

Triple-Stimuli-Responsive Ferrocene-Containing PEGs in Water and on the Surface

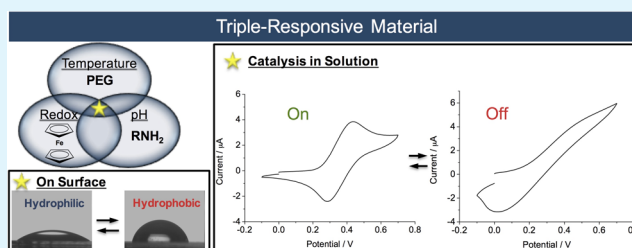
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S Supporting Information

ABSTRACT: Triple-stimuli-responsive PEG-based materials are prepared by living anionic ring-opening copolymerization of ethylene oxide and vinyl ferrocenyl glycidyl ether and subsequent thiol–ene postpolymerization modification with cysteamine. The hydrophilicity of these materials can be tuned by three stimuli: (i) temperature (depending on the comonomer ratio), (ii) oxidation state of iron centers in the ferrocene moieties, and (iii) pH-value (through amino groups), both in aqueous solution and at the interface after covalent attachment to a glass surface. In such materials, the cloud point temperatures are adjustable in solution by changing oxidation state and/or pH. On the surface, the contact angle increases with increasing pH and temperature and after oxidation, making these smart surfaces interesting for catalytic applications. Also, their redox response can be switched by temperature and pH, making this material useful for catalysis and electrochemistry applications. Exemplarily, the temperature-dependent catalysis of the chemiluminescence of luminol (a typical blood analysis tool in forensics) was investigated with these polymers.

KEYWORDS: ferrocene, polyether, redox-active polymer, stimuli responsive, smart surface



1. INTRODUCTION

Smart materials are compounds that can change their properties depending on the environment.¹ Stimuli-responsive polymers, for example, can change their shape,² color,^{3,4} conductivity,⁵ or solubility^{6,7} in response to an external stimulus like light^{8,9} or a change in temperature^{10,11} or pH value.^{12,13} Another interesting feature is redox responsivity, which is far less studied than the other stimuli but can be implemented via (i) cleavable disulfide bridges¹⁴ or (ii) reversible redox behavior of metallocene sandwich complexes, mostly ferrocene (fc), which can be oxidized reversibly to the hydrophilic ferrocenium cation.¹⁵ Polyethers, derived from ethylene oxide (EO) and hydrophobic comonomers exhibit a thermal response in water over a broad temperature range, depending on the structure of the comonomer and the molar fraction incorporated into the backbone.^{6,16–18} Much more attention, however, was drawn to poly(*N*-isopropylacrylamide) (PNIPAM) that is available by radical polymerization and exhibits a lower critical solution temperature (LCST) close to body temperature (ca. 31–33 °C).^{19,20} The LCST of PNIPAM can be affected by a few degrees,²¹ whereas PEG copolymers allow a broad variation of the LCST from 0 to 100 °C (at 1 bar) depending on the copolymer composition.¹⁶

Besides the temperature response, additional stimuli-responsive moieties can be built in a single polymer,²² resulting in multiple-stimuli-responsive materials. A straightforward handle is to introduce carboxylates or amines that are responsive to changes in the pH value. Recently, Roberts and co-workers utilized a copolymer of NIPAM and acrylic acid for

reversible control of electrochemical properties in water: the conductivity of an aqueous copolymer solution was measured at different temperatures; therefore, cyclic voltammetry measurements were performed below and above the LCST.⁵ The same polymer was also used as a pH buffer, whereas the pH value of the system is programmable via the temperature.²³ These dual-stimuli-responsive copolymers show promising properties, combining pH and temperature responsiveness and build the basis for future all-rounder polymers combining several stimuli in one material. Materials combining the three different stimuli-responsive triggers light, pH, and temperature^{24–26} or light, redox, and temperature²⁷ are known to date. To the best of our knowledge, no material has been reported to date, which combines temperature, pH, and redox responsiveness—especially both in solution and on the surface.

Herein, ferrocene-containing polyethers are presented as the first triple-stimuli-responsive organometallic materials that combine (i) thermo-, (ii) pH-, and (iii) redox-responsive behavior (Scheme 1).²⁸

The copolymers (P[EO_x-co-VfcGE_y]) are prepared by anionic copolymerization of vinyl ferrocenyl glycidyl ether (VfcGE) and ethylene oxide (Scheme S1). The ferrocene units introduce both reversible redox response (due to Fe(II)–Fe(III) redox pair) and temperature response (due to the hydrophobicity of the VfcGE units) into the polymer. The

