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Self-Oscillation of Polymer Chains with Rhythmical Soluble-Insoluble Changes

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Abstract: Self-oscillation of polymer chains in an aqueous solution has been achieved. The ruthenium catalyst for the Belousov−Zhabotinsky reaction was polymerized by using *N*-isopropylacrylamide and dissolved into the solution containing the BZ substrates. Periodical soluble−insoluble changes of the polymer chain were spontaneously induced by the BZ reaction. The conformational oscillations of the polymer were measured as the optical transmittance changes of the solution. This is the first report that rhythmical and reversible soluble−insoluble changes of polymer chains are realized under constant and homogeneous conditions. The transducing system from chemical energy of the BZ reaction to optical information has been constructed.

Introduction

Phase transition (i.e., coil−globule transition) of polymer chain induced by environmental changes such as pH, temperature, specific molecules, etc. is of interest for understanding the function of biopolymers as well as for designing new functional polymers. When the polymer chains are cross-linked, the conformational changes lead to macroscopic mechanical changes of the polymer network. In the case that the un-cross-linked polymers are dissolved in an aqueous solution, turbidity of the solution varies due to dissolution and precipitation of the polymer. By utilizing such conformational change of the polymer chain, we could construct the material systems capable of transformation or transmission of energy or information. For example, the biomimetic system of energy transformation from the enzymatic reaction to mechanical energy (biochemomechanical system) has been realized by utilizing a cross-linked polymer gel with immobilized enzymes.[1] Also, several kinds of bioconjugates, in which stimuli-responsive polymers are introduced into proteins, enzymes, antibodies etc., have been prepared to control their solubility or affinity for the purpose of affinity separations, enzyme recovery and recycling, etc.[2,3]

In these systems utilizing stimuli-responsive polymers, the response of the polymer is temporary; that is, the polymer provides only one unique action of either expanding or collapsing toward a stable equilibrium state. Therefore the on−off switching of external stimuli is essential to instigate the action of the polymer. On the other hand, many physiological systems maintain rhythmical oscillations under constant environmental conditions, and act in a dynamic nonequilibrium state, as represented by the autonomic heartbeat, brain waves, and periodic hormone secretion.

We have attempted to construct such a biomimetic energy transformation system generating spontaneous and periodical motion of polymer chains from the chemical energy. As a source of chemical energy, the Belousov−Zhabotinsky (BZ) reaction was used. The BZ reaction is well-known for the oscillating reaction.[4] The overall process is the oxidation of an organic substrate such as malonic acid by an oxidizing agent (bromate) in the presence of metal catalyst under an acidic condition. In the course of the reaction, a cyclic reaction network of intermediates is created, as in the metabolic reaction (e.g., TCA cycle) in living organisms. As a result, the catalyst ion periodically changes between reduced and oxidized states.

In the previous study,[5,6] we prepared the cross-linked polymer network of *N*-isopropylacrylamide (NIPAAm) in which ruthenium(II) tris(2,2′-bipyridine) ($Ru(bpy)_3^{2+}$), a catalyst for the BZ reaction, is covalently bonded to the polymer chain. When the gel is immersed in the aqueous solution containing the BZ substrates except for the catalyst, periodical swelling−deswelling changes of the gel are spontaneously induced by the BZ reaction occurring in the gel. There the catalyst acts as a transducer to convert its periodical redox changes into the mechanical oscillation of the polymer network through the hydrophilic changes of the polymer chains.

Other than the transformation of chemical energy to mechanical energy by using the gel, the transformation to optical information without mechanical changes would be possible by

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using a polymer solution. When the linear poly(NIPAAm-*co*-Ru(bpy)$_3$) chain is dissolved into an aqueous solution of the BZ substrates, soluble−insoluble oscillations of the polymer chain may occur accompanying the periodical turbidity changes of the solution. Thus the chemical energy is converted to generate optical rhythm through the conformational change of the polymer chain. Applications to new optical devices such as an oscillator also may be expected.

