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Synthesis and Chiroptical Properties of Hydroxyphenylglycine-Based Poly(*m*-phenyleneethynylene-*p*-phenyleneethynylene)s

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ABSTRACT: The polymerization of 3′,5′-diiodo-4′-hydroxy-*N*-α-*tert*-butoxycarbonyl-D-phenylglycine ethyl-, hexyl-, and laurylamides **1**−**3** with *p*-diethynylbenzene was carried out to obtain optically active poly(*m*-phenyleneethynylene-*p*-phenyleneethynylene)s [poly(**1**)−poly(**3**)] with M_n's in the range from 6100 to 7300 in 79−82% yields. The specific rotation, CD, and UV−vis spectroscopic data revealed that poly(**1**)−poly(**3**) formed helices with predominantly one-handed screw sense. The presence of intramolecular hydrogen bonding formed between amide side groups was confirmed by solution-state IR spectroscopy. The helical structures were stable to heat and alkali metal hydroxides, while responsive to H_2O and alkali metal alkoxides.

Introduction

Helix is a structural feature of biological macromolecules such as proteins and DNA. Many biological functions and properties of biopolymers are associated with their tertiary and quaternary structures, whose formation is largely regulated by the helical conformation of the polymer chains as well as the folding and chiraliy encoded in their building blocks. There has been considerable interest in development of synthetic helical polymers. Study on nonbiological polymers may lead to a better understanding of the mechanism for helix formation in biopolymers. On the other hand, synthetic helical polymers are under hot pursuits due to their potential applications such as circularly polarized photo- and electroluminescent materials and chiral recognition (separation, catalysis, sensory functions).[1] Among various synthetic helical polymers, much attention has been paid to π-conjugated helical polymers including polyacetylene,[2] poly(phenylenevinylene),[3a] polythiophene,[3b] polyfluorene,[3c] and poly(*p*-phenylene)[3d] substituted with optically active side groups due to their electronic and optical functions. Poly(phenyleneethynylene)s are π-conjugated polymers that also form helices. Poly(phenyleneethynylene)s substituted with polar groups are amphiphilic. Their backbones are hydrophobic, whereas the polar side groups control hydrophilic interactions. This amphiphilic character leads to folding of main chains to form helical structures in polar solvents. Oligo(*m*-phenyleneethynylene)s carrying hydrophilic short ethylene glycol chains fold into a helical conformation, which is thermodynamically driven by solvophobic effects.[4] Amphiphilic poly(*m*-phenyleneethynylene)s undergo conformational transition that is consistent with folding of the main chains into a helix.[5] Poly(*m*-pyridinyleneethynylene)s, analogous polymers of poly(*m*-phenyleneethynylene)s, form helical complexes with saccharides in protic media.[6] Poly(*m*-phenyleneethynylene-*p*-phenyleneethynylene)s are polymers that have conjugated main chains consisting of *m*-phenyleneethynylene and *p*-phenyleneethynylene linkages alternatingly. Poly(*m*-phenyleneethynylene-*p*-phenyleneethynylene)s substituted with ionic groups such as sulfonate and carboxylate also take a helical structure in aqueous solution.[7]

Meanwhile, amino acids are building blocks of peptides and proteins, many of which organize higher order structures by noncovalent forces, mainly hydrogen bonding. Amino acid-containing synthetic polymers form secondary structures utilizing hydrogen bonding. For example, amino acid-based poly(phenylacetylene)s[8] and poly(*N*-propargylamide)s[9] form helices stabilized by intramolecular hydrogen bonding between the amide groups on the side chains. In the present study, we report the synthesis of novel poly(*m*-phenyleneethynylene-*p*-phenyleneethynylene)s [poly(**1**)−poly(**3**)], whose *m*-phenylene unit is derived from hydroxyphenylglycine (Scheme 1). We can expect the polymers to form a helical structure with hydrophobic exterior (alkyl group) and hydrophilic interior (phenol group) in nonpolar solvents. By incorporating amide groups at the *m*-phenylene moieties, we can also expect the formation of intramolecular hydrogen bonds between them, which may be effective to stabilize a helical structure.

Experimental Section

Measurements. ^{1}H (400 MHz) and ^{13}C (100 MHz) NMR spectra were recorded on a JEOL EX-400 spectrometer. IR spectra were measured on a JASCO FTIR-4100 spectrophotometer. The number- and weight-average molecular weights (M_n and M_w) of polymers were determined by gel permeation chromatography (GPC) on a JASCO Gulliver system (PU-980, CO-965, RI-930, and UV-1570) equipped with polystyrene gel columns (Shodex columns K804, K805, and J806), using THF as an eluent calibrated by polystyrene standards at 40 °C. Melting points (mp) were measured on a Yanaco micro-melting point apparatus. Elemental analysis was performed at the Microanalytical Center of Kyoto University. Specific rotations ($[\alpha]_D$) were measured on a JASCO DIP-1000 digital polarimeter. CD and UV−vis spectra were recorded on a JASCO J-820 spectropolarimeter.

Materials. DMF and Et_3N used for polymerization were distilled over CaH_2 prior to use. All other reagents were

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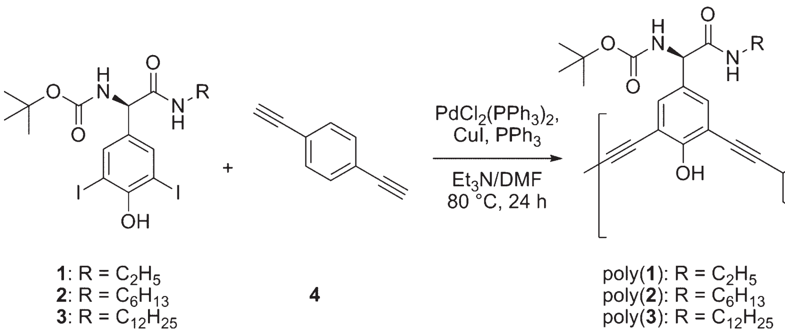
Scheme 1. Polycondensation of Monomers 1−3 with 4



commercially obtained and used as received without purification.

Synthesis of 3′,5′-Diiodo-4′-hydroxy-*N*-α-*tert*-butoxycarbonyl-D-phenylglycine Ethylamide (1). 4′-Hydroxy-*N*-α-*tert*-butoxycarbonyl-D-phenylglycine (10.7 g, 40.0 mmol) and ethylamine (2.0 M in THF, 20 mL, 40 mmol) were dissolved in AcOEt (200 mL), and the resulting solution was stirred at room temperature for 10 min. 4-[4,6-Dimethoxy-1,3,5-triazine-2-yl]-4-methylmorpholinium chloride [TRIAZIMOCH (Tokuyama), 13.0 g, 40.0 mmol] was added to the solution at 0 °C, and the resulting mixture was stirred at room temperature overnight. The mixture was subsequently washed with 0.5 M HCl, saturated aqueous $NaHCO_3$, and saturated aqueous NaCl. It was dried over anhydrous $MgSO_4$ and concentrated on a rotary evaporator. The residue was purified by silica gel column chromatography eluted with *n*-hexane/AcOEt [1/2 (v/v)] to obtain 4′-hydroxy-*N*-α-*tert*-butoxycarbonyl-D-phenylglycine ethylamide as white powder in 73% yield (8.56 g, 29.2 mmol).