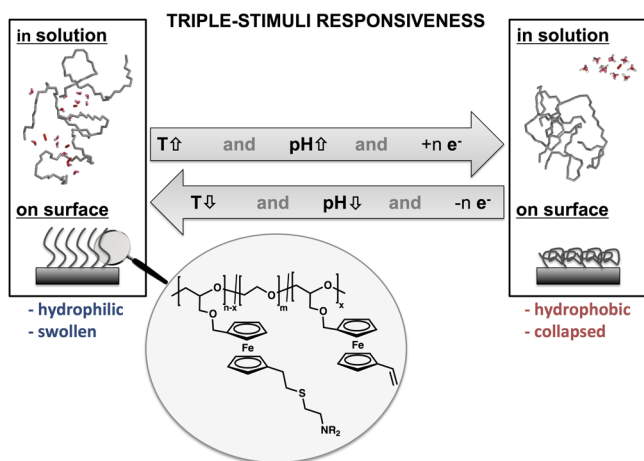
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Scheme 1. Triple-Stimuli-Responsive Behavior of Fc-Containing Polyethers after Functionalization with Cysteamine in Solution and on Surface



pendant double bonds of the ferrocene units of P[EO-*co*-VfcGE] copolymers were postmodified via thiol–ene addition with cysteamine to introduce amine functionalities and thus an additional pH response (Scheme 1 and Scheme S1). The postmodified copolymers carry, in addition to the hydrophobic fc groups, also hydrophilic amino groups and thus exhibit higher cloud point temperatures (T_c) in aqueous solution compared to those of the non-functionalized P[EO-*co*-VfcGE]. Besides this stimuli-responsive behavior in water, the polymers were covalently fixed to benzophenone-modified glass surfaces by radical coupling. On the surface, the same material allowed us to control the hydrophilicity of the polymer layer by adjusting the pH, temperature, or oxidation state.

Because ferrocene is used widely, e.g., in electrochemistry,²⁹ batteries,³⁰ sensing,^{31–33} biology,^{34,35} and catalysis,^{36–39} many fields may benefit from such unique multiple-stimuli-responsive materials. For example, these new materials could be useful in catalysts or sensors, which operate within a defined temperature range depending on pH and the oxidation state of fc or in a defined pH range depending on the temperature and oxidation state of fc.

2. EXPERIMENTAL SECTION

Instrumentation. ¹H NMR spectra (400 MHz) and ¹³C NMR spectra (75.5 MHz) were recorded using a Bruker AMX400. All spectra were referenced internally to the residual proton signals of the deuterated solvent. For SEC measurements in DMF (containing 0.25 g·L⁻¹ of lithium bromide as an additive) an Agilent 1100 Series was used, equipped with PSS HEMA columns (10⁶/10⁵/10⁴ g·mol⁻¹), a UV detector (recording at a wavelength of 275 nm), and a RI detector at a flow rate of 1 mL·min⁻¹ at 50 °C. Molecular weights were determined as apparent values vs PEO standards purchased from PSS (Mainz, Germany). Cyclic voltammetry (CV) was carried out in a conventional three-electrode cell using a WaveDriver 20 bipotentiostat (Pine Instrument Company) and deionized water as solvent for polymer solutions with 5 g·L⁻¹ concentration. No supporting electrolyte was used. A glassy carbon disk served as working electrode. Ag/AgCl and platinum wire were used as reference and counter electrodes, respectively. For the determination of polymer cloud points, the turbidity of a polymer solution in deionized water (concentration 5 mg/mL) was measured in a JASCO V-630 photospectrometer with a JASCO ETC-717 Peltier element by optical transmittance of a light beam (with $\lambda = 500$ nm; 50%) through a quartz cuvette (1 cm). The measured value for the transmission at the beginning of the measurement (with the copolymer being water-

soluble) is set to 100% and recorded versus the temperature of the sample cell. The heating rate was adjusted to 1 °C·min⁻¹ and values were recorded every 0.1 °C. The luminol experiments were performed at the same spectrometer, detecting only the emission intensity at 450 nm.

Reagents. All chemicals and solvents were obtained from Acros Organics, TCI, or Sigma-Aldrich and used without purification. For the anionic polymerization solvents and reagents were dried prior to use. Chloroform-*d* and benzene-*d*₆ were obtained from Deutero GmbH. VfcGE was synthesized according to the published procedures.⁴⁰ VfcGE was dried by azeotropic distillation of benzene to remove traces of water. The synthetic details for the anionic polymerization of EO and VfcGE has been reported earlier⁴⁰ (data for P[EO₂₀₆-*co*-VfcGE₁₀]: $M_n(\text{SEC}) = 2200$ g·mol⁻¹; $\bar{D} = 1.09$; $M_n(\text{NMR}) = 12\,300$ g·mol⁻¹, SEC trace in the Supporting Information). 4-[(3-(chlorodimethylsilyl)propyl)oxy]benzophenone was synthesized according to the literature.⁴⁵

