant-free Au NRs		• surfactant-free Au NRs • lyotropic liquid crystal • multi-walled nanotube hydrogel • hydrogelation of nanotubes with conc. HCl and H ₂ SO ₄ • nanotube hydrogel with ConA	BANT	142			
	• liquid crystal formation					BANT	292			
	• hydrogel formation					BANT	120,121			
physical						BANT	162			
						BANT	16,162			
biological	• protein stabilization	• GFP • artificial chaperone activity for GFP, CAB, & CS • duplex formation of short nucleotide • interlink of a heterogeneous pair of nanochannels • enzymatic channel reactor	• n-type nanotube, exciton dynamics • D-A nanotube		• multi-walled nanotube hydrogel • hydrogelation of nanotubes with conc. HCl and H ₂ SO ₄ • nanotube hydrogel with ConA	BANT	33,35			
	• protein refolding and solubilization					BANT	63			
	• nanopipette and nanochannel					BANT	142			
	• enzymatic channel reactor					BANT	137,449			
medical	• drug loading for delivery system	• HRP, catalase, GOD, or cytochrome c--encapsulated nanocoil end-capped with magnetic nanoparticle • anticancer cisplatin or doxorubicin • poorly water-soluble drug ibuprofen	• complexing with plasmid DNA and delivery			BANT	139,140			
	• non-viral gene transfer vector					BANT	40			
						BANT	35			
						BANT	52			
						BANT	541			
						BANT	555			
						BANT	113,234			
						BANT	571			
						BANT	153			

^aRXN: reaction.

Table S3. Summary of properties, functions, applications, and main action fields of FFNT materials.

Property, Function, and Application		Action Field				SMNT	ref
		Interior	Wall Membrane	Exterior	Whole of Nanostructure and Ensemble of Nanotubes		
chemical	• encapsulation	• aggregation-induced fluorescent nanotube				FFNT	222
	• recognition and sensing	• probing of the number of water molecules				FFNT	300,301
				• intracellular temperature sensing	FFNT	305	
				• phenol detection	FFNT	159	
				• NADH detection	FFNT-coated MWCNT	309,310	
	• functional surface and film			• superhydrophobicity by vertically aligned PNT film	FFNT	160,161	
	• ferroelectrics			• light-induced ferroelectricity	FFNT	172	
	• piezoelectrics			• piezoelectricity	FFNT	178	
	• non-linear optical effect	• heat-sensitive morphological transformation		• piezoelectric resonator	FFNT	175	
	• quantum confinement			• practically usable piezoelectric device	FFNT	403	
physical	• light harvesting		• light-harvesting peptide nanotube	• second harmonic generation	FFNT	179,180	
	• electrode or ultracapacitor		• light-harvesting peptide nanotube	• second harmonic generation	FFNT	304	
	• mechanical reinforcement			• optical waveguiding activity	FFNT	179,181, 407	
	• stiffness, rigidity, and elasticity			• optical and electronic quantum confinement	FFNT	186,187	
	• positioning and alignment			• supercapacitor electrode	FFNT	424	
	• detection of cancer cell and neurotoxin			• enhanced ionic conductivity of polymer electrolytes	FFNT	160,302, 303	
				• reinforcement by nanotube incorporation as a filler	FFNT	191	
				• Young's Modulus	FFNT	190	
				• inkjet printing	FFNT	192,194, 457	
				• detection of human cervical cancer cell	graphene electrode modified with FFNT	195	
medical				• detection of neurotoxin	FFNT	209	
					FFNT	601	

Table S4. Summary of properties, functions, applications, and main action fields of PNT materials.

Property, Function, and Application		Action Field				SMNT	ref
		Interior	Wall Membrane	Exterior	Whole of Nanostructure and Ensemble of Nanotubes		
chemical	• release		• pH-sensitive contraction-expansion motion • pH-sensitive morphological transformation			PNT	151
	• recognition and sensing			• virus (pathogen) recognition • Pb ion detection • aldol condensation		PNT	247
	• catalyst • photoconductivity • stiffness, rigidity, and elasticity	• aldol condensation	• metalloporphyrin arrays		• Young's Modulus	PNT ^a	437
physical	• nanopipette and nanochannel		• interlink of a heterogeneous pair of nanochannels			PNT	141
biological	• drug loading for delivery system • non-viral gene transfer vector • detection of cancer cell and neurotoxin	• anticancer camptothecin	• anticancer camptothecin	• oral nanocarrier for gene delivery • adhesion of cancer cells		PNT	123
						PNT	151
						PNT	539,540
medical	• anticancer camptothecin					PNT	573,574
						PNT	584,585
						PNT	154,155

^aIt is uncertain whether peptide amphiphile-based nanotubes or not.

Table S5. Summary of properties, functions, applications, and main action fields of CPNT and CPPNT materials.

