



# Functional polymers in nonpolar solvents induced by dissociation of macromolecular complexes

Kazuki Sada<sup>1</sup>

Received: 5 August 2017 / Revised: 22 November 2017 / Accepted: 3 December 2017 / Published online: 7 February 2018  
© The Society of Polymer Science, Japan 2018

## Abstract

This review demonstrates our approaches for developing functional polymer systems using dissociation processes in nonpolar media. One is the molecular design of highly swellable gels known as superabsorbent polymers in nonpolar organic solvents, and the other is the supramolecular design of thermo-responsive polymers. Both of them are well documented in water, but no practical molecular design for other media have ever been proposed. For designing these behaviors, the dissociation or release of the low-molecular component from macromolecular complexes should play a key role. Therefore, controlling the dissociation processes in supramolecular chemistry should be another important strategy for developing functional polymer materials.

## Introduction

Supramolecular chemistry is defined as the chemistry of non-covalent bonds and science of association and dissociation among building blocks such as ions, molecules, and their assemblies [1–4]. More recently, it has been expanding from host-guest chemistry in solution in the atomic or nanometer size to material science in the centimeter or larger size via formation of complex assembled structures beyond hierarchical structures [5]. Nowadays, for material science, supramolecular chemistry acts as the most important field for the creation of new functional materials, because both the assembled structures and the molecular structures are closely related to their functions [6–10].

On the other hand, regarding the supramolecular chemistry research, the main attention has focused on the construction and formation of supramolecular assemblies. Many examples of association processes have been reported, such as the inclusion of guest molecules into the host cavity of macrocyclic hosts, well-defined supramolecular assemblies with various geometrical caged structures from ligands and metal ions by coordination bonds [11, 12], crystal engineering of organic compounds [13], gelation of low-molecular-weight gelators [14, 15], supramolecular

liquid-crystalline assemblies [16], supramolecular polymers in solution [17, 18], micelle or vesicle formation of amphiphilic compounds [19], etc. Compared to the vast numbers of studies about the construction of supramolecular assemblies, the destruction of supramolecular assemblies back to elementary building blocks such as the dissolution of organic crystalline materials, decomposition of well-defined supramolecular architectures, transformation from organogel fibers, micelles, and vesicles into molecular dispersions has been attracting less attention. Generally, the disassembly process is investigated only for confirmation of the formation of supramolecular assemblies by breaking the non-covalent bonds between the building blocks or illustration of a stimuli-response by changing the environment.

With respect to non-covalent interactions, the attractive interactions for association are more diverse than the repulsive ones for dissociation. Many attractive interactions can be listed, such as the coordination bond between organic ligands and metal ions, electrostatic attraction between opposite charges, hydrogen bonds,  $\pi/\pi$  interaction, hydrophobic interaction, van der Waals interaction, halogen bonds [20], CH/ $\pi$  hydrogen bonds [21], etc. They have been extensively used for association among the building blocks.

✉ Kazuki Sada  
sadatcm@sci.hokudai.ac.jp

<sup>1</sup> Department of Chemistry, Faculty of Science, Hokkaido University, Sapporo, Hokkaido 060-0808, Japan

Characteristic molecular structures or molecular motifs have already been revealed in many systems, and the media suitable for them have been also extensively investigated. As examples, hydrogen bonds work strongly in nonpolar solvents, but weakly in protic polar solvents, whereas, hydrophobic interactions among long alkyl chains work strongly in water, but weakly in nonpolar solvents for association. Thus, the supramolecular assemblies can be designed from the molecular structures on the basis of knowledge about the attractive interactions, further applicable for material design.

On the other hand, the repulsive interactions are limited to only two types. One is the exchange repulsive force among atoms, and the other is electrostatic repulsion between ions with the same charge. The former exchange repulsive force of atoms is intermolecular repulsion known as steric repulsion due to the approach of atoms closer than the van der Waals radius. It mostly contributes to the formation of three-dimensional structures (shape, size, chirality) of organic molecules or more complex architectures of biopolymers such as proteins and nucleic acids. Moreover, it plays a key role in the molecular recognition of molecules by a key-lock mechanism in supramolecular chemistry. The latter electrostatic repulsion between ionic species with the same sign is driven by a Coulomb force and a sole designable intermolecular repulsive interaction. However, the major drawback is the limitation of the media. The dissociation of an ion-pair into free ions is indispensable and inevitable, and the characteristic properties of ionic materials induced by a repulsive interaction can be realized only in polar media.

This review introduces new approaches for functional polymer systems using dissociation processes, especially in nonpolar media. One is the molecular design of a highly swellable gel in nonpolar organic solvents and the other is the supramolecular design of temperature-responsive polymers. Both of them are well documented in water, but no practical molecular designs for other media have ever been proposed. Recently, we noticed that they can be designed by the release of ions or molecules from macromolecular complexes. The former is the generation of an osmotic pressure derived from dissociated free ions from the polymer chain of ionic polymers. The latter is control of desolvation utilizing the thermal dissociation of macromolecular complexes between low-molecular pseudo-solvating molecules and polymers. In both cases, dissociation from the supramolecular assemblies plays an important role in emerging functions.

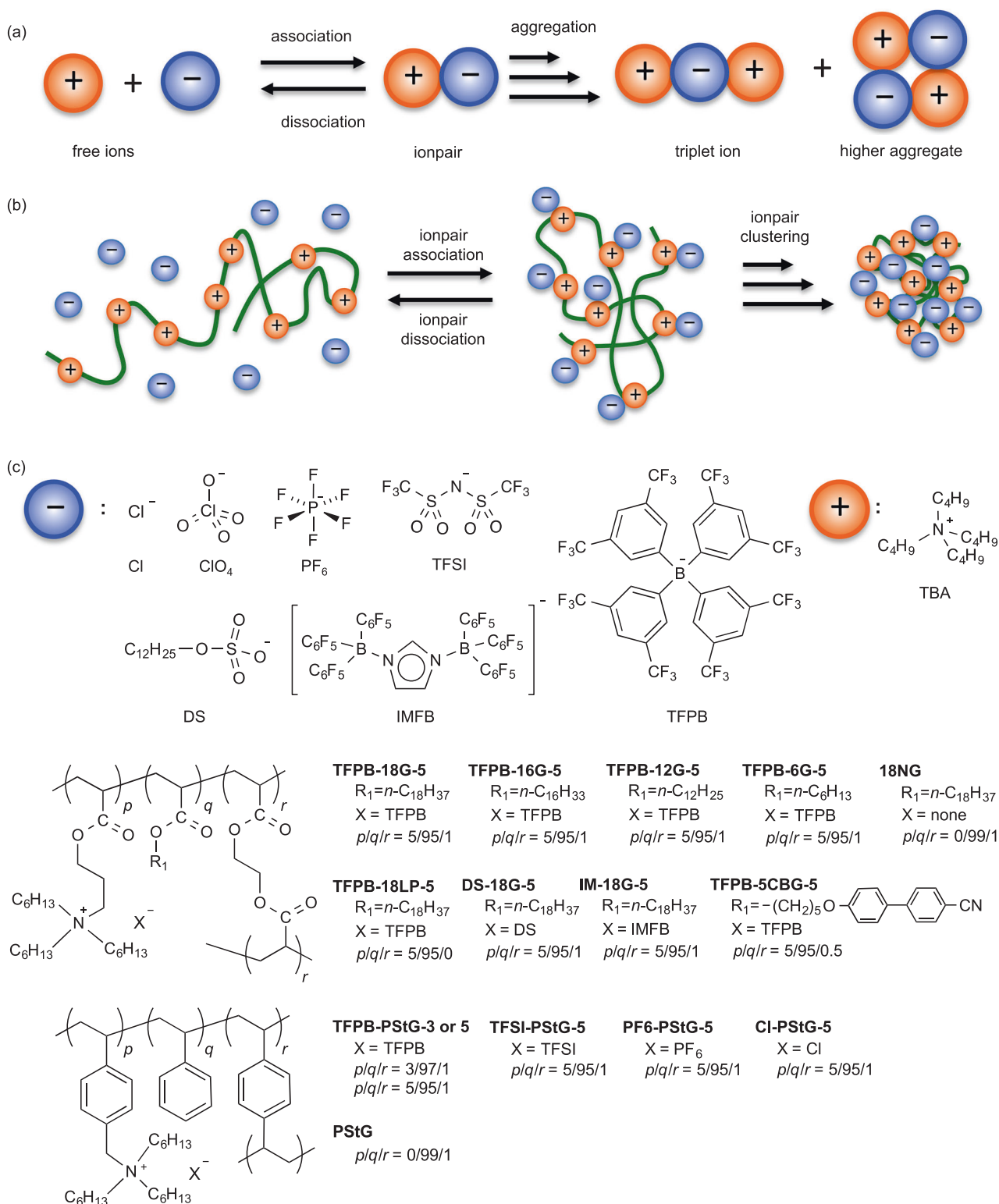
## Lipophilic polyelectrolyte gels

### Polyelectrolytes

Polyelectrolytes are defined as polymer systems carrying covalently bound anionic or cationic groups and dissociating