Attachment of Pendant Amino Groups to the Free Vinyl Bonds of P[EO₂₀₆-*co*-VfcGE₁₀]. A 100 mg amount of P[EO₂₀₆-*co*-VfcGE₁₀] was dissolved in 5 mL of tetrahydrofuran in an argon atmosphere, and 138 mg (1.79 mmol, 20 equiv) of cysteamine and 14 mg (0.0846 mmol, 0.75 equiv compared to double bonds) of azoisobutyronitrile were added. After three freeze–pump–thaw cycles (for deoxygenation), the solution was heated to 75 °C and left for 12 h before it was precipitated into diethyl ether. Yield: 95%. ¹H NMR (CDCl₃, 400 MHz, 298 K): δ (ppm) = 7.31 (m, 5H, aromatic protons of initiator), 4.33 (s, 2H, benzylic signals of the initiator), 4.29–3.91 (m, *fc*-CH₂-O), 3.85–3.10 (residual protons: PEO backbone, *fc*-CH₂-O-CH₂-backbone), 3.00–2.55 (m, *fc*-CH₂-CH₂-S-CH₂-CH₂-).

Chemiluminescence of Luminol. A 0.2 g sample of Luminol was suspended in 20 mL of deionized water, and a 2.5 M sodium hydroxide solution was added dropwise until luminol was fully dissolved. Two milliliters of the luminol solution was transferred to a 1 cm quartz cuvette. Two milligrams of copolymer was dissolved in 0.2 mL of hydrogen peroxide solution (30%). This oxidizing solution was injected via syringe to the cuvette and the chemiluminescence intensity at 450 nm was recorded.

Functionalization of Glass Surfaces with Ferrocene-Containing PEGs. For covalent attachment of the copolymers, glass surfaces were purified via UV–ozone surface treatment and were functionalized with 4-[(3-(chlorodimethylsilyl)propyl)oxy]benzophenone, which was synthesized according to the literature (Scheme S3).⁴⁵ A clean glass surface is wetted with a dry solution of 4-[(3-(chlorodimethylsilyl)propyl)oxy]benzophenone in toluene with catalytic amounts of triethylamine and was left standing overnight under an argon atmosphere. After washing, the triple-stimuli-responsive copolymers were then spin-coated from a toluene solution on the functionalized surfaces and dried at reduced pressure. The samples were irradiated with a UV-A/B lamp for 4 h to link the polymers to the surface (Scheme 2). The height profiles of the modified glass surfaces were analyzed with a contact profilometer (Results and Discussion).

3. RESULTS AND DISCUSSION

Functionalization of P[VfcGE-*co*-EO] Copolymers to Multiple-Stimuli-Responsive Copolymers. The first ferrocene-containing epoxide monomer, namely, ferrocenyl glycidyl ether (fcGE), recently reported by our group copolymers with ethylene oxide (EO), exhibits cloud point temperatures that can be adjusted by variation of the molar ratio fcGE:EO.⁶ Very recently, we presented a bifunctional monomer, namely VfcGE that produces polyfunctional poly(vinyl ferrocenyl glycidyl ether-*co*-ethylene oxide) copolymers (P[VfcGE-*co*-EO]), also exhibiting thermo- and redox-responsive behavior.⁴⁰ Herein, the pendant vinyl groups were further functionalized with amines to introduce pH responsiveness as an additional, third

stimulus (Scheme 1 and Scheme S1) and to attach such polymers to surfaces via radical cross-linking (see below).

Thiol–ene addition is often used for polymer post-modification reactions, because high conversions can be achieved.^{41,42} This technique was used to modify the pendant vinyl groups in the P[VfcGE-co-EO] copolymers to introduce pendant amines. Amines have to be attached to such polymers by postpolymerization reactions, as they cannot be used in the anionic polymerization directly or would have to be protected.

The vinyl groups in P[VfcGE₁₀-co-EO₂₀₆] (M_n (NMR) = 12 300 g·mol^{−1}) were successfully postmodified via radical thiol–ene addition with cysteamine using azobis(isobutyronitrile) (AIBN) as the initiator at 80 °C in tetrahydrofuran. The ¹H NMR spectra of the P[VfcGE-co-EO] copolymers prior to and after functionalization with cysteamine are compared in Figure S1: the resonances for the vinyl groups (between 6.5 and 5.0 ppm) are reduced after the reaction, whereas the new signals for cysteamine and the ethylene bridge between the fc unit and the thio-ether appear (between 3.2 and 2.5 ppm). The degree of functionalization was calculated to be 90–95% under these conditions, i.e., nine amine groups per polymer are available after functionalization, i.e., P[VfcGE₁-ran-CAfcGE₉-co-EO₂₀₆] (the “CA” indicates the repeating units modified with cysteamine).

pH-Control of Cloud Point Temperatures. After modification of the fc-containing PEG copolymers with cysteamine, the toolbox for the variation of the cloud point temperature is enlarged: not only the comonomer:EO ratio determines the cloud point temperature but also the same composition exhibits tunable cloud points depending on the pH values due to protonation/deprotonation of the pendant amines. The cloud point temperatures of the amino-modified P[VfcGE₁-ran-CAfcGE₉-co-EO₂₀₆] were measured at different pH values to prove the additional pH responsiveness of the copolymer (Figure S2). The temperature-dependent transmission of a light beam (500 nm) through a copolymer solution in water (5 mg/mL) is measured. When reaching the cloud point temperature, the copolymer precipitates and the transmission of the light beam drops to a lower transmission value of around 5–10%. The cloud point temperatures can be shifted from 30 °C (pH = 12.0), over 36 °C (pH = 8.5), to 61 °C (pH = 7.0). At lower pH values the polymer becomes too hydrophilic and is soluble over the whole temperature range.