As an oscillating phenomenon of polymer solution, Pojman et al.[7] reported periodic polymerization of acrylonitrile in the BZ solution accompanying a stepwise decrease in transmittance. And Yoshikawa et al.[8] reported conformational oscillation in a single DNA molecule. They utilized a laser beam to trap the molecule, and the oscillation was created by creating a temperature gradient around the focus. So far, however, there is no report that polymer chains exhibiting rhythmical and reversible soluble−insoluble changes are realized in a homogeneous solution. In this study, we have achieved the self-oscillation of a polymer chain in solution. The oscillating behavior of the solution will be discussed through the analysis of the transmittance changes.

Experimental Section

Materials. *N*-Isopropylacrylamide (NIPAAm; Kojin Chemical Co., Tokyo, Japan) was purified by recrystallization from its toluene solution with *n*-hexane. 2,2′-Azobisisobutyronitrile (AIBN; Wako Pure Chemical Industries, Co., Ltd., Osaka, Japan) was recrystallized from methanol. Ruthenium(4-vinyl-4′-methyl-2,2′-bipyridine)bis(2,2′-bipyridine)bis(hexafluorophosphate) (Ru(bpy)$_3$ monomer) was synthesized according to the previous work.[5]

Polymerization. The linear copolymer of NIPAAm with Ru(bpy)$_3$ was prepared as follows: Purified NIPAAm (3.8 g), Ru(bpy)$_3$ monomer (5 wt % or 10 wt % of total monomer), and AIBN (0.16 g) were dissolved in 20 mL of methanol. The solution was degassed twice by a freeze−thaw cycle in an ampule, which was then sealed in vacuo and immersed in a water bath at 60 °C for 24 h. The resulting mixture was purified through dialysis against methanol for 1 week then pure water for 2 days. The dialyzed solution was lyophilized for 3 days. The weight-average molecular weights of the polymer determined by static light scattering (Otsuka Electronics, DLS-7000) were M_w = 141 400 (5 wt % catalyst in feed) and 50 200 (10 wt % catalyst).

LCST Measurements. The LCST (lower critical solution temperature) of the poly(NIPAAm-*co*-Ru(bpy)$_3$) solution was measured under different conditions of reduced and oxidized states. To maintain the oxidized Ru(III) state, Ce(SO$_4$)$_2$ was used as a oxidizing agent. Ce$_2$(SO$_4$)$_3$ was used to maintain the reduced Ru(II) state and the same ionic conditions. The polymer solutions were prepared by dissolving the polymer (5 g/L) in aqueous 0.3 M HNO$_3$ solutions containing 1 mM Ce$_2$(SO$_4$)$_3$ or 1 mM Ce(SO$_4$)$_2$. The LCST measurements were carried out with a spectrophotometer (Shimazu, Model UV-2500) equipped with an electronically controlled thermostated cell holder and magnetic stirrers. The transmittance (%) of the solution was then recorded by raising the temperature at a rate of 1 °C/min.

Measurements of Optical Oscillations. The polymer (5 g/L) was dissolved in the aqueous solution containing the reactants of the BZ reaction: 0.1 M malonic acid, 0.25 M sodium bromate, and 0.3 M nitric acid. Under constant temperature and stirring conditions, the time course of transmittance of the polymer solution at 570 nm was monitored by the spectrophotometer.

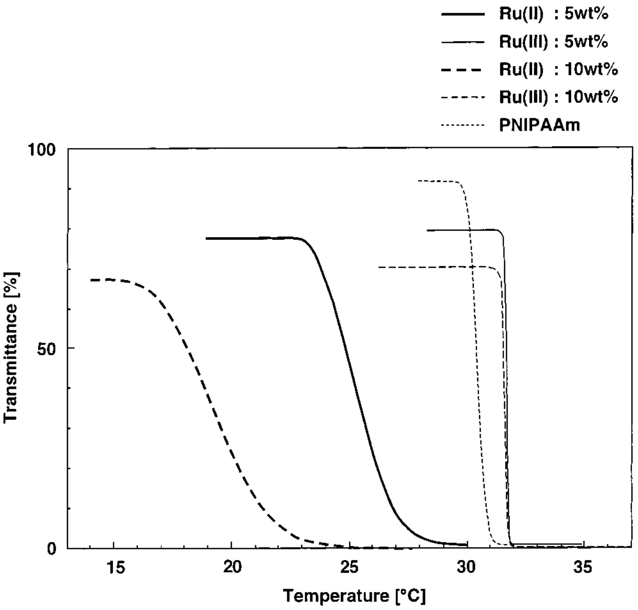

Figure 1. Temperature dependence of optical transmittance for poly(NIPAAm-*co*-Ru(bpy)$_3$) solutions under the different conditions of reduced Ru(II) state (in Ce(III) solution) and oxidized Ru(III) state (in Ce(IV) solution).

