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Selective and Sensitive Fluorescent Sensors for Metal Ions Based on Manipulation of Side-Chain Compositions of Poly(*p*-phenyleneethynylene)s

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The syntheses and metal-responsive properties of poly-(*p*-phenyleenethynylene)s with grafted new pseudo-crownether groups are reported. These polymers exhibit high sensitivities to alkali ions because of their collective optical properties, which are very sensitive to ion-induced conformational changes. The quenching of polymer fluorescence caused by the conformational changes is proportional to the ion concentration. The selectivity of the sensing materials toward Li⁺ ions is significantly enhanced by controlling the size of the binding site via manipulation of the polymer side-chain compositions. The polymers are very stable for their six-month solid-state storage at room temperature.

Conjugated polymers have received considerable attention as sensing materials because of their high sensitivities to analytes. Their high sensitivities over devices using small molecules arise from collective optical and conducting properties of the conjugated polymers, which are extremely sensitive to minor external structural perturbations or to electron density changes within the polymer backbone in the presence of analytes.^{1–3} A variety of conjugated polymers containing molecular recognition sites have been reported as sensing materials for metal ions. One sensing mechanism is based upon ion-induced conductivity changes, arising from a decrease of charge carrier mobility or a change in the polymer conjugation, that are measured via current or potential changes by using cyclic voltammetry. These electrochemical

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sensing polymers include crown ether-substituted polypyrroles⁴ and polythiophenes,⁵ ethylene ether-substituted polythiophenes,⁶ macrocyclic ether-substituted polythiophene,⁷ and calix[4]arenebased polythiophenes.⁸ Another sensing mechanism is based upon electron density changes of polymer backbone in the presence of metal ions, which triggers changes of UV or fluorescence intensity of the polymers. These fluorescent sensing polymers include 2,2'-bipyridyl-phenylene-vinylene-based polymers⁹ and terpyridine-based poly(*p*-phenyleneethynylene)-*alt*-(thienyleneethynylene) polymers.¹⁰ The selectivities of the sensing polymers are completely dependent upon the intrinsic binding properties of recognition sites, which often lack selectivities and can respond to different metal ions.

With this limitation in mind, we report a novel approach to enhance the selectivity of the sensing polymers by manipulating side-chain compositions of poly(*p*-phenyleneethynylene)s. This approach is illustrated in Chart 1. We introduce a new pseudocrown-ether to poly(p-phenyleneethynylene)s as polymer side chains, which would undergo conformational changes upon incorporating metal ions, resulting in attenuation of fluorescence intensity. When phenyl groups in a polymer backbone that are adjacent to those with the binding sites do not have any side chains, polymer 1 lacks selectivity and can respond to alkali metal ions such as lithium and sodium ions. However, when the adjacent phenyl groups contain ethylene oxide side chains, polymer 2 displays a significantly enhanced selectivity and only responds to lithium ions. In contrast, control polymers 3 and 4 with alkyl side chains, instead of ethylene oxide side chains, display no response to any metal ions because of lack of binding sites for metal ions.

- (6) McCullough, R. D.; Williams, S. P. Chem. Mater. 1995, 7, 2001-2003.
- (7) Marsella, M. J.; Swager, T. M. J. Am. Chem. Soc. 1993, 115, 12214–12215.
 (8) Marsella, M. J.; Newland, R. J.; Carroll, P. J.; Swager, T. M. J. Am. Chem.
- Soc. 1995, 117, 9842–9848.
- (9) Wang, B.; Wasielewski, M. R. J. Am. Chem. Soc. 1997, 119, 12–21.
- (10) Zhang, Y.; Murphy, C. B.; Jones, W. E., Jr. *Macromolecules* **2002**, *35*, 630–636.

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 ⁽a) McQuade, D. T.; Pullen, A. E.; Swager, T. M. Chem. Rev. 2000, 100, 2537–2574.
 (b) Swager, T. M. Acc. Chem. Res. 1998, 31, 201–207.
 (c) Bunz, U. H. F. Chem. Rev. 2000, 100, 1605–644.