Temperature Switch of the Redox-Activity (at a Certain pH). The temperature-dependent solubility of the fc-containing copolymers in water is utilized as a switch for the redox activity: if the polymer is soluble in water, a redox response of fc can be measured by cyclic voltammetry (“switch on” = below the cloud point); if the polymer is precipitated, no redox response can be obtained from ferrocene (“switch off” = above the cloud point). Cyclic voltammograms were recorded by applying a cyclic potential in water without adding conducting salt (Figure 1, at constant pH = 8.5, T_c = 36 °C), because the amine functionalities are partially protonated in water and generate enough ions to measure the conductivity.

The cyclic voltammogram below the cloud point temperature at 25 °C shows an oxidation and reduction signal of the fc moieties (a), as the polymer is fully soluble. The voltammogram is symmetrical, which indicates the reversibility of the oxidation process. This demonstrates the high redox activity of fc in the polyether side chains as well as the stability under these conditions. Above the cloud point temperature at 55 °C, the polymer forms bigger aggregates and precipitates, so that no

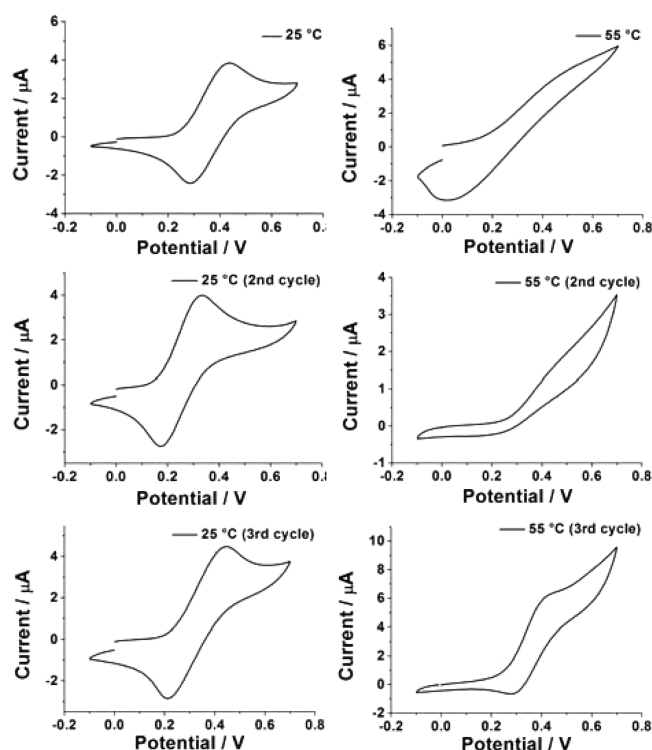


Figure 1. Cyclic voltammograms of P[VfcGE₁-ran-CAfcGE₉-co-EO₂₀₆] copolymer below the cloud point temperature (T_c) at 25 °C (a, c, and e) and above the T_c at 55 °C (b, d, and f) at pH = 8.5 (three cycles).

oxidizing and reducing signals can be observed for the fc units (b). The reversibility of the “on” and “off” states were proven by three cycles. The temperature was lowered again and a cyclic voltammogram of the totally dissolved polymer was recorded at 25 °C (c) with the response of fc. After heating to 55 °C, the redox response disappears again (d). This procedure was repeated for another cycle, which is shown in (e) and (f) with no detectable difference.

Temperature-Dependent Catalysis of Luminol’s Chemiluminescence. This temperature-dependent redox activity of the copolymer is utilized for the temperature-dependent catalysis of luminol’s (3-aminophthalhydrazide) chemiluminescence (Figure 2 and Scheme S2). Luminol is used by forensic investigators to detect traces of blood, particularly iron(II), which is fixed in hemoglobin. For this test, luminol is dissolved in water under basic conditions (pH ca. 10) and then reacts with an appropriate oxidizing agent. The oxidation of luminol proceeds under emission of a distinct chemiluminescence. The chemiluminescence intensity is typically rather low, if no catalyst is added. However, even in the presence of only traces of Fe acting as catalyst, e.g., from blood, a very strong chemiluminescence is detectable.⁴³ Herein this sensitive chemiluminescence of luminol is used to demonstrate the usage of the P[VfcGE₁-ran-CAfcGE₁₃-co-EO₇₅] copolymer as a temperature-dependent catalyst. The polymeric catalyst (P[VfcGE₁-ran-CAfcGE₁₃-co-EO₇₅]) is dissolved in water with hydrogen peroxide and added to luminol. The cloud point temperature of the polymer under those conditions is ca. 25 °C. The intensity of the emitted light is detected at two different temperatures over time: at 21 °C (below the T_c) the detected chemiluminescence is about 5 times higher than that of the same experiment at 28 °C, which lies above the T_c (Figures 2 and S3).