into macromolecular ion (macroion) and low-molecular counter ions in solution [22, 23]. Compared to those of nonionic polymers, polyelectrolytes show characteristic behaviors, because the physical and chemical properties of the polyelectrolytes are strongly affected by change of the state of an ion-pair on the polymer chain, among free ions, a tightly bound ion-pair, and a higher aggregate, as shown in Fig. 1a. For example, polyelectrolytes drastically changes the conformation of a polymer chain by the dissociation and association of the ion-pairs as shown in Fig. 1b. Especially, the dissociation of ion-pairs into free ions generates an osmotic pressure around the polymer and inter- or intramolecular electrostatic repulsion to expand the polymer chain, while the association of free ions to a tightly bound ion-pair or higher-order aggregates induces collapse of the polymer chain [24, 25]. The electrostatic interaction that dominates the association and dissociation of ions is a long-range force compared to other intermolecular interactions, and the strength of the interaction significantly changes depending on the dielectric constant of the medium.

One of the most interesting applications of a polyelectrolyte in water is superabsorbent polymers (SAPs) that can absorb water in a large quantity by immersing in water [26]. Cross-linked poly(sodium acrylate salt) gels swell in water to expand their volumes and the weight of the absorbed water can reach several hundred times their dried weights. Due to this amazing absorption property in water, they have used in many applications and have become a commodity, which has changed the quality of our daily life. However, one major drawback of these functional materials based on polyelectrolytes is the limitation of the applicable media as already discussed. The characteristic behaviors as polyelectrolytes has been achieved only in high polar media, not in nonpolar media whose dielectric constant is  $<20$  [27–30]. In highly polar media, in water and highly polar solvents, such as dimethylformamide (DMF) and dimethylsulfoxide (DMSO), common ion-pairs used in the polyelectrolytes can dissociate into free ions, and electrostatic repulsion between the building block should effectively work. On the other hand, in most of the common organic solvents, they can hardly dissociate, and it generates an attractive interaction among the tightly bound ion-pairs rather than a repulsive interaction. Therefore, the electrostatic repulsion between the polyelectrolytes have been generally discussed in water and related highly polar solvents. Materials based on polyelectrolyte behaviors have been only reported in polar media. In this section, I describe our new approach to create polyelectrolytes and their gels active even in nonpolar solvents, so-called lipophilic polyelectrolytes and lipophilic polyelectrolyte gels for the first time. In particular, as functional polymeric materials, the application to SAPs that swell in many nonpolar organic solvents with high-swelling degrees will be demonstrated.



**Fig. 1** **a** The change of state of an ion-pair, among free ions, a tightly bound ion-pair, and a higher aggregate. **b** Characteristic conformational change of polyelectrolyte by the dissociation and association of

ion-pairs in the polymer chain. **c** Molecular structures of anions, cations as well as polymers and gels in this section with their abbreviations

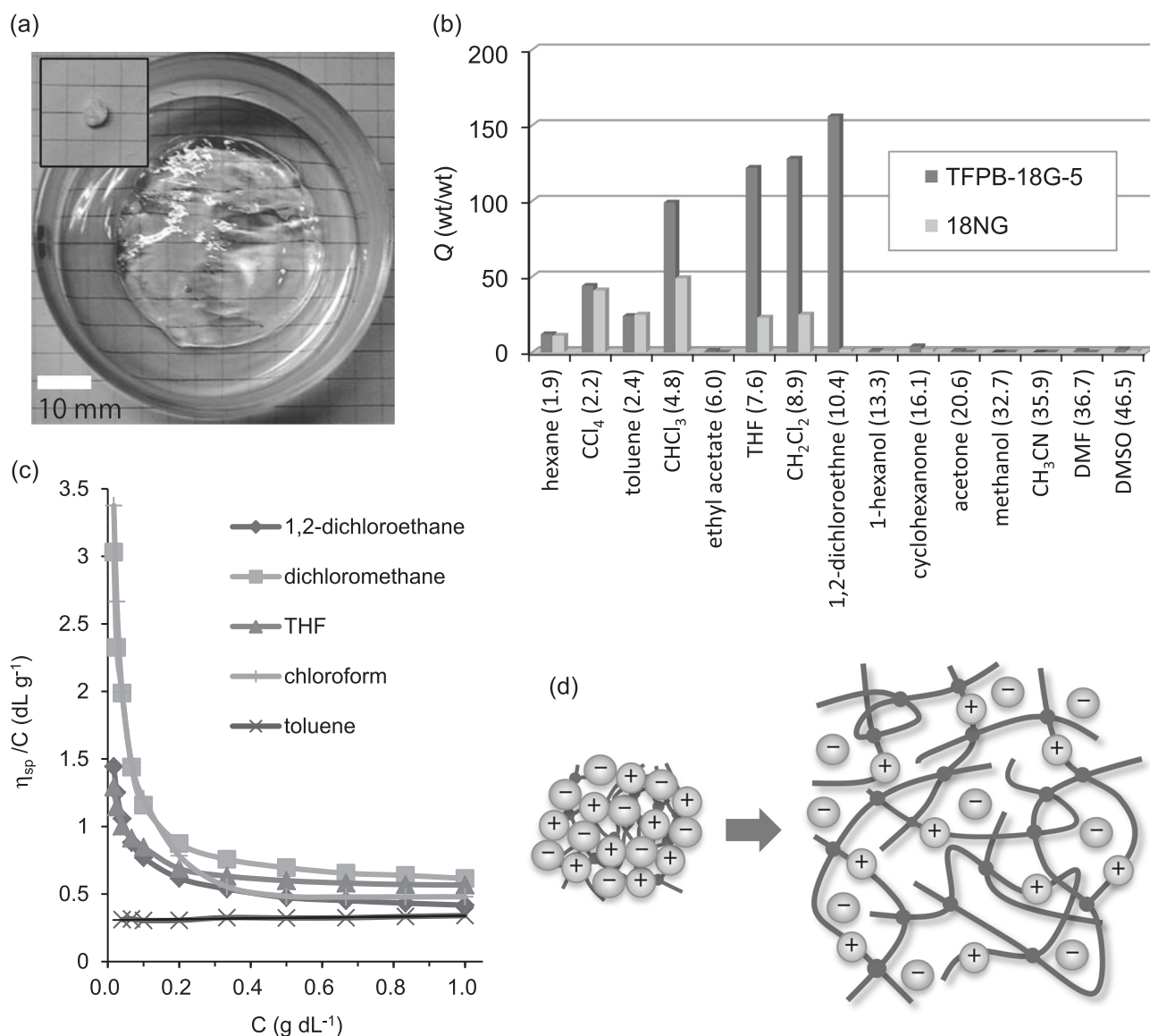
## Designing lipophilic polyelectrolytes

For designing lipophilic polyelectrolytes, the selection of ion-pair and polymer chains in the ionic polymer is of importance. As the key design of the ion-pairs (lipophilic electrolyte) that dissociate into free ions into nonpolar media, we selected tetraarylborates as the anions and tetraalkylammonium or tetraphenylphosphonium as the cations. Especially, due to high stability in acidic media, the tetrakis[3,5-bis(trifluoromethyl)phenyl]borate anion (TFPB) is typically used among the tetraarylborates. The ion-pairs of these hydrophobic ions are known as hydrophobic supporting electrolytes that are soluble and dissociate into ionic species in many less polar organic solvents [31–33]. Their high solubility is attributed to wrapping with lipophilic functional groups, and the high dissociation ability is due to bulky substituents that avoid close contact to the cation, which lengthens the distance between the anion charge and the cation charge and reduces the electrostatic attraction. In fact, the electric conductivity measurement of the tetra (*n*-butyl) ammonium (TBA) salt of TFPB in THF (dielectric constant,  $\epsilon = 7.38$ ) revealed that the salt behaves as a weak electrolyte and partially dissociates into free ions. The ion association constant of the TBA tetraarylborates is two orders of magnitude lower ( $10^3$ – $10^5$ ) than that of the salts of more hydrophilic anions such as chloride (Cl), perchlorate ( $\text{ClO}_4$ ), hexafluorophosphate ( $\text{PF}_6$ ), and bis(trifluoromethanesulfonyl)imide (TFSI), and it easily dissociates in various organic solvents having a higher polarity than chloroform under diluted conditions ( $10^{-3}$ – $10^{-5}$  M) [34, 35]. In toluene, however, the conductivity measurement demonstrates the difficulty in the ion dissociation of TBA-TFPB. Therefore, TFPB is selected as the anionic part for polyelectrolytes. For realization of the lipophilic polyelectrolyte behavior in common nonpolar organic solvents, a flexible polymer with a good compatibility to them should be requisite in addition to a good synthetic accessibility and significant diversity in related monomers. Therefore, we designed polyacrylates and polystyrene bearing the TFPB salt as the ionic part of the lipophilic polyelectrolyte as shown in Fig. 1d. We initially investigated the swelling properties of the lipophilic polyelectrolyte gels as SAPs for organic solvents to prove the validity of our design of an ionic polymer that exhibits a polyelectrolyte behavior in nonpolar organic solvents.