4′-Hydroxy-*N*-α-*tert*-butoxycarbonyl-D-phenylglycine ethylamide (5.29 g, 18.0 mmol), $NaIO_4$ (3.85 g, 18.0 mmol), and NaCl (4.21 g, 72.0 mmol) were dissolved in AcOH/H_2O [9/1 (v/v), 60 mL]. The mixture was stirred for 15 min. Then, KI (8.96 g, 54.0 mmol) was added at 0 °C, and the resulting mixture was stirred at room temperature overnight. After H_2O (200 mL) was added, the solution was extracted with $CHCl_3$. The organic layer was washed first with 1 M aqueous $Na_2S_2O_3 \cdot 5H_2O$ and saturated aqueous NaCl, dried over anhydrous $MgSO_4$, and concentrated on a rotary evaporator. The residue was purified by silica gel column chromatography eluted with *n*-hexane/AcOEt [1/2 (v/v)] to obtain **1** as white powder in 72% yield (7.10 g, 13.0 mmol); mp 134−135 °C, $[\alpha]_D = +33°$ ($c = 0.1$ g/dL, $CHCl_3$, room temperature). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.08 (t, $J = 7.2$ Hz, 3H, CH_3), 1.41 [s, 9H, $(CH_3)_3$], 3.14−3.21 (m, 2H, NHC*H*$_2$), 5.03 (s, 1H, NHC*H*COO), 6.48 (s, 1H, OH), 7.76 (s, 2H, Ar), 7.89 (s, 1H, NH), 8.95 (s, 1H, NH). ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.1, 27.9, 33.9, 55.5, 78.9, 84.9, 134.8, 137.5, 154.3, 169.0, 172.5. IR (cm^{-1}, KBr): 3460, 3315, 2976, 1719, 1620, 1542, 1510, 1460, 1365, 1250, 1053, 953, 863, 647. Anal. Calcd for $C_{15}H_{20}I_2N_2O_4$: C, 32.99; H, 3.69; N, 5.13. Found: C, 32.96; H, 3.65; N, 5.17.

Synthesis of 3′,5′-Diiodo-4′-hydroxy-*N*-α-*tert*-butoxycarbonyl-D-phenylglycine Hexylamide (2). The title compound was synthesized by the procedures similar to those of the preparation of **1**. Yield 71% (white solid); mp 119−120 °C, $[\alpha]_D = +43°$ ($c = 0.1$ g/dL, $CHCl_3$, room temperature). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.85 (s, 3H, CH_3), 1.23−1.44 [m, 15H, C*H*$_2$C*H*$_2$C*H*$_2$CH$_3$, $(CH_3)_3$], 1.78 (s, 2H, NHCH$_2$C*H*$_2$), 3.21 (s, 2H, NHC*H*$_2$), 5.08 (s, 1H, NHC*H*COO), 5.95 (s, 2H, NH), 6.21 (s, 1H, OH), 7.76 (s, 2H, Ar). ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.0, 22.5, 26.4, 28.3, 29.3, 31.3, 39.9, 56.2, 80.5, 82.7, 134.5, 137.8, 153.6, 169.4, 172.8. IR (cm^{-1}, KBr): 3462, 3317, 2927, 1718, 1663, 1540, 1499, 1366, 1234, 1051, 913, 867, 692. Anal. Calcd for $C_{19}H_{28}I_2N_2O_4$: C, 37.89; H, 4.69; N, 4.65. Found: C, 37.92; H, 4.70; N, 4.67.

Synthesis of 3′,5′-Diiodo-4′-hydroxy-*N*-α-*tert*-butoxycarbonyl-D-phenylglycine Laurylamide (3). The title compound was synthesized by the procedures similar to those of the preparation of **1**. Yield 75% (white solid); mp 58−59 °C, $[\alpha]_D = +50°$ ($c = 0.1$ g/dL, $CHCl_3$, room temperature). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.88 (s, 3H, CH_3), 1.22−1.44 [m, 29H, (C*H*$_2$)$_{10}$CH$_3$, (C*H*$_3$)$_3$], 3.21 (s, 2H, NHC*H*$_2$), 5.12 (s, 1H, NHC*H*COO), 5.97 (s, 2H, NH), 6.28 (s, 1H, OH), 7.66 (s, 2H, Ar). ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.1, 22.7, 26.8, 29.2, 29.3, 29.4, 29.5, 29.6, 29.7, 29.8, 31.87, 39.9, 56.2, 80.4, 100.5, 134.4, 137.7, 153.5, 169.4, 172.2. IR (cm^{-1}, KBr): 3600, 3311, 2931, 2858, 1721, 1684, 1620, 1574, 1513, 1460, 1395, 1234, 1052, 925, 864, 707, 639. Anal. Calcd for $C_{25}H_{40}I_2N_2O_4$: C, 43.74; H, 5.87; N, 4.08. Found: C, 43.77; H, 5.71; N, 4.11.

Polymerization. All the polymerizations were carried out in a glass tube equipped with a three-way stopcock under nitrogen. A typical experimental procedure for polymerization **1** with *p*-diethynylbenzene (**4**) is given below.

A solution of **1** (546 mg, 1.00 mmol) and **4** (126 mg, 1.00 mmol), $PdCl_2(PPh_3)_2$ (35 mg, 50 μmol), CuI (4.7 mg, 25 μmol), PPh_3 (26.2 mg, 100 μmol), and Et_3N (2.00 mL, 14.3 mmol) in DMF (3.00 mL) was stirred at 80 °C for 24 h. The resulting mixture was poured into MeOH/acetone [4/1 (v/v), 300 mL] to precipitate a polymer. It was separated by filtration using a membrane filter (ADVANTEC H100A047A) and dried under reduced pressure.

Spectroscopic Data of the Polymers. Poly(**1**): ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.01−1.77 [m, 11H, CH$_2$C*H*$_3$, (CH$_3$)$_3$], 3.48 (s, 2H, NHC*H*$_2$), 5.27 (s, 1H, NHC*H*COO), 6.06 (s, 2H, CONH, NHCOO), 7.26−7.70 (m, 6H, Ar). IR (cm^{-1}, KBr): 3412, 3311, 3056, 2976, 2208, 1724, 1671, 1600, 1486, 1435, 1366, 1236, 1161, 1064, 913, 838, 693. Poly(**2**): ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.80 (s, 3H, CH_3), 1.21−1.89 [m, 17H, (C*H*$_2$)$_4$CH$_3$, (CH$_3$)$_3$], 3.24 (s, 2H, NHC*H*$_2$), 5.30 (s, 1H, NHC*H*COO), 6.07 (s, 2H, CONH, NHCOO), 7.27−7.71 (m, 6H, Ar). IR (cm^{-1}, KBr): 3424, 3314, 3050, 2930, 2857, 2212, 1720, 1648, 1619, 1550, 1512, 1395, 1365, 1249, 162, 1053, 925, 864, 642. Poly(**3**): ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.84 (s, 3H, CH_3), 1.19−1.66 [m, 31H, (C*H*$_2$)$_{11}$CH$_3$, (CH$_3$)$_3$], 3.23 (s, 2H, NHC*H*$_2$), 5.14 (s, 1H, NHC*H*COO), 5.99 (s, 2H, CONH, NHCOO), 7.21−7.77 (m, 6H, Ar). IR (cm^{-1}, KBr): 3421, 3328, 3056, 2925, 2853, 2209, 1722, 1663, 1602, 1498, 1436, 1366, 1234, 1163, 1051, 913, 837, 692.