^{(2) (}a) Yang, J. S.; Swager, T. M. J. Am. Chem. Soc. 1998, 120, 11864–11873.
(b) Gaylord, B. S.; Heeger, A. J.; Bazan, G. C. J. Am. Chem. Soc. 2003, 125, 896–900. (c) Jones, R. M.; Bergstedt, T. S.; McBranch, D. W.; Whitten, D. G. J. Am. Chem. Soc. 2001, 123, 6726–6727.

 ^{(3) (}a) Ho, H. A.; Leclerc, M. J. Am. Chem. Soc. 2003, 125, 4412–4413. (b) DiCesare, N.; Pinto, M. R.; Schanze, K. S.; Lakowicz, J. R. Langmuir 2002, 18, 7785–7787.

⁽⁴⁾ Bartlett, P. N.; Benniston, A. C.; Chung, L.-Y.; Dawson, D. H.; Moore, P. Electrochim. Acta 1991, 36, 1377–1379.

^{(5) (}a) Bauerle, P.; Scheib, S. Adv. Mater. **1993**, *5*, 848–853. (b) Scheib, S.; Bäuerle, P. J. Mater. Chem. **1999**, *9*, 2139–2150.



EXPERIMENTAL SECTION

Instrumentation. ¹H NMR and ¹³C NMR spectra were taken on a 400-MHz Varian Unity Inova spectrophotometer in the indicated solvents at the indicated fields. UV spectra were taken on a Hewlett-Packard 8452A diode array UV-visible spectrophotometer. Fluorescence spectra were obtained on a steady-state 1681 Spex Fluorolog fluorometer at room temperature. Fluorescence measurements were performed in 3.3 \times 10⁻⁸ and 5.2 \times 10⁻⁸ M chloroform solutions for polymers 1 and 2, respectively. The polymer chloroform solutions with different metal ion concentrations were prepared for fluorescent measurements of the metal ions. Molecular weights of the polymers were determined by gel permeation chromatography by using a Waters Associates model 6000A liquid chromatograph. Three American Polymer Standards Corp. Ultrastyragel columns in series with porosity indexes of 10³, 10⁴, and 10⁵ Å were used and housed in an oven thermostated at 30 °C. Mobile phase was HPLC grade THF, which was filtered and degassed by vacuum filtration

through a 0.5- μ m Fluoropore filter prior to use. The polymers were detected by a Waters model 440 ultraviolet absorbance detector at a wavelength of 255 nm and a Waters model 2410 refractive index detector. The polymer solutions were prepared at ~1 mg/mL concentration. Molecular weight was measured relative to polystyrene standards.

Materials. Unless otherwise indicated, all reagents and solvents were obtained from commercial suppliers (Aldrich, Fluka, Acros, Lancaster) and were used without further purification. Airand moisture-sensitive reactions were conducted in oven-dried glassware using standard Schlenk line or drybox techniques under an inert atmosphere of dry argon. 1,4-Diethynylbenzene, 1,4-bis-(dodecyloxy-2,5-diethynyl)benzene, and 1,4-bis((triethylene glycol monomethyl ether)oxy)-2,5-diethynylbenzene were prepared and characterized according to previous procedures.¹¹ Toxic chemicals

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such as oxalyl chloride were handled in a fume hood by wearing gloves.