### Lipophilic polyelectrolyte gels as SAPs for organic solvents

Lipophilic polyelectrolyte gels were synthesized under the standard radical copolymerization conditions of an ionic monomer and a nonionic monomer in the presence of the suitable crosslinker [36–42]. In all cases, the resulting gels

were insoluble in all solvents, and swelled or collapsed by immersion in organic solvents. As examples, the volume of TFPB-18G-5 expanded largely by soaking in 1,2-dichloroethane as shown in Fig. 2a. As summarized in Fig. 2b, it showed high-swelling degrees [ $Q = (\text{weight of absorbed solvent}) / (\text{weight of dried gel})$ ]; chloroform ( $Q = 99$ ), THF ( $Q = 122$ ), dichloromethane ( $Q = 128$ ), and 1,2-dichloroethane (1,2-DCE) ( $Q = 158$ ) [36]. When the degree of crosslinking was lowered to 0.2 mol%, the swelling degree was improved by several hundred times ( $Q \sim 480$  in dichloromethane). Compared to the swelling degrees of the nonionic analog (18NG), this large swelling degree was caused by permeation of a large amount of solvent into the inside of the gel due to the osmotic pressure derived from the difference in the ion concentration between the outside and inside of the polymer gels and the electrostatic repulsion among the ionic parts on the polymer chain generated by dissociation of the ionic group in the gel network. On the other hand, in the polar solvents whose dielectric constant is  $>10$ , TFPB-18G-5 collapsed even though the ion-pair is able to dissociate. This low swelling ability originated from the poor compatibility between the polymer chain with a long alkyl chain and the polar solvents. In the extremely nonpolar solvents, whose dielectric constant is smaller than 3, TFPB-18G-5 swelled as much as 18NG, due to the good compatibility between the polymer chain and the nonpolar media. The effect of the ionic part was suppressed due to the formation of a tightly bound ion-pair. Therefore, a sufficient polarity of the medium for dissociation of the ionic part and a sufficient compatibility of the polymer chain to the medium should be required for a high-swelling ability. In order to reveal the origin of the high-swelling ability and confirm the characteristic polymer solution behavior as a polyelectrolyte, we prepared the linear polymer (TFPB-18LP-5) of TFPB-18G-5 without the crosslinker, and investigated its solution properties in nonpolar solvents. As expected, the reduced viscosity increased with the decreasing concentrations in the organic solvents in which TFPB-18G-5 significantly swelled [43]. This solution behavior of TFPB-18LP-5 was typical for charged polymers as shown in Fig. 2c, because dissociation of the ionic part on the polymer chain was enhanced by dilution and an induced electrostatic repulsion among the charges, which was the same as common polyelectrolytes in water. This result indicated that the non-cross-linked TFPB-18LP-5 behaves as a polyelectrolyte in nonpolar solvents. More recently, the scattering experiments for TFPB-18LP-5 and TFPB-18G-5 in chloroform indicated that the high-swelling ability of TFPB-18G-5 originated from the effect of the ionic group. However, the prominent effector of the electrostatic repulsion among the dissociated ions was not observed [44]. Instead, the increase in the osmotic pressure among the polymer chains affects the high-swelling ability.

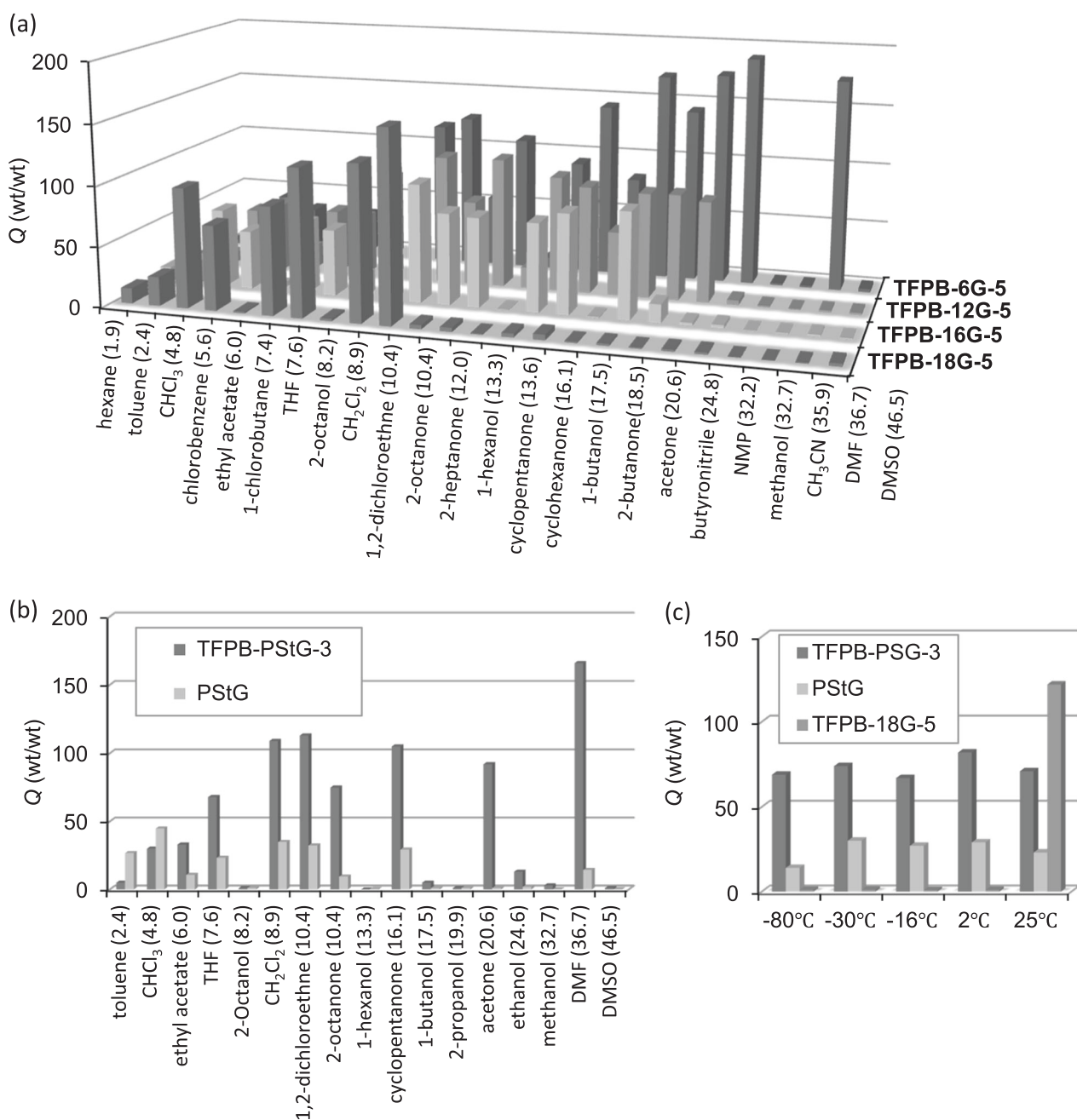


**Fig. 2** **a** Photos of a wet gel of TFPB-18G-5 in DCE and a dried gel (inset). **b** Swelling degrees of TFPB-18G-5 and 18NG in organic solvents at room temperature. Dielectric constant is given in

parentheses. **c** Concentration dependence on reduced viscosity of TFPB-18G-5 in organic solvents at 30.0 °C. **d** Schematic image for swelling of TFPB-18G-5 in organic solvents

Since TFPB-TBA should dissociate into the freely mobile TFPB anion from the polymer chain in chloroform, according to the above-mentioned conductive measurement, the effect of the electrostatic repulsion should be suppressed. However, not freely mobile, but the weakly bound TFPB anions near the polymer chain of TFPB-18G-5 should increase the osmotic pressure and induce a repulsive interaction between them without dissociation. At this stage, we could not propose a clear illustration for the real structure of TFPB-18G-5, but dissociation of the ion-pair in nonpolar media should play a key role in the polyelectrolyte behavior and high-swelling property for these ionic polymer and gels as shown schematically in Fig. 2d.