Results and Discussion

Monomer Synthesis and Polymerization. 3′,5′-Diiodo-4′-hydroxy-*N*-α-*tert*-butoxycarbonyl-D-phenylglycine amide monomers **1**−**3** were synthesized by the route illustrated in Scheme 2. First, 4′-hydroxy-*N*-α-*tert*-butoxycarbonyl-D-phenylglycine was condensed with amines using TRIAZIMOCH as a condensation agent to obtain the corresponding 4′-hydroxy-*N*-α-*tert*-butoxycarbonyl-D-phenylglycine amides. Then, the amides were iodinated with potassium iodide, sodium periodate, and sodium chloride to

Scheme 2. Synthesis of Monomers 1−3

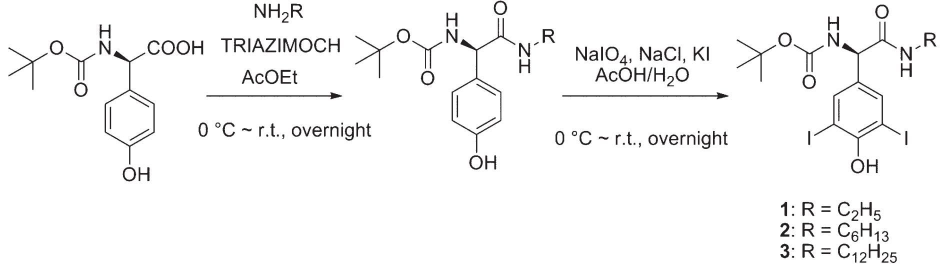


Table 1. Polycondensation of Monomers 1−3 with 4[a]

monomers	yield[b] (%)	M_n[c]	M_w/M_n[c]
1+**4**	79	6100	1.48
2+**4**	82	6600	1.63
3+**4**	81	7300	1.51

[a] Conditions: $[\mathbf{1}]_0=[\mathbf{2}]_0=[\mathbf{3}]_0=[\mathbf{4}]_0=0.2$ M, $[PdCl_2(PPh_3)_2]=0.01$ M, $[CuI]=0.005$ M, $[PPh_3]=0.02$ M, $Et_3N/DMF=2/3$ (v/v), 80 °C, 24 h. [b] MeOH/acetone = 4/1 (v/v)-insoluble part. [c] Determined by GPC eluted with THF calibrated by polystyrene standards.

Table 2. Specific Rotations of the Monomers and Polymers Measured in Various Solvents[a]

	$[\alpha]_D$			
compound	$CHCl_3$	THF	CH_2Cl_2	DMF
1	+33	+31	—[b]	—[b]
poly(**1**)	+113	+137	+284	−20
2	+43	+40	—[b]	—[b]
poly(**2**)	+377	+396	+523	+37
3	+50	+45	—[b]	—[b]
poly(**3**)	+174	+202	+332	+34

[a] Measured at room temperature (c = 0.10−0.11 g/dL). [b] Not determined.

afford 3′,5′-diiodo-4′-hydroxy-*N*-α-*tert*-butoxycarbonyl-D-phenylglycine amides **1**−**3**. All the monomers were obtained as white powders and characterized by ^1H, ^{13}C NMR, and IR spectroscopies besides elemental analysis.

The Sonogashira−Hagihara polycondensation of **1**−**3** with **4** was carried out in DMF at 80 °C for 24 h. The corresponding polymers [poly(**1**)−poly(**3**)] with M_n's ranging from 6100 to 7300 were obtained in 79−82% yields as listed in Table 1. The structures of the polymers were characterized spectroscopically. The ^1H NMR and IR spectra of the polymers exhibited signals reasonably assignable to the *m*-phenyleneethynylene-*p*-phenyleneethynylene structures illustrated in Scheme 1. All the polymers were soluble in CH_2Cl_2, $CHCl_3$, THF, DMF, and DMSO, while insoluble in hexane and MeOH.

Chiroptical Properties of Poly(1)−Poly(3). A specific rotation of a polymer larger than that of the corresponding monomer is commonly accepted as evidence of the presence of a chiral higher order structure such as helix. As listed in Table 2, poly(**1**)−poly(**3**) showed plus-signed specific rotations with 3.4−9.9-fold larger than those of the monomers in $CHCl_3$, THF, and CH_2Cl_2. This result suggests that poly(**1**)−poly(**3**) fold into a helical conformation with predominantly one-handed screw sense in these solvents. It is noteworthy that the magnitudes of the specific rotations varied with solvent, while the sign was plus in every case. Poly(**1**)−poly(**3**) kept the predominant helical sense unaltered in the solvents.

We next measured the CD and UV−vis spectra of poly(**1**)−poly(**3**) in $CHCl_3$ at room temperature. All the polymers exhibited strong plus and minus Cotton effects around 375 and 325 nm, respectively, as shown in Figure 1. They absorbed light around 350 nm, and the relative intensity of the UV−vis absorption peaks agreed with that of the CD signals. These CD signals and UV−vis absorption peaks definitely come from the conjugated phenyleneethynylene backbone because the λ_{max}'s of the monomers locate at shorter wavelength regions (**1**: 237; **2**: 238; **3**: 238; **4**: 276 nm) than those of the polymers. Thus, it is concluded that the polymers possess a helical conformation with an excess of one-handedness in the solvent. The order of ellipticities was poly(**2**) > poly(**3**) > poly(**1**), which agreed with that of specific rotations, but did not correlate with the alkyl chain length in the amino acid units. We also measured the CD spectra of poly(**1**)−poly(**3**) in DMF at room temperature to observe negligibly weak CD signals as predicted from the small specific rotation listed in Table 2. The polymers showed a UV−vis absorption peak with a molar absorptivity and a wavelength almost the same in DMF and $CHCl_3$. [The CD and UV−vis spectra of poly(**2**) are depicted in Supporting Information as representatives.] It seems that the polymers exist in a helical conformation with equal population of left- and right-handed screw senses. We further measured the fluorescence spectra of poly(**1**)−poly(**3**) to find that they emitted almost no fluorescence.