Compound 6 (Scheme 1). To a dried round-bottomed flask were added 5[4-(4-carboxybutoxy)-2,5-diiodophenoxy]pentanoic acid (2.0 g, 3.56 mmoL), CH₂Cl₂ (60 mL), and oxalyl chloride (6 mL, 69.8 mmoL), and then a catalytic amount of DMF was added. The mixture was stirred at room temperature for 6 h until the solid disappeared. The solvent and excess oxalyl chloride was removed under reduced pressure to give the 5 as a faint yellow solid. Without further purification, 5 was dissolved in the dried CH₂Cl₂ (20 mL) and then added dropwise to the solution of bis-(2-(2-(2-methoxy)ethoxy)ethyl)5-aminoisophthalate (4) (3.54 g, 7.48 mmol) in dried CH₂Cl₂ (20 mL) and pyridine (1.0 mL, 12.4 mmol). The reaction mixture was stirred at room temperature for 8 h. The solvent was removed, and the residue was diluted with ethyl acetate (50 mL), washed with 10% NaHCO₃ (30 mL \times 3) and brine (30 mL \times 3), and dried over anhydrous MgSO₄. The solvent was evaporated, and the crude compound was purified by column chromatography on silica gel with EtOAc/acetone (5: 1, V/V) and then recrystallization from EtOAc/hexane to give the target compound 6 (4.0 g, 76% yield) as a white solid: ¹H NMR (ppm, DMSO-d₆) 10.35 (s, 2H), 8.48 (s, 4H), 8.12 (s, 2H), 7.29 (s, 2H), 4.40 (m, 8H), 3.96 (m, 4H), 3.73 (m, 8H), 3.55 (m, 8H), 3.44-3.50 (m, 16H), 3.33-3.35 (m, 8H), 3.15 (s, 12H), 2.39 (m, 4H), 1.76 (m, 8H). ¹³C NMR (ppm, CDCl₃) 22.40, 28.70, 37.02, 59.18, 64.73, 69.26, 69.94, 70.79, 70.84, 70.94, 72.10, 86.48, 122.84, 124.95, 126.30, 131.34, 138.96, 152.83, 165.60; HRMS, Calcd 1473.3738 for $[M + H]^+$ (C₆₀H₈₇I₂N₂O₂₄). Found 1473.3738.

Compound 8 (Scheme 2). 5-[4-(4-Carboxybutoxy)-2,5-diiodophenoxy]pentanoic acid (5.0 g, 8.90 mmoL) in CH_2Cl_2 (60 mL) was reacted with oxalyl chloride (8 mL, 93.10 mmol) in the presence of a catalytic amount of DMF to prepare 5 according to above procedure. Compound 5 was dissolved in dried CH_2Cl_2 (40 mL) and added dropwise to the mixture of (3,5-bis(dodecyloxy)-





phenyl)methanol, dried THF (30 mL), and pyridine (2.5 mL). The reaction mixture was stirred at 40 °C for 8 h. The solvent was removed, and the residue was diluted with ethyl acetate (50 mL), washed with 10% NaHCO3 (30 mL \times 3) and brine (30 mL \times 3), and dried over anhydrous MgSO₄. The solvent was evaporated, and the crude compound was purified by column chromatography on silica gel with hexanes/EtOAc (10:1, v/v) to give the target compound 8 (9.34 g, 71% yield) as a faint yellow oil: ¹H NMR (ppm, CDCl₃) 7.14 (s, 2H), 6.45 (s, 4H), 6.37 (s, 2H), 5.02 (s, 4H), 4.05 (t, J = 7.0 Hz, 4H), 3.88–3.93 (m, 8H), 2.46 (t, J = 7.0 Hz, 4H), 1.83–1.88 (m, 8H), 1.70–1.77 (m, 8H), 1.52 (m, 8H), 1.38– 1.41 (m, 8H), 1.24–1.28 (m, 56H), 0.86 (t, J = 7.0 Hz, 12H); ¹³C NMR (ppm, CDCl₃) 14.42, 22.01, 22.98, 26.35, 28.90, 29.55, 29.64, 29.70, 29.88, 29.93, 29.96, 32.21, 34.17, 64.87, 66.50, 68.39, 70.03, 86.56, 101.26, 106.69, 123.08, 138.32, 153.12, 160.76, 173.46. HRMS, Calcd 1478.7623 (C78H128I2O10). Found 1478.7622.