To confirm the validity and reliability of the molecular design for polyelectrolyte gels working in other solvents, we prepared a series of ionic poly(acrylate ester) gels from hexadecyl (TFPB-16G-5), dodecyl (TFPB-12G-5), and hexyl acrylate (TFPB-6G-5) [37] and an ionic polystyrene-based polyelectrolyte gel (TFPB-PStG-3) [38] under similar conditions. Swelling experiments indicated that the solvents with a prominent swelling degree moved to a more polar region by shortening the alkyl chain of the poly(acrylate ester) as shown in Fig. 3a. This result agrees with the change in the compatibility of these acrylate polymer chains and the solvents. The polystyrene-based polyelectrolyte gel, bearing a similar lipophilic electrolyte of about



**Fig. 3** **a** Swelling degrees of TFPB-18G-5, TFPB-16G-5, TFPB-12G-5, TFPB-6G-5 in organic solvents at room temperature (25 °C). Dielectric constant is given in parentheses. **b** Swelling degrees of TFPB-PStG-3 and nonionic analog polystyrene gel (PStG) in

organic solvents at room temperature (25 °C) with dielectric constant in parentheses. **c** Swelling degrees of TFPB-PStG-3, PStG, and TFPB-18G-5, in acetone at various temperatures; -80, -30, -16, 2, and 25 °C

3–10 mol%, was synthesized and its swelling ability in various organic solvents was evaluated. The introduction of the TFPB salt enhanced the swelling degrees in the organic solvents that are compatible with the polystyrene polymer chain such as DMF, acetone, and 1,2-DCE (Fig. 3b). This behavior is consistent with those of the other ionic polyacrylate gels with the TFPB anion as the

freely mobile counter ion. However, at low temperature, the swelling degrees of TFPB-18G-5 were mostly suppressed due to aggregation among the octadecyl groups by a strong alkyl–alkyl interaction, but TFPB-PStG-3 exhibited high-swelling degrees at -80 °C, as shown in Fig. 3c. Under the extreme environment in which TFPB-18G-5 cannot swell, TFPB-PStG-3 showed a swelling degree

comparable to that at room temperature. The low temperature did not affect the swelling ability due to a stable electrostatic interaction, but the slow kinetics for expanding the polymer chain demands more time for equilibrium swelling after immersion of TFPB-PStG-3 in cool solvents. This material is the first example for SAP working at a low temperature, as a new functional polymer gel [38]. As the last example of lipophilic polyelectrolyte gels, the same ionic part (TFPB salt) was incorporated in the mesogenic polymer network based on the cyanopentylbiphenyl mesogen (TFPB-5CBG-5), and they had a high-swelling ability in some organic solvents and 5CB(4-cyano-4'-pentylbiphenyl) as a liquid crystal solvent similar to the pendant mesogenic group [42].

Another important factor for the high-swelling ability is ionization and compatibility of the ionic part, especially the counter anion in the lipophilic polyelectrolytes. As already described, the conductive measurement of various TBA salts suggested superiority of the TFPB anion compared to other smaller anions as working electrolytes. In order to verify the influence of the ionic part on the swelling ability, we prepared a variety of lipophilic polyelectrolyte gels with tetraalkylammonium and various anions as listed in Fig. 1c on the basis of TFPB-18G-5 or TFPB-PStG-3 [38, 40]. Based on the results of the swelling ability, larger anions covered with hydrophobic groups, i.e., TFPB and IMHFB ( $\mu$ -(1*H*-imidazolato  $\kappa$ -N1:  $\kappa$ -N3 hexakis(pentafluorophenyl) borate), had a significant enhancement of the swelling degree in the solvents with dielectric constants from 4.8 to 10 [40]. This change in comparison to nonionic analogs is attributed to the ionic dissociation of the pendant ion-pairs on the polymer chain to induce electrostatic repulsion and generation of the osmotic pressure. Other anions, such as dodecyl sulfate, TFSI, and PF<sub>6</sub> have no enhancement and decrease the swelling degree especially in nonpolar solvents due to the difficulty of ionization by dissociation or higher aggregation of ion-pairs. Consequently, the dissociation of the ionic groups should play a key role in the high-swelling ability, and the size and hydrophobicity of the anion and cation contribute to the ionic dissociation and generation of osmotic pressure for the polymer chain, which provide polyelectrolyte behaviors in nonpolar solvents.

To summarize this section, we clarified that the molecular design of superabsorbent materials corresponding to various organic solvents is possible by controlling both the compatibility between the polymer chain and medium and ion dissociation ability of the ionic functional group [37]. The introduction of lipophilic ion-pairs enables the creation of polyelectrolytes that function in a wide range of organic solvents. Therefore, at this stage, we can design and prepare polymer gels with high-swelling degrees ( $Q > 100$ ) as superabsorbent polymers for all the solvents more polar than chloroform.

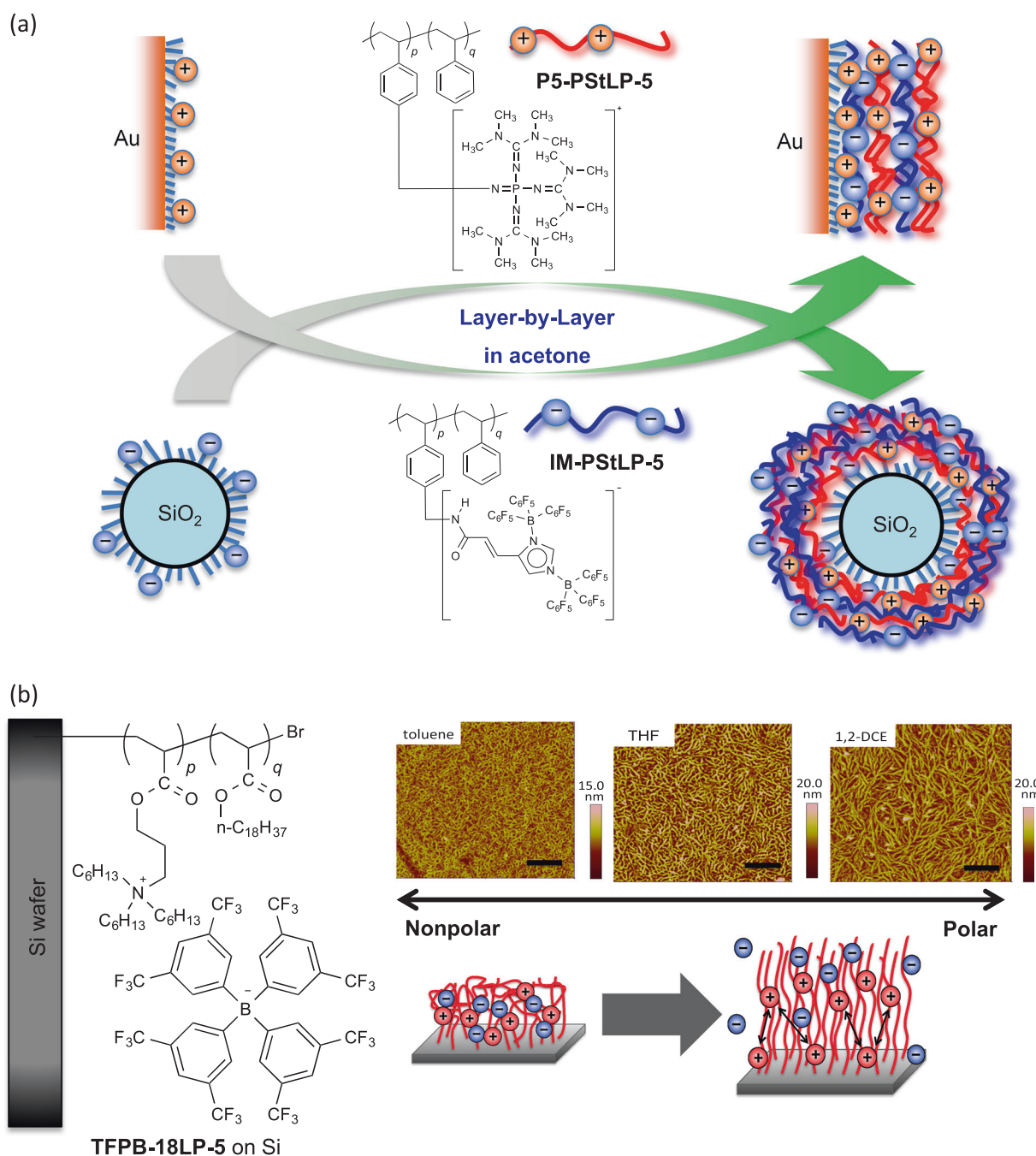
## Other applications of lipophilic polyelectrolytes

As already mentioned, the development of SAPs is the most important application for lipophilic polyelectrolytes. The utility for electrostatic repulsion and osmotic pressure via dissociation of an ion-pair in nonpolar media prompted us to explore other functional materials or molecular systems. For polymeric materials, we reported layer-by-layer assemblies in less polar solvents [45]. Anionic polystyrene (IM-PStLP-5) with IMHFB as the hydrophobic anionic group on the polymer chain and cationic polystyrene (P5-PStLP-5) with P5 as the hydrophobic cationic group on the polymer chain were newly prepared, and a Layer-by-Layer technique was applied to a gold surface or silica nanoparticles with a similar lipophilic electrolyte to form a multilayer by alternating repeated immersions of the IM-PSLP-5 solution and P5-PSLP-5 solution as shown in Fig. 4a.