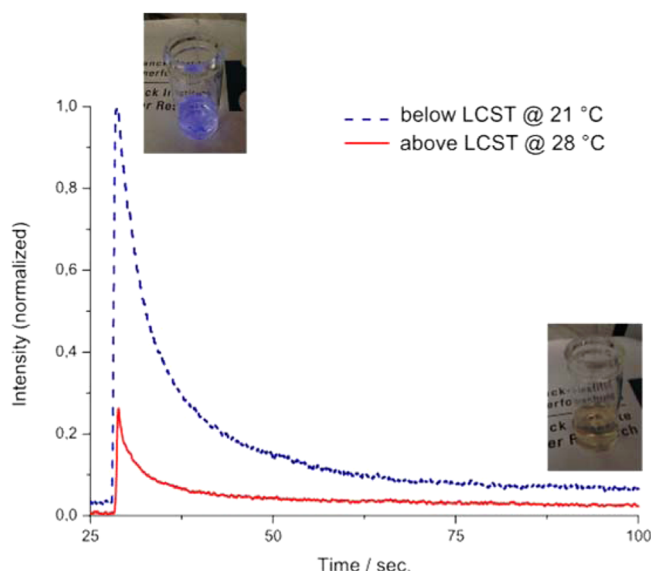


Figure 2. Chemiluminescence of luminol after the addition of hydrogen peroxide in the presence of the functionalized copolymer at 21 °C (below T_c) and 28 °C (above T_c).

As the polymer is completely dissolved below the T_c , it can catalyze the reaction as expected for an Fe(II) species (“switch on”). If the temperature is increased above the copolymer’s cloud point temperature, a strong decrease of both the chemiluminescence intensity and half-life time are detected, because the polymeric catalyst is “switched off”, i.e., precipitated, proving that the efficiency of the catalytic properties of the iron(II) centers are strongly influenced by the solubility of the copolymer.

pH Switch of the Redox-Activity (at a Certain Temperature). P[VfcGE₁-ran-CAfcGE₁₃-co-EO₇₅] was utilized to switch ferrocene’s redox activity by the variation of the pH value at a certain temperature. The aqueous solution of P[VfcGE₁-ran-CAfcGE₁₃-co-EO₇₅] was analyzed by cyclic voltammetry at three different pH values (pH 6, 7, and 8 at constant temperature of 25 °C). The cyclic voltammogram of the copolymer solution at pH 6, at which the copolymer is completely soluble, because the amine groups are partially protonated, shows a clear redox response of ferrocene and a reversible oxidation of fc to ferrocenium (“switch on”, Figure 3).

It is also noticeable that the reduction peak splits into two signals, leading to the conclusion that consecutive reactions occur at the iron centers, causing partial decomposition at this pH.⁴⁴ In the cyclic voltammograms at pH 7 and 8 the oxidation signal is strongly decreased (“switch off”) and instead an uneven, flattened curve is measured. The reduction peak is comparable to the one, measured at pH 6, but the measured negative current is much lower. The reason for appearance of such a reduction peak is that low amounts of copolymers with oxidized ferrocenium species are still present and dissolved in the polymer solution. With an increasing amount of ferrocenium species (fc⁺) the polymer becomes more hydrophilic and finally totally water-soluble as a polycation. This pH-dependent switching of the redox activity in a physiological relevant regime might be of potential use for future nanoparticulate drug delivery or diagnostic vehicles, which is a topic of current studies.

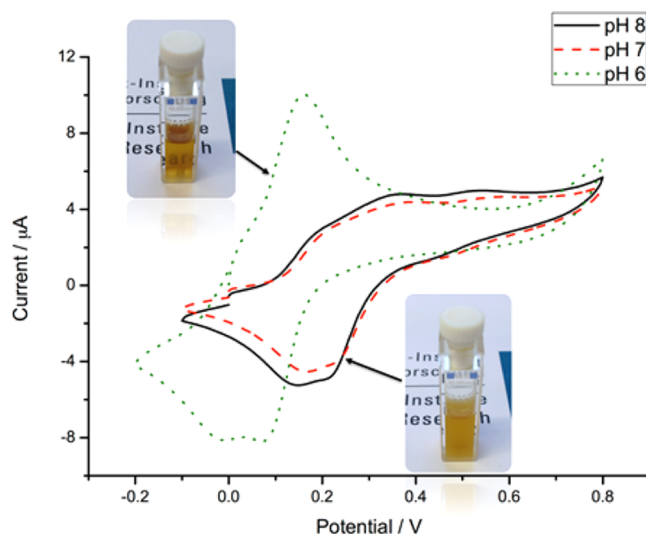


Figure 3. Cyclic voltammogram of cysteamine-functionalized P[VfcGE₁-ran-CAfcGE₁₃-co-EO₇₅] copolymer at 25 °C at three different pH values, whereas only below pH 6 is the copolymer totally water-soluble and precipitates above pH 7.