We further measured the CD and UV−vis spectra of poly(**1**)−poly(**3**) films fabricated from a THF solution (4 wt %) on a quartz glass plate by spin-coating. As depicted in Figure 2, all the samples showed a clear CD signal around 400 nm based on the conjugated main chain. It is assumed that the polymers also form a chiral higher order structure in film state. Since the CD and UV maxima appeared at regions longer than those of solution state, the conjugation seems to become long in film state compared with solution state presumably in a manner similar to poly(thiophene)s[10a] and poly(*p*-phenylene)s.[10b] The shift of the absorption peak to a longer wavelength in the film means the presence of an intermolecular electronic interaction between the polymer molecules and/or higher planarity of the polymer.

Confirmation of Intramolecular Hydrogen Bonding. As described in the Introduction, poly(**1**)−poly(**3**) possibly form intramolecular hydrogen bonding between the side chains to stabilize the helical structure in a manner similar to polyisocyanides,[11] poly(*N*-propargylamide)s,[12] poly(*N*-propargylcarbamate)s,[13] poly(*N*-butynylamide)s,[14] and poly(phenylacetylene)s.[15] We measured the solution-state IR spectra of the polymers to check the presence of hydrogen bonding (see Supporting Information). As listed in Table 3, poly(**1**)−poly(**3**) exhibited the $\nu_{C=O}$ of amide group at 1660−1666 cm^{-1}, which are 12−17 cm^{-1} lower than those of the corresponding monomers **1**−**3**. Judging from the low compound concentration (c = 40 mM), it is concluded that all the polymers form intramolecular hydrogen bonding between the amide groups at the side chains. On the other hand, it is considered that no hydrogen bonding exists between the

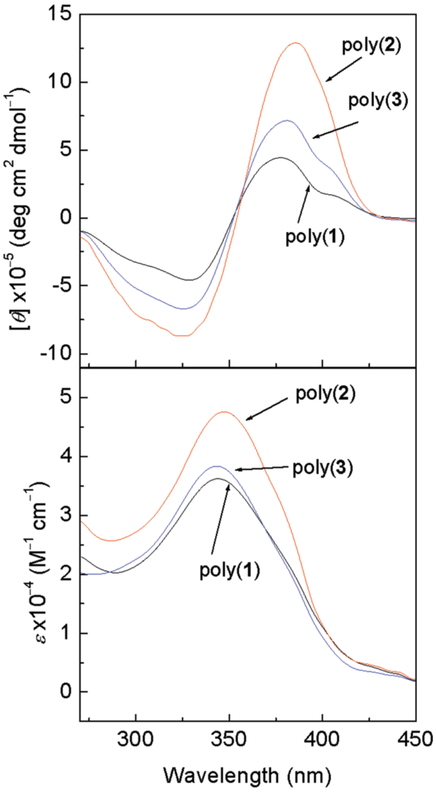


Figure 1. CD and UV−vis spectra of poly(**1**)−poly(**3**) measured in $CHCl_3$ at room temperature ($c = 4.0 \times 10^{-5}$ mol/L).

carbamate groups because the differences of $\nu_{C=O}$ of carbamate groups between the monomers and polymers are negligibly small.

The H−D exchange rates also supported the presence of hydrogen bonding between the amide groups of the polymers. As illustrated in Figure 3, monomer **2** exchanged the N−H protons for deuteriums almost completely for 240 min. On the other hand, poly(**2**) did it apparently slower than **2** at the same concentration. It means that intramolecular hydrogen bonding in poly(**2**) prevents the H−D exchange reaction of N−H protons, which supports the results of solution-state IR spectroscopic measurement. Poly(**2**) exhibited the N−H signal broadly at a position 0.1 ppm lower than **2** did, which also supports the existence of hydrogen bonding in poly(**2**).

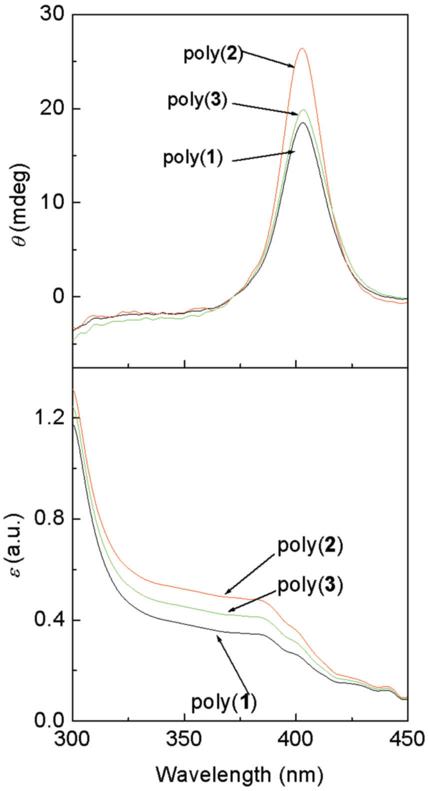


Figure 2. CD and absorption spectra of poly(**1**)−poly(**3**) films measured at room temperature fabricated on a quartz glass plate by spin-coating of a polymer solution in THF (4 wt %).

Table 3. Solution-State IR Spectroscopic Data (Amide and Carbamate C═O Absorption Peaks) of the Monomers and Polymers[a]

	wavenumber (cm^{-1})	
compound	amide C═O	carbamate C═O
1	1678	1702
poly(**1**)	1666	1701
2	1678	1702
poly(**2**)	1665	1700
3	1677	1701
poly(**3**)	1660	1700

[a] Measured in $CHCl_3$ (c = 40 mM).

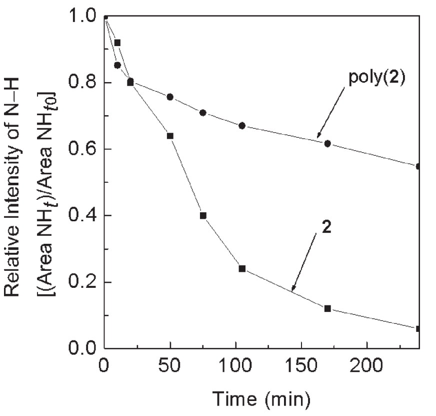


Figure 3. Time dependence of N−H signal intensity of **2** and poly(**2**) of the ^{1}H NMR spectra measured in $CDCl_3/CD_3OD$ [9/1 (v/v)] (c = 200 mM) at room temperature.