Another example is the development of a lipophilic polyelectrolyte polymer brush. Drastic expansion and shrinking of the layer distance in the polyelectrolyte polymer brushes have been well documented, but the media are mostly water or highly polar solvents. We attempted to develop a polyelectrolyte brush working in nonpolar solvents [46]. Surface-initiated activators regenerated by atom transfer radical polymerization method provided the moderate polymer brush of TFPB-18LP-5 on a Si wafer. The surface morphology variation induced by immersing in organic solvents was investigated. Immersion in 1,2-DCE resulted in twining of large fibers due to extension of the polymer chains that was caused by good compatibilities of the polymer chain and dissociation of the TFPB counter anion from TFPB-18LP-5 as shown in Fig. 4b. This expansion is consistent with the high-swelling ability of the lipophilic polyelectrolyte gels in the same solvent. These results clearly support the extension of the lipophilic polyelectrolyte polymer chain due to the dissociation of the ionic group.

## Future of lipophilic polyelectrolytes

As mentioned in the introduction, the characteristic behavior of ionic polymers due to dissociation of the ionic group, known as polyelectrolyte behavior, has never been realized in a solvent other than water, in particular, in nonpolar solvents. In this section, I described the molecular design of the lipophilic polyelectrolyte by combination of a hydrophobic polymer chain and hydrophobic ion-pair wrapped by large hydrophobic groups. The control of the size of both the anion and cation should play a key role in the dissociation of the ionpair in many organic solvents. Among the applications of lipophilic polyelectrolytes, we demonstrate SAPs for the organic solvents with a wide range of polarities from chloroform to DMSO or DMF. Development of SAPs for oils and other nonpolar



**Fig. 4** **a** Formation of layer-by-layer assembly of IM-PSiLP-5 and P5-PSiLP-5. **b** Solvent-induced morphology change of lipophilic polyelectrolyte polymer brush of TFPB-18LP-5 on Si

solvents has not yet been achieved, but our recent approach revealed that the mixing of these media with ethanol at about 10% v/v drastically increases the swelling ability of the lipophilic polyelectrolyte gels [41]. On the other hand, according to the classical Bjerrum theory, if both the anions and cations have a radius greater than three nanometers, the ion association constant sufficiently decreases to dissociate to free ions into extremely nonpolar media with dielectric constants  $<3$  [47–49]. The

development of large hydrophilic ions should be the primary target for high-swelling materials. The systematic survey for the relationship between the ion association constant and the polarity or other parameters of various solvents is also important for the selection of ion-pairs for polyelectrolytes. Accordingly, this investigation for ion-pairs and compatibility of the polymer chain to the media will provide us the precise design for polyelectrolytes and SAPs in various media [50–52].



## New design of thermo-responsive polymers in nonpolar solvents

### Stimuli-responsive polymers

The stimuli-sensitive polymer is another important material for smart and functional organic materials and defined as a polymer that has a drastic change in its polymer conformation between the coil and globe triggered by an environmental change [53–56]. As a stimulus, temperature, light, electric and magnetic fields, pH, and chemical compounds have been employed. The change in the polymer conformation is mostly accompanied by the change in the polymer solubility by intermolecular association among the polymer chains. They are used as smart materials for devices that detect and respond to environmental changes. A high number of stimuli-responsive polymers has been designed and reported, but most of them were derivatives from a thermo-responsive polymer by modification with sensitive groups that respond to these stimuli and modulation of the phase transition temperature. Thus, the design of a thermo-responsive polymer should be of significance for developing new stimuli-sensitive polymers in various media.

### Thermo-responsive polymers

Thermo-responsive polymers are the stimuli-sensitive polymers that exhibit a phase separation by cooling or heating of the polymer solution [57–82]. Based upon the thermo-responsiveness, they are divided into two types. One is the LCST (lower critical solution temperature) type and the other is the UCST (upper critical solution temperature) type. The LCST-type thermo-sensitive polymers become a homogenous solution below the phase transition temperature, and the phase separation of the polymer occurs above it. The UCST-type polymers are insoluble at low temperature and becomes soluble above the phase transition temperature. The drastic change in solubility around the phase transition temperature is characteristic of the thermo-responsiveness.

The most famous example of the LCST-type thermo-sensitive polymers is *N*-isopropylacrylamide (NIPAM) in water [58, 70]. It undergoes an LCST-type phase separation around 35 °C similar to our body temperature. Many amphiphilic polymers including poly(ionic liquid)s have been reported to have an LCST-type phase separation. [57–63, 70–76] These results inspired the enormous number of applications in the field of biomaterials [64, 77, 78]. On the other hand, the LCST thermosensitivity in organic solvents can be seen in many versatile polymers, but most of them showed their LCST phase transition temperature above 350 K [65–67, 79, 80], as shown in Fig. 5a. Some examples exhibiting the LCST-type responsiveness at ambient

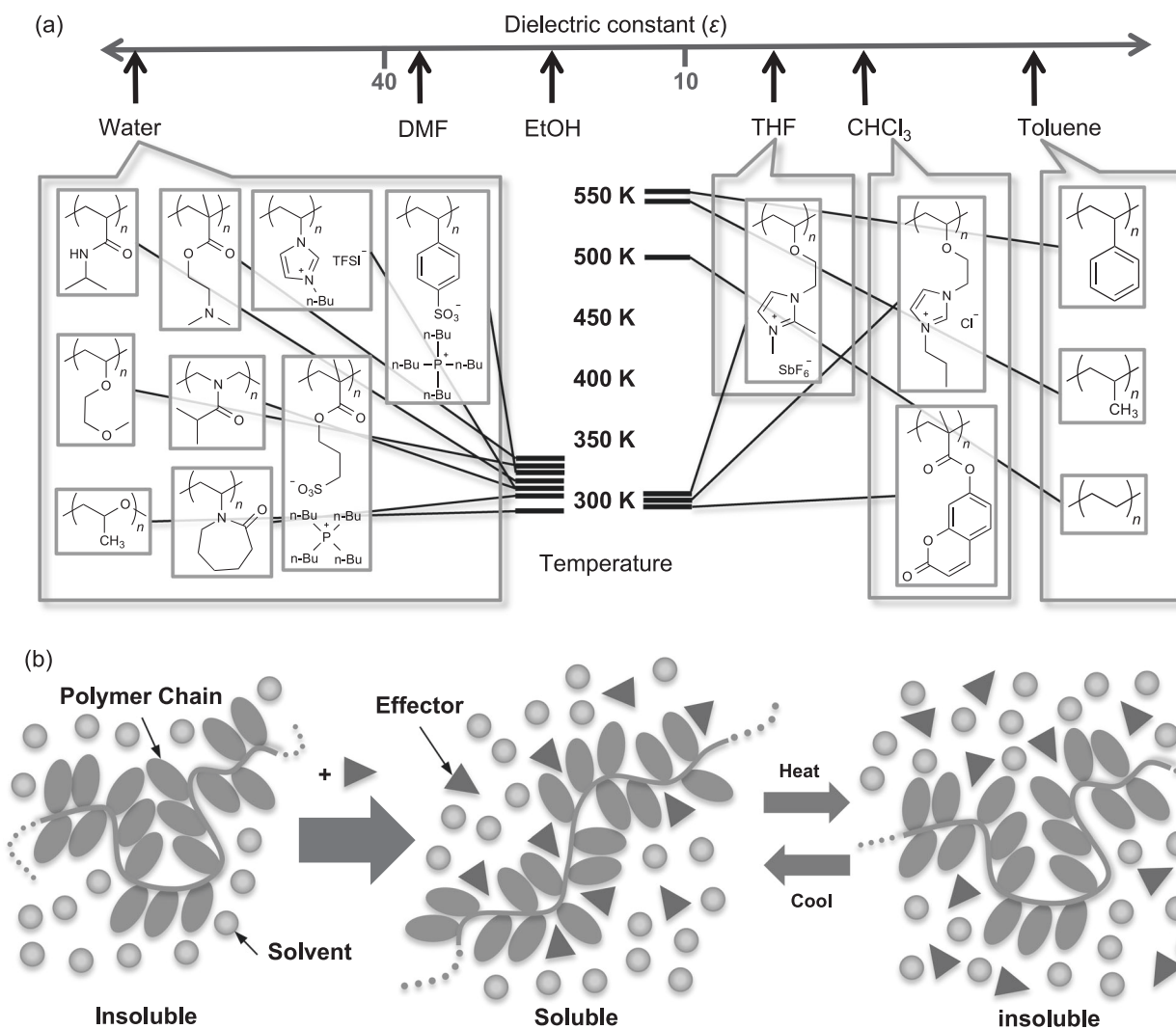
temperatures were quite rare, and they were often discovered by accident or by trial and error [68, 69, 81, 82]. Therefore, the rational design of LCST polymers in organic solvents still remains unclear.