Results and Discussion

The Ru(bpy)$_3$ complex has different absorption spectra in reduced Ru(II) and oxidized Ru(III) states as an inherent property. Prior to LCST measurement, we measured the absorption spectra of the poly(NIPAAm-*co*-Ru(bpy)$_3$) in both states. The polymer solution exhibited the absorption maximum at 453 nm in the reduced state and at 421 nm in the oxidized state, and has an isosbestic point at 570 nm. In the LCST measurement, we must detect the optical transmittance changes based on soluble−insoluble changes of the polymer, not on the redox changes of the Ru(bpy)$_3$ moiety. Therefore, the 570 nm wavelength was used in the following experiments.

Figure 1 shows the transmittance changes of poly(NIPAAm-*co*-Ru(bpy)$_3$) (5 wt % and 10 wt % Ru(bpy)$_3$) solutions as a function of temperature under the different conditions of reduced Ru(II) sate and oxidized Ru(III) state. Due to the characteristics of the thermosensitive NIPAAm component, the transmittance suddenly decreases as temperature increases, demonstrating the LCST. When the Ru(bpy)$_3$ site is kept in an oxidized state, the LCST shifts higher than that of the reduced state. The rise in the LCST by oxidation is due to an increase in hydrophilicity of the polymer by the charge increase of the catalyst. This phenomenon is identical with that generally observed in NIPAAm-based polyelectrolyte gels when their ionic charges increase. The difference of the LCST between reduced and oxidized states becomes larger as the Ru(bpy)$_3$ content increases in the polymer. Due to the significant difference in the polymerization rate constants between NIPAAm monomer and Ru(bpy)$_3$ vinyl monomer, the catalyst concentration and distribution in the linear polymer are likely to be different from those in the monomer solution. The actual immobilization yield of the catalyst in the polymer is estimated to be about 75% from the amount of the catalyst extracted with methanol during the process of purification in our previous study on the gels.[6] We also obtained a linear correlation between the catalyst concentrations in the monomer solution and the resulting gel

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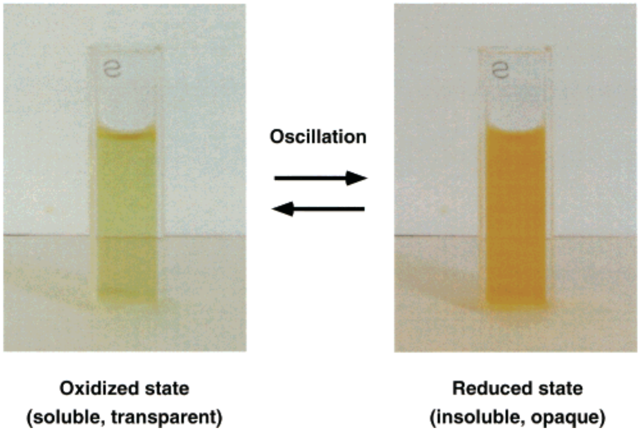

Figure 2. Periodical soluble−insoluble changes for poly(NIPAAm-*co*-Ru(bpy)$_3$) solution.

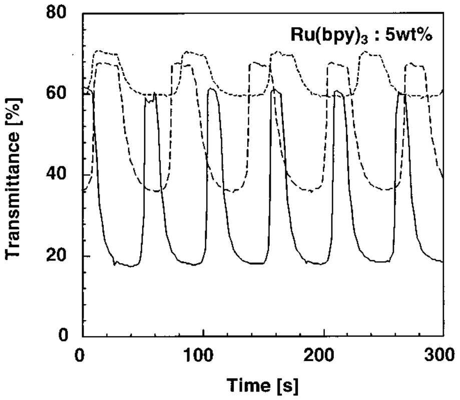

Figure 3. Oscillating profiles of optical transmittance for poly(NIPAAm-*co*-Ru(bpy)$_3$) (Ru(bpy)$_3$ = 5 wt % in feed composition) solution at constant temperatures.

by spectroscopic analysis. Therefore, a quantitative relation of the catalyst content must be kept for the two polymers at least.