On Surface Stimuli Response. The triple-stimuli-responsive copolymers are covalently linked to a glass surface to generate multiple-stimuli-responsive polymer films and to enable pH- and temperature-dependent electrocatalysis reactions on the surface.

To allow covalent binding of the copolymers, glass surfaces were functionalized with 4-(3'-chlorodimethylsilyl)-(propoxybenzophenone) (Scheme S3) and the triple-stimuli-responsive copolymers were then spin-coated on the functionalized surfaces. The samples were irradiated with a UV-A/B lamp to link the polymers to the surface (Scheme 2).⁴⁵ The height profiles of the modified glass surfaces were analyzed with a contact profilometer (Figure S4; topographic pictures of two glass surfaces modified with polymer P[VfcGE₁-ran-CAfcGE₆-co-EO₁₁₅] are shown in Figure S5). The film thicknesses of covalently bound P[VfcGE₁-ran-CAfcGE₆-co-EO₁₁₅] were determined to be 20.1 ± 3.3 nm (surface 1, Figure S4a) and 19.3 ± 2.9 nm (surface 2, Figure S4b), respectively, with homogeneous roughness of less than 16%.

The copolymer P[VfcGE₁-ran-CAVfcGE₆-co-EO₁₁₅] exhibited a cloud point at 33 °C at pH 7.0 in solution. After surface attachment, the stimuli-responsive behavior of the polymer films were analyzed by contact angle measurements, which were performed at various temperatures, pH values and after oxidation/reduction (Fe(II) or Fe(III)).

Temperature-Dependent Contact Angle Measurements. The polymer-modified glass surfaces were placed on a furnace and after equilibration 3 μ L of water was dropped on the sample; the contact angles were determined in the temperature range from 10 to 70 °C (Figure 4a). Two reference samples were also measured, which were not modified after the UV–ozone treatment. For the reference surfaces the determined contact angles follow the Eötvös rule, which, briefly explained, describes the almost linear decay of the surface tension of a liquid on a surface with increasing temperature.⁴⁶ For the polymer-modified surfaces this behavior is superimposed with the change in hydrophilicity over temperature (T_c); i.e., the contact angles (θ) stay rather constant (up to 30–40°), which indicates that the Eötvös rule

Scheme 2. Schematic Representation of Polymer Film Formation (Covalent Linkage of P[VfcGE₁-*ran*-CAfcGE₉-*co*-EO₂₀₆] to the Modified Glass Surface)