### Designing LCST thermo-responsive polymers by supramolecular design

Based on the behavior of NIPAM in water, it can be understood that the dehydration process of water molecules that surround the polymer chain of NIPAM is important for the LCST behavior. Hydration of the NIPAM polymer chain, i.e., formation of a hydrogen bond between the amide groups of NIPAM and water molecules, contributes to solubilization of NIPAM at low temperature, while the dehydration of water molecules from the polymer chain by heating induces aggregation of the hydrophobic group of NIPAM to achieve phase separation of NIPAM at higher temperatures [56, 57, 70]. In other words, the LCST phase separation implies a desolvation process, i.e., the dissociation of solvated molecules from the polymer chain, followed by aggregation of the polymer chain, because the desolvated polymer chain becomes unstable in the medium. This mechanism prompted us to design a thermo-sensitive polymers of a ternary solution system by designing supramolecular interaction between the polymer chain and surrounding environment, as shown in Fig. 5b. By combining a polymer and a solvent that has a poor compatibility to the polymer chain due to difficulty in solvating with the solvent molecules, a pseudo-solvating molecule that can interact with the polymer chain and has a high affinity for the solvent is allowed to coexist as a third component, called an effector. Heating of the polymer solution induced dissociation of the macromolecular complexes between the effectors and the polymer chain, and phase separation is expected to occur by desolvation of the pseudo-solvating molecules. Based on the solution behavior of NIPAM in water, we successfully deduced the LCST phenomena and attempted to design a new LCST polymer phase separation in organic solvents [83, 84]. Two types of supramolecular interactions were used for the attractive interaction in nonpolar media at low temperature, but decomposed by a slight heating around 320 K. One is the charge transfer (CT) interaction between the pyrene groups in the polymer chain and low-molecular acceptors, and the other is a hydrogen bond (HB) between the urea groups in the polymer chain and low-molecular alcohols or other hydrogen bond compounds.

### Breaking charge transfer (CT) interaction induces the LCST phase transition

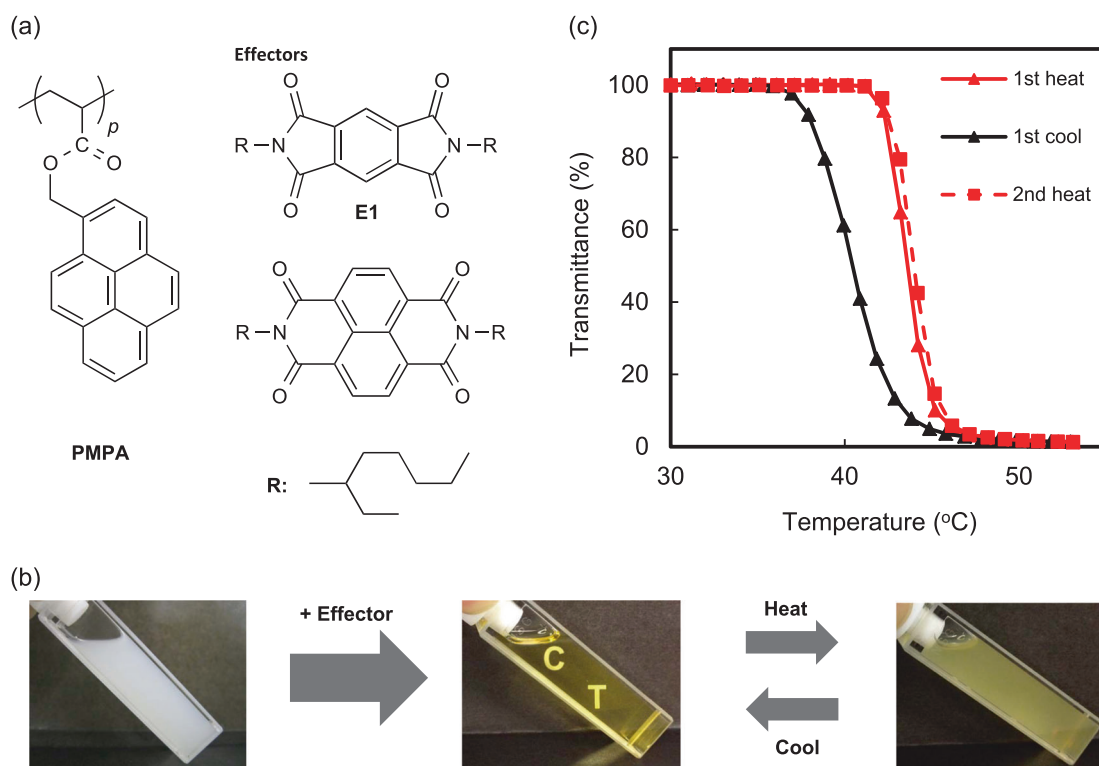
The CT complexes are prepared by mixing an electron donor and an acceptor at a 1:1 ratio in many types of media.



**Fig. 5** **a** Typical examples for LCST homopolymers in various solvents and their phase transition temperature. **b** Supramolecular design of thermo-sensitive polymers by using effector as the third component

The most famous example is organic conductors and superconductors in the crystalline state, and they are also used for the construction of catenanes and fibrous aggregates of organogels in solution. Our supramolecular design is based on thermal cleavage of the CT complex of the macromolecular donor and low-molecular acceptors. For the macromolecular donor, the pyrene ring was selected as a large aromatic  $\pi$ -plane that is able to easily form  $\pi$ - $\pi$  stacking among them to collapse the polymer chain [83]. Moreover, it acts as a donor in the presence of suitable acceptors to form CT complexes. Thus, poly(2-methylpyrenyl acrylate) (PMPA) was prepared by radical polymerization of the pyrene monomer under the standard conditions. As expected, the solubility of PMPA is not high in a wide range of organic solvents, due to the strong  $\pi$ - $\pi$  interaction between the pyrene rings. By the addition of suitable acceptors as effectors shown in Fig. 6a, the polymer

suspension in some organic solvents, such as 1,2-DCE and toluene, became a clear solution and the color of the solution changed due to formation of CT complexes. The complexation of the effectors to the pyrene unit of the polymer chain interfered with the  $\pi$ - $\pi$  stacking to increase the solubility even in poor solvents. By heating, the polymer solution became turbid again, and the polymer suspension became a clear solution by cooling back to room temperature. This reversible transition between the phase separated state and the homogeneous solution should be recognized as the LCST phase transition, and the turbidity of the solution could be monitored by the change in the absorption at 800 nm as shown in Fig. 6b. Deposition of the polymer from the solution is attributed to partial decomposition of the CT complexes between the pyrene pendant groups on the polymer chain and low-molecular acceptors. This process is essentially the same as desolvation of water



**Fig. 6** **a** Molecular structures of PMPA and an effectors. **b** and **c** Photographic images and transmittance change of PMPA solution in the presence of effector E1 upon heating and cooling