Polymer 1. Monomer **6** (1.0 equiv), 1,4-diethynylbenzene (1.1 equiv), and iodobenzene as polymer end groups (0.1 equiv) were polymerized for polymer **1** by using the Sonogashira cross-coupling reaction in the presence of 5% (PPh₃)₄Pd and 5% CuI in DMF and diisopropylamine at 60 °C for 2 days. The iodobenzene (0.3 equiv) was added to the mixture, which reacted for another 3 h. The polymer was precipitated in ethanol, filtered, washed

with acetone, and dried under vacuum at room temperature: ¹H NMR (ppm, DMSO- d_6) 10.38 (s, 2H), 8.50 (s, 4H), 8.14 (s, 2H), 7.55 (d, 4H), 7.19 (s, 2H), 4.39 (m, 8H), 4.10 (m, 4H), 3.70 (m, 8H), 3.54 (m, 8H), 3.45 (m, 16H), 3.33 (m, 8H), 3.15 (s, 12H), 2.39 (m, 4H), 1.85 (m, 8H). Gel permeation chromatography analysis (mobile phase: THF, polystyrene standards) indicates that M_w of the polymer is 75 633, and its polydispersity is 2.56.

Polymer 2. Monomer **6** and 1,4-bis((triethylene glycol monomethyl ether)oxy)-2,5-diethynylbenzene were polymerized in a way similar to that for polymer **1**: ¹H NMR (ppm, DMSO- d_6) 10.35 (s, 2H), 8.48 (s, 4H), 8.15 (s, 2H), 7.11 (s, 4H), 4.41 (m, 8H), 4.17 (m, 8H), 3.73 (m, 12H), 3.55 (m, 12H), 3.47 (m, 24H), 3.35 (m, 12H), 3.17 (s, 18H), 2.45 (m, 4H), 1.83 (m, 8H). M_w of the polymer is 29 447, and its polydispersity is 1.93.

Polymer 3. Monomer **8** and 1,4-diethynylbenzene were polymerized to give polymer **3** in a way similar to that for polymer **1** except using toluene as reaction solvent: ¹H NMR (ppm, CDCl₃) 7.47 (d, J = 6.4 Hz 4H), 6.98 (s, 2H), 6.44 (s, 4H), 6.37 (s, 2H), 5.00 (s, 4H), 4.00 (t, 4H), 3.91–3.86 (m, 8H), 2.49 (t, 4H), 1.91 (m, 8H), 1.74–1.69 (m, 8H), 1.39 (m, 16H), 1.23 (m, 56H), 0.85 (t, J = 7.0 Hz, 12H). M_w of the polymer is 129 945, and its polydispersity is 4.35.

Polymer **4**: Monomer **8** and 1,4-bis-dodecyloxy-2,5-diethynylbenzene were polymerized to give polymer **4** in a similar way for polymer **3**. ¹H NMR (ppm, CDCl₃): 6.96 (s, 4H), 6.42 (s, 4H), 6.36 (s, 2H), 4.97 (s, 4H), 3.97–3.89 (m, 16H), 2.45 (t, 4H), 1.88– 1.73 (m, 20H), 1.45–1.23 (m, 108H), 0.85 (t, 18H). M_w of the polymer is 37,065 and its polydispersity is 2.12.

RESULTS AND DISCUSSION

To allow for the coupling of pseudo-crown-ether groups to the backbone of poly(p-phenyleneethynylene)s, we developed a synthesis strategy based on the use of the intermediate, 5[4-(4chlorocarbonylbutoxy)-2,5-diiodophenoxy]pentanoyl chloride (5). Monomers 6 and 8 were obtained by coupling the intermediate with bis(2-(2-(2-methoxyethoxy)ethoxy)ethyl)5-aminoisophthalate (4) and 3,5-didodecyloxybenzyl alcohol (7) in THF solution in the presence of pyridine, respectively. Poly(p-phenyleneethynylene)s are typically synthesized by a cross-coupling polymerization under Sonogashira conditions of a diiodoaryl monomer with a diethynyl monomer. Polymer 1 synthesized by cross-coupling of 1,4diethynylbenzene and monomer 6 has a high molecular weight of 75 633 and is readily soluble in common organic solvents such as CH₂Cl₂, CHCl₃, THF, DMF, DMSO, and toluene. Polymer 2, synthesized by cross-coupling of 1,4-bis((triethylene glycol monomethyl ether)oxy)-2,5-diethynylbenzene and monomer 6, has a little lower molecular weight of 29 447 compared with polymer 1 because steric hindrance from the (triethylene glycol monomethy ether)oxy groups slows down the polymerization. Polymer 2 is also readily soluble in common organic solvents such as CH2Cl2, CHCl₃, THF, DMF, DMSO, and toluene, but insoluble in ethanol, acetone, and water. For comparison purposes, polymers 3 and 4 were synthesized from monomer 8 with 1,4-diethynylbenzene and 1,4-bis(dodecyloxy-2,5-diethynyl)benzene, respectively, by using the same conditions for polymer 1 except using toluene as the reaction solvent. Similar steric hindrance from dodecyloxy groups leads to a little lower molecular weight for polymer 4 (M_w 37 065) in comparison with polymer **3** (M_w 129 945). Polymers **3** and **4** are readily soluble in common solvents such as CH₂Cl₂, CHCl₃,