As compared with the homopolymer of NIPAAm (PNIPAAm), the LCST of the copolymer in the reduced Ru(II) state is lower than that of PNIPAAm, even though the ionic charge is introduced into the polymer. In the reduced state, the effect of the hydrophobicity of the bipyridine ligand surrounding the ruthenium ion would be predominant over the ionization effect and make the polymer more hydrophobic than PNIPAAm. Due to the hydrophobic interaction, the sharpness of the transmittance change may become duller in the reduced state, and the LCST decreases more significantly with the increase in Ru(bpy)$_3$ content, as observed in Figure 1. In the oxidized Ru(III) state, on the other hand, the LCST of the copolymer is slightly higher than that of PNIPAAm. As the charge number increases, the contribution of ionic effect increases, which makes the polymer more hydrophilic than PNIPAAm. In the oxidized state, there is a small difference in the LCST, regardless of increasing Ru(bpy)$_3$ content. The ionic effect in the oxidized state is enhanced by increasing the Ru(bpy)$_3$ content. However, since the LCST in the reduced state largely decreases with increasing Ru(bpy)$_3$ content, the increase in LCST by enhanced ionic effect in the oxidized state is compensated. As a result, little variation of LCST in the oxidized state is found as a function of Ru(bpy)$_3$ content.

From the deviation of the LCST between the Ru(II) and Ru(III) states, we may expect that the polymer undergoes periodical soluble−insoluble changes when the Ru(bpy)$_3$ moiety is oxidized and reduced periodically by the BZ reaction at constant temperature. Synchronized with the periodical changes between Ru(II) and Ru(III) states of the Ru(bpy)$_3$ site, the polymer becomes hydrophobic and hydrophilic, and exhibits cyclic soluble−insoluble changes. These periodic changes of polymer chains can be easily observed as cyclic transparent and opaque changes for the polymer solution with color changes due to the redox oscillation of the catalyst (Figure 2). Figure 3 shows the oscillation profiles of transmittance for the polymer solution at constant temperatures. As the temperature increases, the amplitude in the transmittance increases and the period becomes short. It is a general tendency that the oscillation period of the BZ reaction decreases as temperature increases, following the Arrhenius equation.[9,10] In the BZ reaction, the oscillation period mainly depends on the duration of the reduced state.[11] This indicates that the reaction process for the consumption of bromide ions (called “process A” in the FKN mechanism[4]) is a period-determining process in the overall BZ reaction, and becomes a dominant factor in increasing the period. Also in our polymer solution, an increase in period is attributed to the elongation of reduced state.

The increase in amplitude with temperature can be interpreted qualitatively by comparing Figures 1 and 3, although the chemical composition and ionic strength of solutions needed to affect the LCST are different in both experiments (i.e., since the Ce solution not containing the BZ substrates was used for the LCST measurement to maintain the oxidized or reduced states, the difference in transmittances at a certain temperature in Figure 1 is not necessarily consistent with the amplitude of the transmittance oscillation at the same temperature in Figure 3). As observed in Figure 1, the degree of difference in the transmittance between reduced and oxidized states depends on the temperature because the transmittance in the reduced state drops more gradually over a wide temperature range while it drops abruptly in the oxidized state. Consequently, the difference in transmittance between two states becomes large at high temperature. This results in the large amplitude of oscillations at high temperature in Figure 3.

Figure 4 shows the oscillating behavior of the polymer with higher Ru(bpy)$_3$ content. It can be seen by comparing with the results in Figure 3 that the amplitude increases at each temperature. This result is attributed to the large difference of LCST between reduced and oxidized states of high Ru(bpy)$_3$ content (see Figure 1). It is suggested that the hydrophilic−hydrophobic changes of polymer become more remarkable due to an increase in molar content of the redox site.