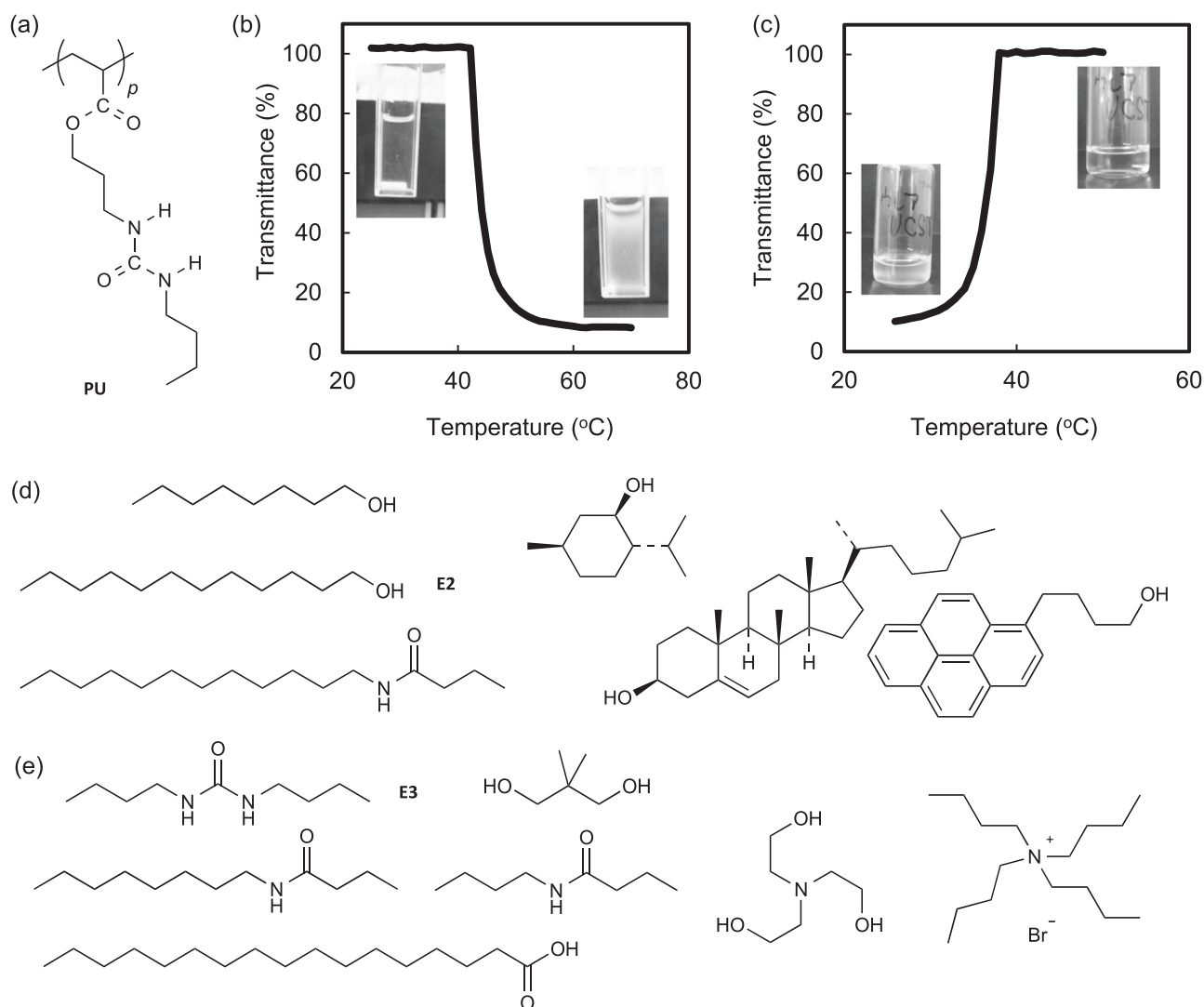
molecules from the solvated NIPAM by heating. In our case, the effectors act as desolvated species from the polymer chain, and the unsolvated PMPA regenerates the  $\pi$ - $\pi$  stacking among the pyrene groups to become insoluble in the solvent. Based on an investigation of the thermodynamic parameters of the association between the effector and PMPA, the phase transition occurs at the temperature at which about 20% of the polymer chain interacts with the effector. A thermo-responsive polymer system can be realized by the formation and thermal dissociation of the CT complex between the macromolecular pyrene and low-molecular acceptors. Moreover, we successfully prepared PMPA gels by polymerization in the presence of a bifunctional crosslinking agent, and investigated its swelling ability [85]. In the presence of a suitable acceptor, the PMPA gels exhibited a high-swelling ability in DCE and collapsed by heating. Therefore, the PMPA gels should be the LCST-type thermo-responsive polymer gels working in some organic solvents.

### Breaking hydrogen bond (HB) interaction induces the LCST phase transition

Another example for designing LCST behaviors by a supramolecular interaction involves hydrogen bonding of the urea group as an association functional group in the

polymer chain in nonpolar media. Urea groups are known to have the remarkable ability to form a one-dimensional hydrogen bond network between its two hydrogen atoms and carbonyl group, and they are used as building blocks for low-molecular organogels in aprotic solvents. Thus, we expected that hydrogen bonding compounds can cleave hydrogen bonds between the urea groups on the polymer chain and act as effectors to adjust the solubility of the polymer and realize an LCST thermal behavior [84].

We prepared the polymer with the urea group (PU) as shown in Fig. 7a by the standard radical polymerization. PU alone is not soluble in nonpolar solvents, but it became soluble when a few equivalents of an effector to the urea group was added to the solution. Further examination of the temperature response revealed that the LCST-type phase separation was observed when a small amount of alcohol, such as 1-dodecanol (E2), was added as an effector as shown in Fig. 7b. On the other hand, *N,N'*-dibutylurea (E3) induced UCST-type phase separation as shown in Fig. 7c. A survey of chemical compounds as effectors of PU indicated that the compounds with hydrogen bonding groups showed the UCST-type or LCST-type phase separation. When alcohols, amides, etc., shown in Fig. 7d were added, it showed an LCST behavior. Interestingly, however, when the bromide anion, carboxylic acid, urea derivative, etc., shown in Fig. 7e were added, it showed a UCST behavior.



**Fig. 7** **a** Molecular structure of PU. **b** Transmittance change of PU solution in the presence of E2 upon heating. **c** Transmittance change of PU solution in the presence of E3 upon heating. **d** Effectors for LCST phase separation. **e** Effectors for UCST phase separation

From evaluation of the association constants of the model compounds, the reason for this different thermal response should be the difference in the association constants between the urea group and other hydrogen bond functional groups. When it is sufficiently low ( $K < 1 \text{ M}^{-1}$ ), the effectors induced an LCST-type phase separation. When the association constant is about 50 times that of the LCST-type ( $K > 50 \text{ M}^{-1}$ ), UCST is induced. The lower binding affinity undergoes to the LCST phase separation by heating via desolvation of the effector. On the other hand, for UCST, the high-binding affinity keeps the high solubility at high temperature, because no decomposition of the macromolecular complexes takes place. While, at low temperature, precipitation undergoes by strong association of the polymer chain, and small amount of the effector might coprecipitate. This should increase the solubility of the polymer by heating and cause UCST phase transition.

Moreover, the coexistence of two effectors for the LCST and UCST induced a polymer solution that exhibits both the LCST and UCST phase transitions in a single polymer system, and the temperature range could be controlled over a wide range from 10 to 70 °C by controlling the amounts of the two effectors. This study clearly showed that the addition of an effector in the polymer solution should be an easy method to generate the LCST and UCST phase separation from the polymer suspension. The supramolecular design among the solvent, polymer, and effector should include a wide range of thermo-sensitive polymers.

### Implications for effector system for LCST and UCST behaviors

Our design for the thermo-sensitive polymers clearly demonstrates the significance of the solvation and

desolvation process between the polymer chain and low-molecular effectors. In our design, the effector acts as the third component in the system, neither the polymer nor solvent, and its desolvation induced a significant entropic gain due to release of the bound effector to the polymer chain into the solution by heating. As a result, the association constants between them should be relatively small compared to those used in supramolecular chemistry. Indeed, for both of our successful examples, the effectors have a low affinity to the polymer chain. This indicated that this process is entropy dominant, and the dissociation of macromolecules and effectors gains entropy, thus the LCST-type temperature response can be easily achieved at ambient temperatures.

From a comparison of NIPAM in water, in our systems, since the solvent has no ability for solvation of the polymer chain, and the effector as a solvating molecule accesses both the solvent molecule and the polymer chain, the roles of the solvent and effector are clearly separated. However, for the LCST behaviors of NIPAM in water, the water molecule acts both as the solvent and effector. Thus, based on our estimation, the association constants between the water and amide groups in NIPAM should be extremely low at around  $K < 10^{-2} \text{ M}^{-1}$ , because the concentration of the water molecule should be  $55 \text{ mol L}^{-1}$  as the media. Therefore, the semi-diluted condition of the effectors should be accessible to a wide range of LCST phase transitions in our system. Finally, careful supramolecular design for desolvating molecules as effectors and the polymer chain solvated by the effector should provide a wide range of LCST and USCT polymer phase transitions. We believe that our design of a thermosensitive polymer should be of significance for the new de novo design of the stimuli-responsive polymers.