Conformational Analysis. We examined the conformation of the polymers based on molecular mechanics method (MMFF94).[16] Several attempts have been made to analyze the conformation of poly(*m*-phenyleneethynylene)s so far. Molecular dynamics simulations have revealed that amine-[17] and ester-functionalized[18] poly(*m*-phenyleneethynylene)s energetically prefer helical conformations to coiled and extended ones in water, wherein surrounding water molecules play an important role to fold the polymer chains. Preference of helical structure is understood because it maximizes the interactions between the polar side chains and solvents, and also π-stacking interaction, and minimizes unfavorable contacts between the hydrocarbon backbone and polar solvents.[19] Judging from the nature of poly(*m*-phenyleneethynylene)s, it is likely that poly(**1**)−poly(**3**) in the present study also take helical structures with stacked phenylene moieties. Figure 4 illustrates a possible conformation of 48-mer of **1**, whose geometries were fully optimized by the molecular mechanics method. The diameter of the pore (distance between inner edge carbon atoms at diagonal positions) is 24.0 Å, which is much larger than that of poly(*m*-phenyleneethynylene)s (12.0−14.4 Å)[18] due to the presence of *p*-phenylene linkages. The helical pitch is 3.8 Å,

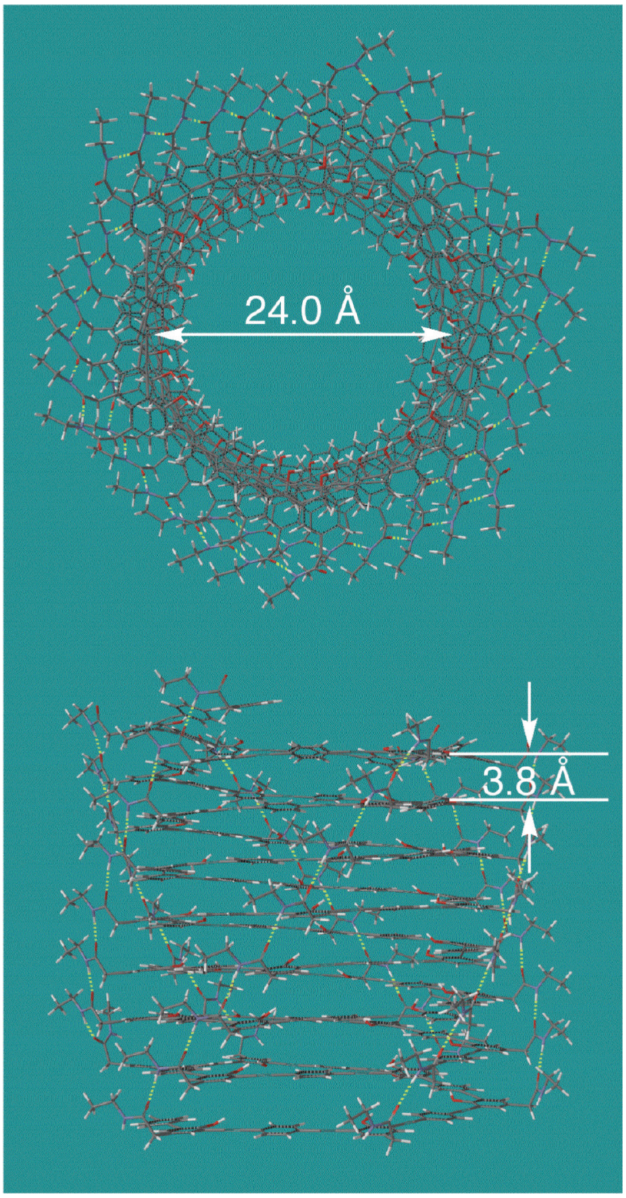


Figure 4. Top and side views of poly(**1**) (48-mer) optimized by MMFF94. $(CH_3)_3COCONH-$ groups were omitted for clarity. The green dotted lines represent hydrogen bonds between the amide groups.

which is consistent with the turns of the helix being near van der Waals contact and comparable to π-stacking between aromatic rings.[18] The distance between amide carbonyl oxygen at *n*th unit and amide hydrogen at (*n* + 6)th unit ($\rangle C{=}O\cdots H{-}N\langle$) is 1.78 Å. Namely, the polymer forms hydrogen bonding between the amide groups at *n*th and (*n* + 6)th monomer units as represented with green dotted lines in Figure 4. Accordingly, it is surrounded by regulated six hydrogen-bonding strands. The hydroxy groups inside of the helix cannot form hydrogen bonding each other because the distance is too long. It is considered that the bisignated CD signals at 375 and 325 nm of the polymers (Figure 1) are caused by exciton chirality based on the cooperative interaction between the main chain chromophore,[20] because the λ_{max} of the UV−vis absorption is positioned at the inflection point of the plus and minus CD signals. Judging from the positive first and negative second Cotton effects together with the molecular modeling, the helical sense is considered to be right-handed as illustrated in Figure 4.

Effects of Temperature and Solvents on the Polymer Conformation. The helical structures of poly(phenyleneethynylene)s are commonly susceptible to temperature.[21] We measured the CD and UV−vis spectra of poly(**1**)−poly(**3**) to find almost no changes at 0−50 °C (see Supporting Information). The helical structures of poly(**1**)−poly(**3**) are thermally stable compared to common poly(phenyleneethynylene)s reported so far. It is likely that intramolecular hydrogen bonds contribute to stabilize the helical structure.

Formation of hydrogen bonding is commonly disturbed by polar solvents. It is therefore considered that the helical structures of poly(**1**)−poly(**3**) are sensitive to H_2O and MeOH. We examined the solvent effect on the helicity of the polymers. Figure 5 depicts the CD and UV−vis spectra of poly(**1**)−poly(**3**) measured in THF/H_2O with various compositions at room temperature. All the polymers decreased the intensity of Cotton effect upon raising H_2O content. The addition of 2 vol % H_2O to THF immediately weakened the CD signals of poly(**1**) around 375 nm to 64% of the original, and further increase of H_2O volume ratio led to continuous decrease of the CD intensity. On the other hand, ε around 350 nm kept 96% intensity of the original even when the H_2O content reached 20 vol %. Poly(**2**) exhibited similar CD and UV−vis spectroscopic changes to those of poly(**1**) upon raising H_2O content. These results indicate that poly(**1**) and poly(**2**) partially transform the helical sense according to the increase of H_2O content, keeping a total helix content almost the same irrespective of THF/H_2O compositions. As described above, hydrogen bonds exist between the amide side chains. H_2O molecules possibly bring about exchange of hydrogen-bonding pairs here and there, leading to decrease of one-handedness of the helix. On the contrary, poly(**3**) largely diminished the intensity of UV−vis absorption simultaneously with decrease of CD. Conjugated helical polymers decrease the ε values because the conjugation length becomes short when the main chains are irregularly twisted.[22] It is therefore considered that poly(**3**) partly transformed the structure from helix into random structure as well as helix inversion. The long alkyl groups of poly(**3**) are presumably aggregated to collapse the helical structure upon raising H_2O content because it is likely that the helical structure with hydrophobic chains spreading outside of the helix is unfavorable when the H_2O content of the media is high. The difference of hydrophobicity of the polymers is also understood from the solubility. Namely, poly(**1**) and poly(**2**) were completely soluble in THF/H_2O = 80/20 (v/v), while poly(**3**) was not.

We have reported that MeOH breaks intramolecular hydrogen bonding formed between amide groups to deform the secondary structure of amino acid-derived polyacetylenes.[9e,9f] Judging from the CD and UV−vis spectroscopic changes in Figure 6, it seems that poly(**1**) and poly(**2**) partially transform the screw sense keeping the helical structure, while poly(**3**) went into a random structure upon raising MeOH content. This tendency is similar to the case of THF/H_2O depicted in Figure 5. It appears that MeOH also interacts with the amide groups by hydrogen bonding. Poly(**1**) did not dissolve in THF/MeOH mixtures when the MeOH content was higher than 20%. The helix cavity is considered to be large enough compared to solvents as shown in Figure 4. It is therefore likely that polar solvents such as MeOH and water go inside of the cavity and interact with the hydroxy groups to affect the helical structure as well.