Our next interests are the polymerization effect of catalyst on the oscillating behavior of the BZ reaction, as well as the effect of cross-linking the polymer chains on the synchronization of each polymer’s oscillation. The diffusion or mass transport of the substrates will play an important role especially in the cross-linked polymer network system. In the previous study, we investigated the oscillating profiles of redox changes when the BZ reaction occurred in the bulk gel at the submillimeter

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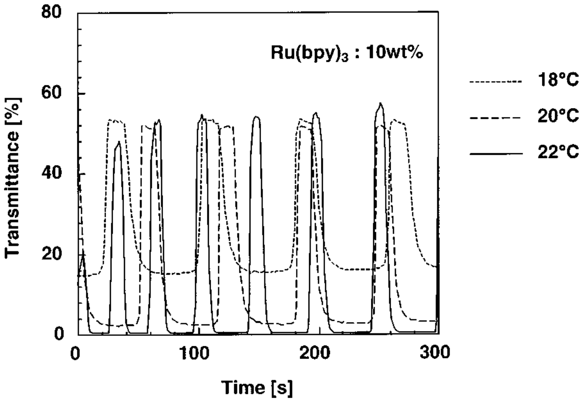

Figure 4. Oscillating profiles of optical transmittance for poly(NIPAAm-*co*-Ru(bpy)$_3$) (Ru(bpy)$_3$ = 10 wt % in feed composition) solution at constant temperatures.

level.[11] In the gel system, diffusion of substrate from the surrounding bulk solution to the gel phase, as well as of the products from the gel to the bulk phase, was found to play an important role in the oxidizing and reducing rates of the ruthenium catalyst. The diffusion effects result in elongation of the period and broadening of the pulse width. On the other hand, the polymer solution system must be free from such diffusion effects. The polymer solution system has an advantage over the gel system in that the oscillation is less subject to disturbance by mass transfer. To clarify such effects in detail, we have been investigating the dependence of the oscillation period on the initial substrate concentration for three systems: (i) the conventional BZ solution with nonpolymerized catalyst, (ii) the polymer solution with polymerized catalyst by NIPAAm, and (iii) the suspension of submicron-sized gel beads, i.e., the cross-linked polymer network of the polymerized catalyst. The period (T [s]) can be expressed as a function of the substrate concentration, [M], in the following empirical equation with a good correlation of more than $r = 0.99$: $T = a[\mathrm{MA}]^{-b}[\mathrm{NaBrO_3}]^{-c}[\mathrm{HNO_3}]^{-d}$, where a, b, c and d are constants. It was found that the concentration dependence of the period for the nonpolymerized solution (the constants in the equation are $a = 2.97$, $b = 0.414$, $c = 0.794$, and $d = 0.743$) was partly similar to that of the polymer solution ($a = 2.97$, $b = 0.413$, $c = 0.934$, and $d = 0.567$), but largely different from that of the gel beads suspension ($a = 5.75$, $b = 0.506$, $c = 0.667$, and $d = 0.478$). Compared with the period under the same substrate concentrations, the period increased in the following order: (i) < (ii) < (iii). Although there are a few differences between (i) and (ii) which are likely due to the polymerization effect of the catalyst, the effect of diffusion or mass transport on soluble−insoluble oscillation in the polymer solution system may not be as significant as that in the gel system. The dynamics of phase separation for the polymer chain also would be important for understanding the nature of the polymer oscillation in our system, especially for comparing the response time of the polymer chain with the reaction rate of each subprocess in the BZ reaction. A detailed analysis regarding the dynamics will be done in the next paper.

Conclusions

We have achieved self-oscillation of polymer chains in an aqueous solution by polymerizing the catalyst of the BZ reaction with NIPAAm. This is the first report that rhythmical soluble−insoluble changes of polymer chains are realized under constant and homogeneous conditions. In this polymer solution system, the chemical energy of the BZ reaction was converted into the optical rhythm through conformational changes of the polymer. Namely, the transducing system from the chemical energy to the optical information has been constructed. The oscillation rhythm can be controlled by changing the temperature, the catalyst content in the polymer, and the substrate concentration. By utilizing the periodical and autonomous change in transmittance, applications to new optical devices such as an oscillator also may be expected.

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