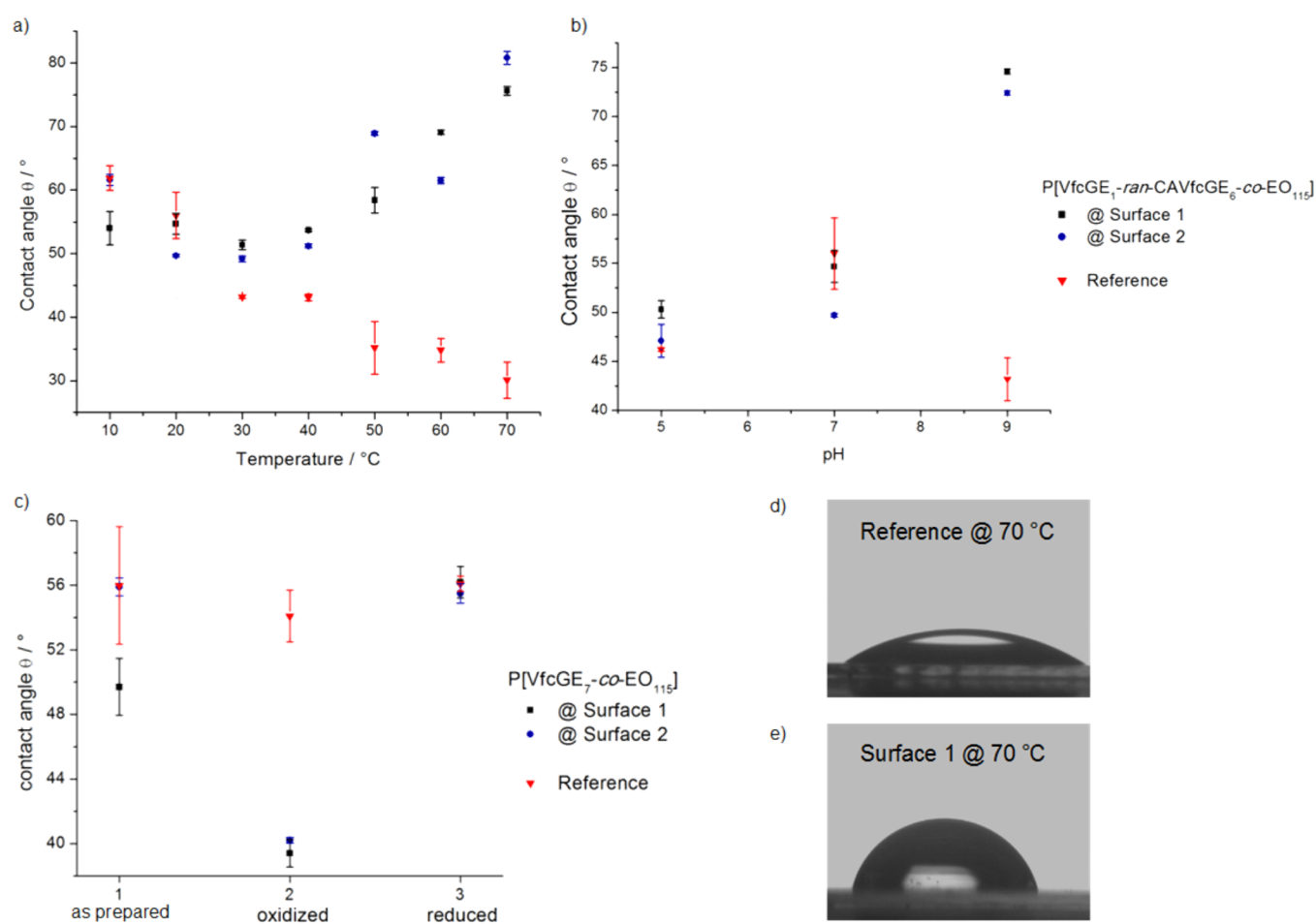
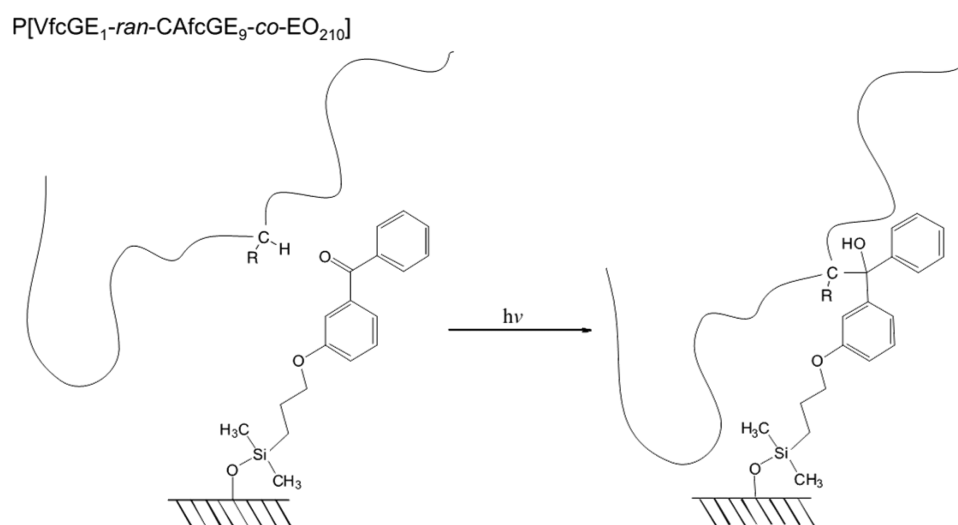


Figure 4. Contact angles of polymer-modified glass surfaces (black squares and blue circles; compared to the unmodified glass surface as a reference, red triangles) at different conditions: (a) P[VfcGE₁-*ran*-CAVfcGE₆-*co*-EO₁₁₅]-modified glass surface, temperature dependency; (b) P[VfcGE₁-*ran*-CAVfcGE₆-*co*-EO₁₁₅]-modified glass surface, pH dependency; (c) P[VfcGE₇-*co*-EO₁₁₅]-modified glass surface: m, oxidation-state dependency; (d) picture of a water droplet on the glass reference sample at 70 °C; (e) picture of a water droplet on the surface 1 at 70 °C.

is leveled by the temperature-responsive polymer that becomes more and more hydrophobic. However, above temperatures of 40 °C the contact angles increase significantly from initially $\theta = 51\text{--}54^\circ$ (up to 40 °C) to $\theta = 76\text{--}81^\circ$ (at 70 °C, also compare

Figure 4d, which shows a picture of the reference glass surface (taken during contact angle measurements with a water droplet at 70 °C) and Figure 4e, where surface 1 at 70 °C shows a more hydrophobic surface).