Responsiveness to Bases. Since the present polymers carry phenol moieties, they possibly interact with bases to change the conformation. We first studied the effect of

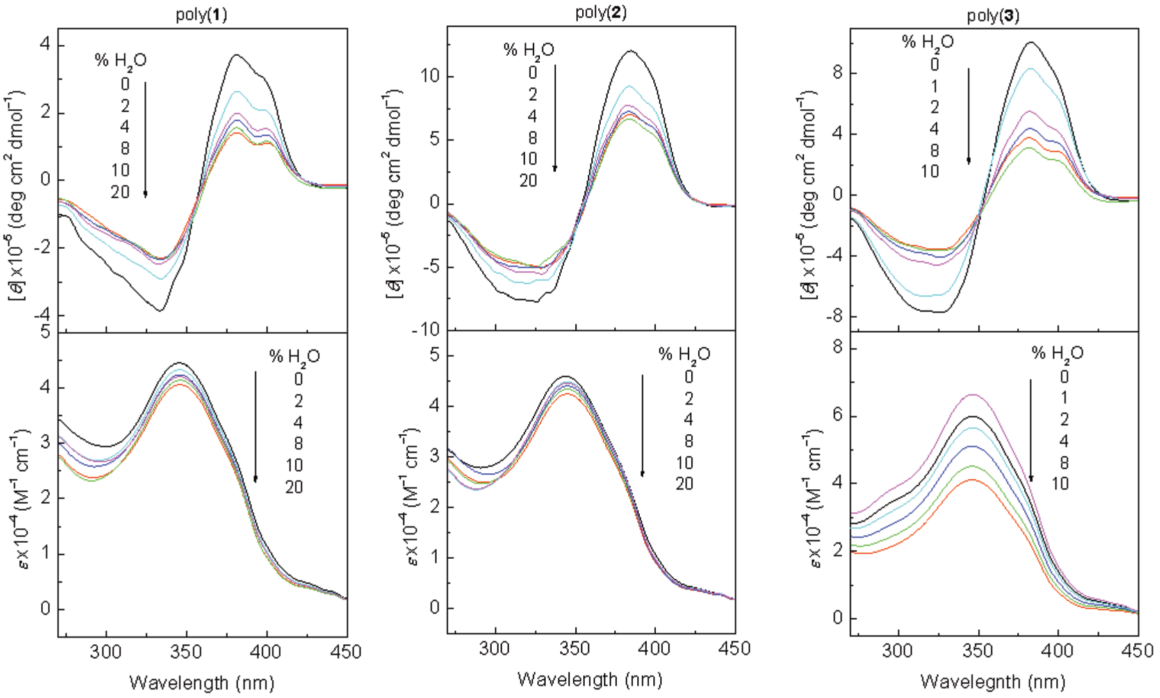


Figure 5. CD and UV−vis spectra of poly(**1**)−poly(**3**) measured in THF/H$_2$O with various compositions (c = 4.0 × 10^{-5} mol/L) at room temperature.

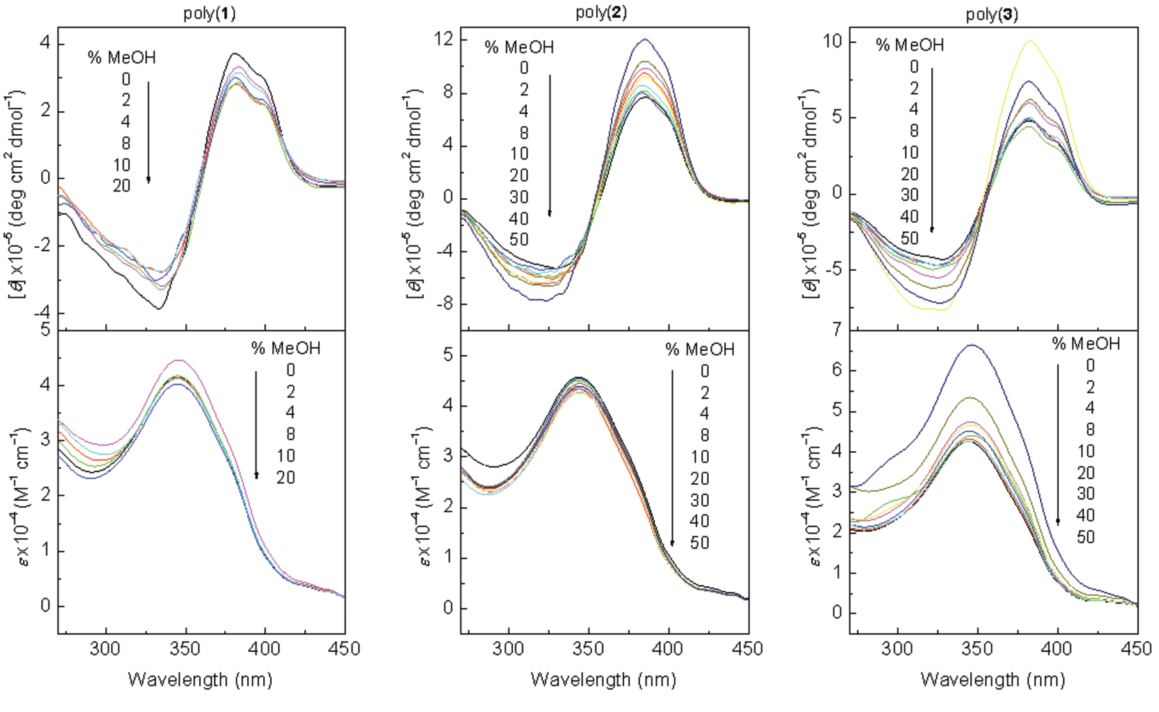


Figure 6. CD and UV−vis spectra of poly(**1**), poly(**2**), and poly(**3**) measured in THF/MeOH with various compositions (c = 4.0 × 10^{-5} mol/L) at room temperature.

NaOH (2.5−500 equiv) on the CD and UV−vis spectra of poly(**1**)−poly(**3**) in THF/H$_2$O = 99/1 (v/v) to find only small spectroscopic changes (see Supporting Information). We also added LiOH and KOH to find slight changes as well (see Supporting Information). Consequently, it is concluded that the polymer conformation is scarcely affected by alkali metal hydroxides under these conditions.

We next examined the effect of addition of alkali metal alkoxides to the polymer solutions in THF/MeOH = 99/1 (v/v). As depicted in Figure 7, the polymers apparently decreased the CD intensity upon addition of 12.5 equiv of CH_3ONa, CH_3CH_2ONa, and $(CH_3)_3COK$. It should be noted that poly(**1**) and poly(**2**) slightly decreased the UV−vis absorption, while poly(**3**) largely decreased the intensity. In a manner similar to H$_2$O and MeOH additions to THF solutions shown in Figures 5 and 6, poly(**1**) and poly(**2**) seem to transform the screw sense almost keeping the total helix content, while poly(**3**) partly transforms into a random structure upon the metal alkoxide addition. The polymer conformation was more susceptible to metal alkoxides than to metal hydroxides. This is explained by the basicity of metal alkoxides stronger than that of metal hydroxides.