Property, Function, and Application		Action Field				SMNT	ref
		Interior	Wall Membrane	Exterior	Whole of Nanostructure and Ensemble of Nanotubes		
chemical	• template and scaffold			• carboxylated polymer pore • CPNT/fullerene, CPNT/single-wall CNT, CPNT/Ag clusters • scaffold for polymerization		CPNT	336
	• liquid crystal formation • hydrogel formation					CPNT	148,355, 356
	• functional surface and film				• columnar mesophase • nanotube hydrogel confined in water micro-droplet • porous thin film containing sub-nm channel	CPPNT	29,30, 102,145- 147,347- 350
physical	• energy migration • mechanical reinforcement		• p-type nanotube			CPNT	60
	• stiffness, rigidity, and elasticity • positioning and alignment				• reinforcement by nanotube incorporation as a filler • stiffest and strongest fiber	CPNT	138
					• utilization of nanostructured ionic liquid	CPNT	189
biological	• transmembrane transport	• alkali or alkaline-earth cation transport				CPNT	523,524
		• transport of anticancer drugs			• transmembrane nanopore formation	CPPNT	128
		• transmembrane protein channel mimic				CPNT	129,530, 531
medical	• antimicrobial activity • drug loading for delivery system	• doxorubicin (DOX)			• membrane permeation	CPPNT	128
				• anticancer RAPTA-C, organoiridium anticancer complex	CPNT	208	
	• non-viral gene transfer vector			• gene transfection	CPNT	576	
					CPPNT	29,30, 152	
					CPNT	156	

Table S6. Summary of properties, functions, applications, and main action fields of PRNT materials.

Property, Function, and Application		Action Field				SMNT	ref
		Interior	Wall Membrane	Exterior	Whole of Nanostructureu and Ensemble of Nanotubes		
chemical	• encapsulation	• 3,3'-diethylthiacarbocyanine iodide, zinc(II) protoporphyrin, biotin	• 3,3'-diethylthiacarbocyanine iodide, zinc(II) protoporphyrin,			PRNT	111
	• catalyst	• 1-D array of superparamagnetic NPs • reduction of 4-nitrophenol to 4-aminophenol using NaBH ₄	• reduction of 4-nitrophenol to 4-aminophenol using NaBH ₄			PRNT	46
	• template and scaffold		• solid NT of α-Fe ₂ O ₃ NPs, solid NT of Au NPs			PRNT	132,133
physical biological	• micron size engine • positioning and alignment • enzymatic channel reactor	• self-propelled microtube • interior surface covered with α-glucosidase • interior surface covered with CalB			• electrophoretic deposition	PRNT	50
						PRNT	487
medical	• drug loading for delivery system		• ATP-induced chemomechanical motion and scission		• ATP-induced chemomechanical motion and scission	PRNT	125
	• virus trap	• infectious hepatitis B virus, Influenza virus A PR8				PRNT	44
						PRNT	112,130

Table S7. Summary of properties, functions, applications, and main action fields of MONN and BBCNT materials.

Property, Function, and Application		Action Field			SMNT	ref
		Interior	Wall Membrane	Exterior	Whole of Nanostructure and Ensemble of Nanotubes	
chemical	• adsorption				• safranine T, fuchsin basic, calcein, cytochrome c	MONN 158
	• separation				• magnetic separation, practical separation of organic dyes (MB, FB, R6G)	MONN 277
	• catalyst	• model Knoevenagel condensation, tandem deacetalization-Knoevenagel RXN ^a , Suzuki-Miyaura cross-coupling RXN, Henrt RXN • Suzuki-Miyaura cross-coupling RXN • oxo-vanadium complex to oxidize thiols to disulfides • Au nanoparticles to reduce 4-nitrophenol		• Suzuki-Miyaura cross-coupling RXN		MONN 326,327
	• catalyst	• model Knoevenagel condensation, tandem deacetalization-Knoevenagel RXN, Suzuki-Miyaura cross-coupling RXN, Henrt RXN				MONN 47,329
	• catalyst					MONN 330
	• encapsulation and extraction	• positively charged dyes (MB, ethidium bromide, ST) and PAMAM G2 dendrimers	• one-pot deacetalization-Knoevenagel RXN	• one-pot deacetalization-Knoevenagel RXN		BBCNT 212
						BBCNT 325
						BBCNT 49
						BBCNT 103

^aRXN: reaction.

Table S8. Summary of properties, functions, applications, and main action fields of RFBMNT materials.

Property, Function, and Application		Action Field				SMNT	ref
		Interior	Wall Membrane	Exterior	Whole of Nanostructure and Ensemble of Nanotubes		
chemical	• encapsulation	• double-stranded DNA			• guest-driven folding and zipping	RFBMNT	53
	• recognition and sensing	• detection of biogenic amine		• detection of biogenic amine		RFBMNT	220
	• catalyst	• Suzuki-Miyaura coupling RXN ^a		• Suzuki-Miyaura coupling RXN		RFBMNT	296
physical	• light harvesting	• Suzuki-Miyaura coupling RXN	• light-harvesting system in water			RFBMNT	331
	• photoconductivity		• supramolecular light-harvesting nanotube			RFBMNT	122
	• energy migration		• charge carrier mobility			RFBMNT	419
biological	• nanopipette and nanochannel		• conductivity and charge carrier mobility			RFBMNT	421,422
	• supramolecular channel reactor	• interlink of dissimilar semiconducting nanotubes				RFBMNT	184,185
medical		• interlink of a heterogeneous pair of nanochannels		• interlink of a heterogeneous pair of nanochannels		RFBMNT	435-437
		• reversible pulsating motion sensitive to thermal stimuli, collective helicity switching		• reversible pulsating motion sensitive to thermal stimuli, collective helicity switching		RFBMNT	433
	• dexamethasone and tamoxifen	• guest-driven inflation		• guest-driven inflation		RFBMNT	135
		• reversible open-closed motion sensitive to a thermal signal		• reversible open-closed motion sensitive to a thermal signal		RFBMNT	54
						RFBMNT	83
						RFBMNT	579,580

^aRXN: reaction