pH-Dependent Contact Angle Measurements. The pH dependency of the polymer-modified surfaces was measured at constant temperature (20 °C) by applying 3 μ L of an aqueous solution at a certain pH value (pH = 5, 7, and 9) and comparing results to those of the control surface (Figure 4b). Both polymer-modified surfaces show higher contact angles, thus becoming hydrophobic, with increasing pH values (Figure 4b): At pH 5.0 and 7.0 the amine groups are partially protonated, which increases the hydrophilicity of the polymer on the glass surfaces, resulting in contact angles of $\theta = 47\text{--}50^\circ$ (pH = 5) similar to those of the reference. At pH = 7.0 both polymer-modified surfaces show a slight increase in the contact angle to the same degree as the reference ($\theta = 50\text{--}55^\circ$); however, at pH = 9.0 with the ammonium groups being deprotonated, a strong increase of the contact angles of up to $\theta = 75^\circ$ for the polymer-modified surfaces is observed, which indicates a more hydrophobic surface, whereas the reference remains rather unchanged ($\theta = 42^\circ$).

Oxidation-Dependent Contact Angle Measurements. The film thicknesses of covalently bound P[VfcGE₇-co-EO₁₁₅] were determined to be 35.8 ± 6.7 nm (surface 1) and 48.3 ± 5.3 nm (surface 2). The redox-activity of P[VfcGE₇-co-EO₁₁₅] at surfaces 1 and 2 were analyzed by reversible oxidation of the surfaces prior to the contact angle measurements (Figure 4c). The contact angles of the polymer-modified surfaces before oxidation (at 20 °C) were determined to be similar to those of the reference surface ($\theta > 50^\circ$). Treating the polymer film with an aqueous hydrogen peroxide solution oxidizes ferrocene to the hydrophilic ferrocenium cation [Fe(II) \rightarrow Fe(III)], resulting in a reduction of the contact angle to $\theta \approx 40^\circ$. For subsequent reduction, the samples were treated with sodium ascorbate to reduce the ferrocenium cation back to the uncharged ferrocene with again an increase of the contact angle to the starting value of $\theta > 50^\circ$.

4. CONCLUSION

In summary, we have synthesized the first triple-stimuli-responsive organometallic polymer exhibiting pH, temperature, and redox response. These PEG-based copolymers are composed of a randomly distributed amino-functionalized ferrocene comonomer within an ethylene oxide chain that undergoes phase transitions in solution or after covalent modification of glass surfaces. For the first time, thermo- and pH-responsive behavior is combined with the redox activity of ferrocene, resulting in a temperature- and pH-dependent control of the redox activity of the system ("on and off" switch of the redox-active state).

By variation of the pH value, a single copolymer exhibits different cloud point temperatures from 30 °C up to 61 °C. In addition, this pH-dependent cloud point can be utilized to control the redox response of the polymer solutions: at a certain pH, redox activity can be switched by temperature variation: above the cloud point, the polymer is agglomerated and the fc species cannot be detected by cyclic voltammetry. As soon as the temperature decreases below the cloud point, a strong redox signal can be recorded. This tool allows us to use these materials also as temperature-dependent catalyst. We chose the chemiluminescent oxidation of luminol as an example: only if the polymer is below its cloud point temperature (LCST), i.e., dissolved, is a strong chemiluminescence detectable. A much weaker chemiluminescence is detectable above the cloud point temperature of the copolymer. After covalent attachment to glass surfaces, this temperature

response allows us to switch from hydrophilic surfaces at low temperature to hydrophobic surfaces at temperatures above 40 °C.

In addition to temperature, the redox activity can be controlled by the variation of the pH (at a constant temperature). This allows developing pH sensors on the basis of ferrocene's redox activity. Polymer films can also be switched from hydrophilic (at low pH) to hydrophobic (at high pH). Herein, we adjusted the pH switch to occur in the physiological relevant regime between pH 6 and 7 (switched off below pH 7, switched on above pH 7), which may be interesting for future drug delivery or diagnostic carriers as the intracellular pH value is with a pH of 6–6.5 in many cells slightly lower than the extracellular environment, if specific cell targeting to, e.g., tumor cells is achieved, for example.

We are currently working on drug delivery systems with selective and triple triggered release. Also, these triple-stimuli-responsive materials could find use in electrochemical reactions, in which fc acts as catalyst. Therefore, it could also serve as mediator in sensors, which operate at certain temperatures and pH regions.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsami.5b07945.

Synthetic strategy of P[VfcGE₁-ran-CAfcGE₉-co-EO₂₀₆], ¹H NMR spectra turbidity measurements, chemiluminescence of luminol, synthesis of 4-(3'-chlorodimethylsilyl(propoxy)benzophenone), height profiles, topographic pictures of polymer-modified glass surfaces, SEC traces, and additional characterization data and contact angle measurements (PDF)

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Author Contributions

All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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