Figure 1. Fluorescence spectra of 3.3×10^{-8} M polymer 1 in chloroform solutions with different metal ions at an excitation wavelength of 405 nm.

THF, and toluene, but insoluble in acetone, ethanol, DMF, DMSO, and water. The UV-visible absorption and fluorescence spectra of the polymers were recorded in their dilute CHCl₃ solution at room temperature. Polymer 1 displays absorption maximum at 422 nm and emission maximum at 448 nm, which were ascribed to the $\pi - \pi$ transition of the conjugated polymer backbone. Polymer 2 exhibits absorption maximum at 442 nm, emission maximum at 472 nm, significant red shifts in its absorption and emission compared with that of polymer 1. These red shifts are due to an electron-donating effect from the dialkoxy groups. Control polymer **3** exhibits maximum absorption and emission at 414 and 445 nm, and polymer 4 shows maximum absorption and emission at 438 and 473 nm, respectively. These red shifts in absorption and emission spectra of the polymer 4 also result from the electron-donating effect of the dialkoxy groups compared with the polymer **3**. All fluorescence spectra were obtained by using excitation wavelengths at 405 and 420 nm for polymers 1 (see Figure 1) and 2, respectively. Use of shorter excitation wavelengths does not shift the maximum emission wavelength of the polymers but decreases their fluorescence intensity. All polymers obey Beer-Lambert's law in their dilute chloroform solutions. The molar absorption coefficients of the polymers 1 and 2 are 2.99 \times 10^6 and 2.17×10^6 L mol⁻¹ cm⁻¹, and those of polymers **3** and **4** are 8.69 \times 10⁶ and 2.34 \times 10⁶ L mol⁻¹ cm⁻¹, respectively. The higher molecular weight polymer exhibits the larger molar absorption coefficients because of the more enhanced conjugation with the higher molecular weight.

Ion-responsive properties of the polymers 1 and 2 were evaluated by their emission spectra. Some representative results for the polymer 1 are shown in Figure 1. It is apparent that addition of metal ions causes quenching of the polymer 1 fluorescence, which presumably comes from conformational changes of the polymer backbone when the binding sites incorporate metal ions. Control experiments using polymers 3 and 4 (lacking metal-binding sites) in lieu of polymers 1 and 2 exhibit no quenching of polymer fluorescence for all metal ions tested. This finding confirms that the pseudo-crown-ether side chains are vital for ion recognition in the polymers 1 and 2.