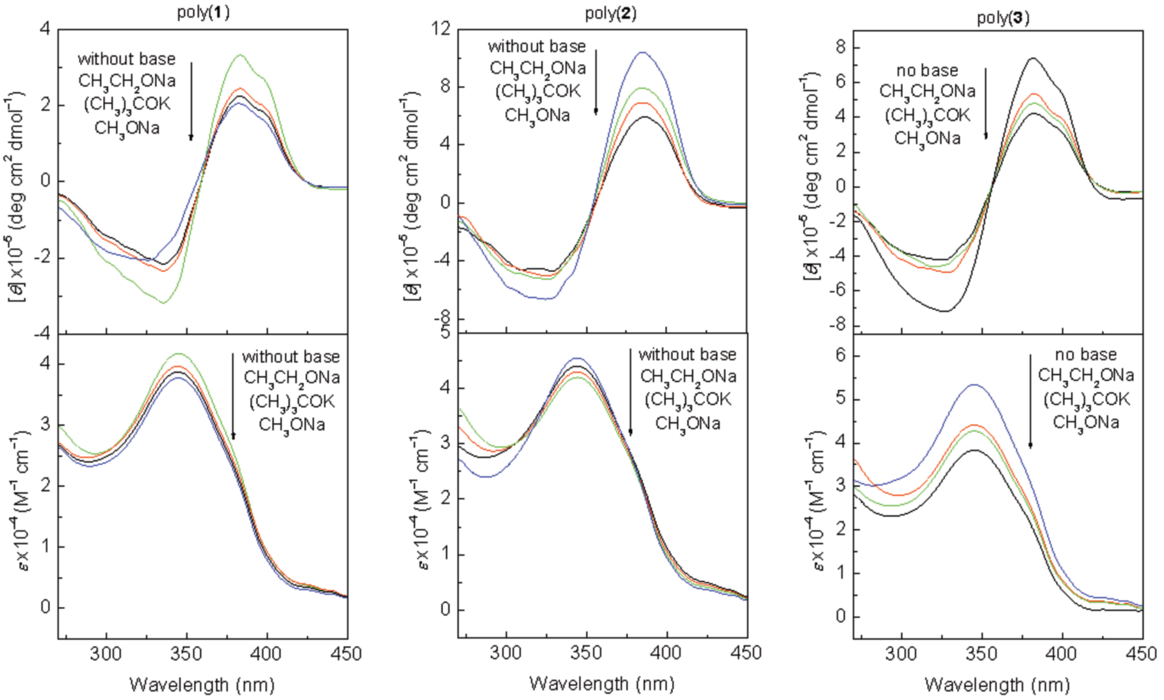


Figure 7. CD and UV−vis spectra of poly(**1**)−poly(**3**) upon addition of CH_3ONa, CH_3CH_2ONa, and $(CH_3)_3COK$ measured in THF/MeOH = 99/1 (v/v, $c = 4.0 \times 10^{-5}$ mol/L, $c_{\text{base}} = 5.0 \times 10^{-4}$ mol/L) at room temperature.

It is also assumed that metal alkoxides are accessible inside of the helical polymers to interact with the phenolic hydroxy groups, while metal hydroxides are not. This difference is understood from the difference of hydrophilicity between hydroxides and alkoxides. The difference of solvent may be another possible reason. Namely, in less polar THF/MeOH, the bases can go inside of the helix compared to the case in more polar THF/H_2O. The order of decrease of CD intensity was $CH_3ONa > (CH_3)_3COK > CH_3CH_2ONa$ in all cases, presumably depending on the size of alkoxide together with basicity and hydrophilicity.

Conclusions

In this article, we have demonstrated the synthesis of novel hydroxyphenylglycine-based poly(*m*-phenyleneethynylene-*p*-phenyleneethynylene)s [poly(**1**)−poly(**3**)] and elucidated the secondary structure. All the polymers formed thermally stable helical structures with predominantly one-handed screw sense, which was confirmed by specific rotation, CD, and UV−vis spectroscopic measurements. Unlike the amphiphilic helical polyphenyleneethynylenes cited in the Introduction, the present polymers formed a helix with hydrophobic exterior (alkyl group) and hydrophilic interior (phenol group) in nonpolar solvents. Solution-state IR spectroscopic and molecular modeling studies suggested that intramolecular hydrogen bonding was regularly formed between the amide groups at *n*th and ($n + 6$)th units at the side chains of the polymers to stabilize the helical conformation. Poly(**1**) and poly(**2**) mainly transformed the screw sense in THF by the addition of H_2O and MeOH, while poly(**3**) transformed the structure from helix into random coil. Poly(**1**)−poly(**3**) decreased one-handed helicity upon base addition. The addition of metal alkoxides gave results similar to the cases of H_2O and MeOH.

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Supporting Information Available: CD and UV−vis spectra of poly(**2**) measured in $CHCl_3$ and DMF (Figure S1), solution-state IR spectra of **2** and poly(**2**) measured in $CHCl_3$ (Figure S2), temperature-variable CD and UV−vis spectra of poly(**1**)−poly(**3**) (Figure S3), CD and UV−vis spectra of poly(**1**)−poly(**3**) upon addition of NaOH (Figure S4), and CD and UV−vis spectra of poly(**1**)−poly(**3**) upon addition of NaOH, KOH, and LiOH (Figure S5). This material is available free of charge via the Internet at http://pubs.acs.org.

References and Notes

(1) (a) Pu, L. *Chem. Rev.* **1998**, *98*, 2405. (b) McQuade, D. T.; Pullen, A. E.; Swager, T. M. *Chem. Rev.* **2001**, *101*, 2537. (c) Nakano, T.; Okamoto, Y. *Chem. Rev.* **2001**, *101*, 4013.

(2) For reviews: (a) Lam, J. W. Y.; Tang, B. Z. *Acc. Chem. Res.* **2005**, *38*, 745. (b) Masuda, T. *J. Polym. Sci., Part A: Polym. Chem.* **2007**, *45*, 165. (c) Yashima, E.; Maeda, K.; Furusho, Y. *Acc. Chem. Res.* **2008**, *41*, 1166. (d) Yashima, E.; Maeda, K. *Macromolecules* **2008**, *41*, 3.

(3) (a) Peeters, E.; Delmotte, A.; Janssen, R. A. J.; Meijer, E. W. *Adv. Mater.* **1997**, *9*, 493. (b) Langeveld-Voss, B. M. W.; Janssen, R. A. J.; Christiaans, M. P. T.; Meskers, S. C. J.; Dekkers, H. P. J. M.; Meijer, E. W. *J. Am. Chem. Soc.* **1996**, *118*, 4908. (c) Geng, Y.; Trajkovska, A.; Katsis, D.; Ou, J. J.; Culligan, S. W.; Chen, S. H. *J. Am. Chem. Soc.* **2002**, *124*, 8337. (d) Dubus, S.; Marceau, V.; Leclerc, M. *Macromolecules* **2002**, *35*, 9296.