There is a slight decrease in UV–visible spectra of the polymer upon addition of $LiPF_6$ or $NaPF_6$ to the polymer **1** chloroform solution. The UV–visible spectra of the polymer remain essentially



Figure 2. Changes in the emission intensity of 3.3×10^{-8} M polymer 1 in chloroform solutions as a function of added different metal ions at an excitation wavelength of 405 nm.

identical upon addition of KPF₆ to the polymer 1 chloroform solution. The UV-visible spectra are significantly less responsive to the polymer conformational change caused by the polymer binding with the metal ions. However, addition of 10 mM Li⁺ or Na⁺ ions to the polymer **1** solution causes significant attenuation of the polymer fluorescence intensity (Figure 1). Polymer 1 has larger responses to Li⁺ and Na⁺ ions, which reflects a better size match with the binding sites. It displays the least sensitivity to K⁺ ions because of its larger size. Moreover, polymer 1 also exhibits linear responses to Li⁺ or Na⁺ ions (Figure 2). The detection limits for Li^+ and Na^+ ions are 4.0 \times 10^{-5} and 6.0 \times 10^{-5} M, respectively. Nevertheless, it is apparent that polymer **1** lacks adequate selectivity and responds to different metal ions because of the relative flexibility of its binding size. As a result, it is difficult to calibrate the response of polymer 1 to Li⁺ ions in the presence of different metal ions such as Na⁺ ions. With this limitation in mind, we present a novel approach and demonstrate the feasibility to control the binding size and enhance selectivity toward metal ions by manipulating polymer side-chain compositions. Polymer 2 was prepared by introducing ethylene oxide side chains to phenylene groups in the polymer backbone, adjacent to those with the binding sites. Addition of LiPF₆ to the polymer 2 chloroform solution causes a slight decrease in UV-visible spectra of the polymer while the UV-visible spectra of the polymer remain essentially identical upon addition of NaPF₆ or KPF₆ to the polymer **2** chloroform solution. However, addition of Li⁺ ions to the polymer solution significantly reduces the polymer fluorescence intensity (Figure 3). Polymer 2 displays a significantly reduced response to Na⁺ ions, compared with polymer 1 while retaining its high sensitivity to Li⁺ ions (Figure 3). This enhanced selectivity of polymer 2 occurs because the ethylene oxide side chains limit the expansion of the binding size, which is a best size match for Li⁺ ions. Moreover, the enhanced selectivity does not affect linear response of polymer 2 to Li⁺ ions (Figure 4). The tolerance level for selective determination of Li⁺ ions at its detection limit of 4.0 \times $10^{-5}~M$ in the mixture of alkali ions is that the concentration of Na⁺ ions is less than 0.5 mM. This tolerance level is completely dependent on Li⁺ ion concentration. The level increases with an increase of Li⁺ ion concentration.



Figure 3. Fluorescence spectra of 5.2×10^{-8} M polymer 2 in chloroform solutions with different metal ions at an excitation wavelength of 420 nm.



Figure 4. Changes in the emission intensity of 5.2×10^{-8} M polymer **2** in chloroform solutions as a function of added different metal ions at an excitation wavelength of 420 nm.

To test ion binding reversibility of polymers **1** and **2**, we recycled the polymers by washing the polymer chloroform solutions containing metal ions with distilled water (100 mL \times 10), removing the solvent, washing the polymers with ethanol and acetone completely, and drying them under vacuum at room temperature. The recycled polymer **1** or **2** in chloroform solution shows similar responses to the metal ions, which indicates that the bindings of the polymers with the metal ions are somewhat reversible. This good feature allows for potential preparation of reusable fiber-optic sensors for metal ions by immobilizing the polymers on optic fibers, whose binding ions could be washed away with water.

Polymers 1 and 2 are very stable during solid storage since they display almost the same responses to the metal ions after six-month storage at room temperature. Polymers 1 and 2 exhibit almost the same responses to Li^+ or Na^+ ions when they were stored in chloroform solution for two months.

We have designed and synthesized poly(*p*-phenyleneethynylene)s with a new pseudo-crown-ether as a binding site for alkali ions. The sensitivity of these polymers results from ion recognition-induced conformational changes on the polymer backbones, which lead to quenching of polymer fluorescence. The selectivity of the sensing material to Li^+ ions is significantly enhanced by controlling polymer side-chain compositions to manipulate the size of binding site.

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SUPPORTING INFORMATION AVAILABLE

Preparation of starting materials and UV–visible and fluorescence spectra of 1-4. This material is available free of charge via the Internet at http://pubs.acs.org.

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