(4) (a) Gin, M. S.; Yokozawa, T.; Prince, R. B.; Moore, J. S. *J. Am. Chem. Soc.* **1999**, *121*, 2643. (b) Prince, R. B.; Barnes, S. A.; Moore, J. S. *J. Am. Chem. Soc.* **2000**, *122*, 2758. (c) Tanatani, A.; Mio, M. J.; Moore, J. S. *J. Am. Chem. Soc.* **2001**, *123*, 1792. (d) Heemstra, J. M.; Moore, J. S. *J. Am. Chem. Soc.* **2004**, *126*, 1648.

(5) Arnt, L.; Tew, G. N. *Macromolecules* **2004**, *37*, 1283.

(6) Abe, H.; Masuda, N.; Waki, M.; Inouye, M. *J. Am. Chem. Soc.* **2005**, *127*, 16189.

(7) (a) Tan, C.; Pinto, M. R.; Kose, M. E.; Ghiviriga, I.; Schanze, K. S. *Adv. Mater.* **2004**, *16*, 1208. (b) Zhao, X. Y.; Schanze, K. S. *Langmuir* **2006**, *22*, 4856.

(8) (a) Li, B. S.; Cheuk, K. K. L.; Ling, L.; Chen, J.; Xiao, X.; Bai, C.; Tang, B. Z. *Macromolecules* **2003**, *36*, 77. (b) Cheuk, K. K. L.;

Lam, J. W. Y.; Chen, J.; Lai, L. M.; Tang, B. Z. *Macromolecules* **2003**, *36*, 5947. (c) Cheuk, K. K. L.; Lam, J. W. Y.; Lai, L. M.; Dong, Y. P.; Tang, B. Z. *Macromolecules* **2003**, *36*, 9752.

(9) (a) Gao, G.; Sanda, F.; Masuda, T. *Macromolecules* **2003**, *36*, 3932. (b) Gao, G.; Sanda, F.; Masuda, T. *Macromolecules* **2003**, *36*, 3938. (c) Sanda, F.; Araki, H.; Masuda, T. *Macromolecules* **2004**, *37*, 8510. (d) Sanda, F.; Terada, K.; Masuda, T. *Macromolecules* **2005**, *38*, 8149. (e) Zhao, H.; Sanda, F.; Masuda, T. *J. Polym. Sci., Part A: Polym. Chem.* **2005**, *43*, 5168. (f) Zhao, H.; Sanda, F.; Masuda, T. *Macromol. Chem. Phys.* **2005**, *16*, 1653.

(10) (a) Yamamoto, T.; Kokubo, H. *J. Polym. Sci., Part B: Polym. Phys.* **2000**, *38*, 84. (b) Yamamoto, T.; Iijima, T.; Ozawa, Y.; Toriumi, K.; Kubota, K.; Sasaki, S. *J. Polym. Sci., Part A* **2007**, *45*, 548.

(11) (a) Kamer, P. C.; Nolte, R. J. M.; Drenth, W. *J. Am. Chem. Soc.* **1988**, *110*, 6828. (b) Deming, T. J.; Novak, B. M. *J. Am. Chem. Soc.* **1992**, *114*, 7926. (c) Cornelissen, J. J. L. M.; Donners, J. J. J. M.; René de Gelder; Graswinckel, W. S.; Metselaar, G. A.; Rowan, A. E.; Sommerdijk, N. A. J. M.; Nolte, R. J. M. *Science* **2001**, *239*, 676.

(12) (a) Nomura, R.; Tabei, J.; Nishiura, S.; Masuda, T. *Macromolecules* **2003**, *36*, 561. (b) Nomura, R.; Yamada, K.; Tabei, J.; Takakura, Y.; Takigawa, T.; Masuda, T. *Macromolecules* **2003**, *36*, 6939. (c) Tabei, J.; Nomura, R.; Sanda, F.; Masuda, T. *Macromolecules* **2003**, *36*, 8603.

(13) (a) Nomura, R.; Nishiura, S.; Tabei, J.; Sanda, F.; Masuda, T. *Macromolecules* **2003**, *36*, 5076. (b) Sanda, F.; Nishiura, S.; Shiotsuki, M.; Masuda, T. *Macromolecules* **2005**, *38*, 3075.

(14) (a) Nomura, R.; Tabei, J.; Masuda, T. *Macromolecules* **2002**, *35*, 2955. (b) Tabei, J.; Shiotsuki, M.; Sanda, F.; Masuda, T. *Macromolecules* **2005**, *38*, 5860.

(15) (a) Li, B. S.; Cheuk, K. K. L.; Yang, D.; Lam, J. W. Y.; Wan, L. J.; Bai, C.; Tang, B. Z. *Macromolecules* **2003**, *36*, 5447. (b) Li, B. S.; Kang, S. Z.; Cheuk, K. K. L.; Wan, L.; Ling, L.; Bai, C.; Tang, B. Z. *Langmuir* **2004**, *20*, 7598. (c) Okoshi, K.; Sakajiri, K.; Kumaki, J.; Yashima, E. *Macromolecules* **2005**, *38*, 4061. (d) Okoshi, K.; Sakurai, S.; Ohsawa, S.; Yashima, E. *Angew. Chem., Int. Ed.* **2006**, *45*, 8173.

(16) Halgren, T. A. *J. Comput. Chem.* **1996**, *17*, 490. The molecular mechanics calculation was carried out with Wavefunction Inc., Spartan '08 Macintosh.

(17) (a) Adisa, B.; Bruce, D. A. *J. Phys. Chem. B* **2005**, *109*, 7548. (b) Adisa, B.; Bruce, D. A. *J. Phys. Chem. B* **2005**, *109*, 19952.

(18) Lee, O. S.; Saven, J. G. *J. Phys. Chem. B* **2004**, *108*, 11988.

(19) Hill, D. J.; Mio, M. J.; Prince, R. B.; Hughes, T. S.; Moore, J. S. *Chem. Rev.* **2001**, *101*, 3893.

(20) *Circular Dichroism: Principles and Applications*, 2nd ed.; Beroya, N., Nakanishi, K., Woody, R. W., Eds.; Wiley-VCH: New York, 2000; Chapter 12.

(21) (a) Prince, R. B.; Saven, J. G.; Wolynes, P. G.; Moore, J. S. *J. Am. Chem. Soc.* **1999**, *121*, 3114. (b) Prince, R. B.; Brunsveld, L.; Meijer, E. W.; Moore, J. S. *Angew. Chem., Int. Ed.* **2000**, *39*, 228.

(22) (a) Nomura, R.; Tabei, J.; Masuda, T. *J. Am. Chem. Soc.* **2001**, *123*, 8430. (b) Deng, J.; Tabie, J.; Shiotsuki, M.; Sanda, F.; Masuda, T. *Macromolecules* **2004**, *37*, 1891. (c) Tabei, J.; Nomura, R.; Sanda, F.; Masuda, T. *Macromolecules* **2004**, *37*, 5149.