## Concluding remarks

We demonstrated the molecular design of two different functional materials in nonpolar media. One is a super-absorbent polymer and the other is a thermo-sensitive polymer. They have been extensively studied in water, but the molecular designs in other media have remained unclear. Our results clearly provided a generalized molecular design for them based on deduction from the observations in water, which should expand their applicability. With respect to supramolecular chemistry, the key factor for both phenomena is dissociation of the building blocks from macromolecular complexes. For the former, a tightly bound macromolecular ion-pair dissociates into free ions, which induces the high extension of the polymer chain and high-swelling ability of the network. For the latter, thermal dissociation of the effector from the macromolecular

complexes induced the LCST polymer phase separation. Moreover, in both cases, the binding affinities are relatively low, and the counter ion or the effector is weakly bound and surrounds the polymer chain, which increases the osmotic pressure of the polymer chain and suppresses their close contact. Therefore, supramolecular control of the polymer solvation should be a key role for the solution property of the functional polymeric materials. Based on this concept, we are going to develop a series of new functional materials.

**Acknowledgements** This work was partially supported by JSPS KAKENHI Grant Numbers JP23350048, JP26288054. I deeply appreciate all the collaborators, especially the laboratory members at Kyushu University and Hokkaido University for their helpful discussion and enthusiastic support of the experiments and the analysis.

## Compliance with ethical standards

**Conflict of interest** The author declares that they have no conflict of interest.

## References

1. Lehn J-M. Supramolecular chemistry – receptors, catalysts, and carriers. *Science*. 1985;227:849–56.
2. Vögtle F. Supramolecular chemistry an introduction. New York, USA: Wiley, Chichester; 1989.
3. Lehn J-M. Supramolecular chemistry concepts and perspectives. Weinheim, Germany: Wiley-VHC; 1995.
4. Atwood JL, et al. Comprehensive supramolecular chemistry, 1st ed. Vol. 1–11. Oxford, U.K.: Pergamon; 1996.
5. Harada A, Takashima Y, Nakahata M. Supramolecular polymeric materials via cyclodextrin-guest interactions. *Acc Chem Res*. 2014;47:2128–40.
6. Stupp SI, LeBonheur V, Walker K, Li LS, Huggins KE, Keser M, Amstutz A. Supramolecular materials: Self-organized nanostructures. *Science*. 1997;276:384–9.
7. Boal AK, Ilhan F, DeRouchey JE, Thurn-Albrecht T, Russell TP, Rotello VM. Self-assembly of nanoparticles into structured spherical and network aggregates. *Nature*. 2000;404:746–8.
8. Niemeyer CM. Nanoparticles, proteins, and nucleic acids: Biotechnology meets materials science. *Angew Chem Int Ed*. 2001;40:4128–58.
9. Ikkala O, ten Brinke G. Functional materials based on self-assembly of polymeric supramolecules. *Science*. 2002;295:2407–9.
10. Zhang SG. Fabrication of novel biomaterials through molecular self-assembly. *Nat Biotechnol*. 2003;21:1171–78.
11. Fujita M. Metal-directed self-assembly of two- and three-dimensional synthetic receptors. *Chem Soc Rev*. 1998;27:417–25.
12. Stang PJ, Olenyuk B. Self-assembly, symmetry, and molecular architecture: Coordination as the motif in the rational design of supramolecular metallacyclic polygons and polyhedral. *Acc Chem Res*. 1997;30:502–18.
13. Desiraju GR. Supramolecular synthons in crystal engineering- A new organic-synthesis. *Angew Chem Int Ed*. 1995;34:2311–27.
14. Terech P, Weiss RG. Low molecular mass gelators of organic liquids and the properties of their gels. *Chem Rev*. 1997;97:3133–59.
15. van Esch JH, Feringa BL. New functional materials based on self-assembling organogels. *Angew Chem Int Ed*. 2000;39:2263–6.

16. Kato T, Mizoshita N, Kishimoto K. Functional liquid-crystalline assemblies: Self-organized soft materials. *Angew Chem Int Ed*. 2006;45:38–68.
17. De Greef TFA, Smulders MMJ, Wolffs M, Schenning APHJ, Sijbesma RP, Meijer EW. Supramolecular polymerization. *Chem Rev*. 2009;109:5687–754.
18. Aida T, Meijer EW, Stupp SI. Functional supramolecular polymers. *Science*. 2012;335:813–7.
19. Antonietti M, Forster S. Vesicles and liposomes: A self-assembly principle beyond lipids. *Adv Mater*. 2003;15:1323–33.
20. Metrangolo P, Neukirch H, Pilati T, Resnati G. Halogen bonding based recognition processes: A world parallel to hydrogen bonding. *Acc Chem Res*. 2005;38:386–95.
21. Nishio M. CH/ $\pi$  hydrogen bonds in crystals. *Cryst Eng Comm*. 2004;6:130–58.
22. Oosawa F. *Polyelectrolytes*. New York, USA: Marcel Dekker; 1971.
23. Forster S, Schmidt M. *Polyelectrolytes in solution*. *Adv Polym Sci*. 1995;120:51–133.
24. Dautzenberg H, Jaeger W, Kötzt J, Philipp B, Seidel C, Stscherbina D. *Polyelectrolytes*. Munich: Hanser; 1994.
25. Cohen Stuart MA, Huck WTS, Genzer J, Müller M, Ober C, Stamm M, Sukhorukov GB, Szleifer I, Tsukruk VV, Urban M, Winnik F, Zauscher S, Luzinov I, Minko S. Emerging applications of stimuli-responsive polymer materials. *Nat Mater*. 2010;9:101–13.
26. *Superabsorbent Polymers: Science and Technology*, Buchholz, FL, Peppas, NA, editors. ACS Symposium Series, Vol. 573. American Chemical Society: Washington D.C. USA; 1994.
27. Jousset S, Bellissent H, Galin JC. Polyelectrolytes of high charge density in organic solvents. *Synth viscosimetric Behav Macromol*. 1998;31:4520–30.
28. Liu X, Hu O, Tong Z. Viscosity behavior of polyelectrolyte copolymers containing sulfonate groups in mixed organic solvents. *J Polym Sci, Part B: Polym Phys*. 1997;35:1433–8.
29. Zagar E, Zigon M. Solution properties of carboxylated polyurethanes and related ionomers in polar solvents (DMF and LiBr/DMF). *Polym (Guildf)*. 2000;41:3515–21.
30. Bhavsar RS, Kumbharkar SC, Rewar AS, Kharul UK. Polybenzimidazole based film forming polymeric ionic liquids: synthesis and effects of cation–anion variation on their physical properties. *Polym Chem*. 2014;5:4083–96.
31. Berns DS, Fuoss RM. Electrolyte-solvent interaction. IX. Tetraalkylammonium tetraphenylborides in acetonitrile-carbon tetrachloride mixtures at 25°. *J Am Chem Soc*. 1960;82:5585–8.
32. Fabry TL, Fuoss RM. Electrolyte-solvent interaction. XIV. Triisopropanolamine borate with triisooamylbutylammonium salts. *J Phys Chem*. 1964;68:907–10.
33. Coetzee JF, Sharpe WR. Solute-solvent interactions. VI. Specific interactions of tetraphenylarsonium, tetraphenylphosphonium, and tetraphenylborate ions with water and other solvents. *J Phys Chem*. 1971;75:3141–6.
34. Bhattacharyya DN, Lee CL, Smid J, Szwarc M. Ions and ion pairs in tetrahydrofuran (THF) solution. Alkali metal salts of tetraphenylboride. *J Phys Chem*. 1965;69:608–11.
35. Tsierkezos NG, Philippopoulos AI. Studies of ion solvation and ion association of *n*-tetrabutylammonium hexafluorophosphate and *n*-tetrabutylammonium tetraphenylborate in various solvents. *Fluid Phase Equilibria*. 2009;277:20–8.
36. Ono T, Sugimoto T, Shinkai S, Sada K. Lipophilic polyelectrolyte gels as super-absorbent polymers for nonpolar organic solvents. *Nat Mater*. 2007;6:429–33.
37. Ono T, Sugimoto T, Shinkai S, Sada K. Molecular design of superabsorbent polymers for organic solvents by crosslinked lipophilic polyelectrolytes. *Adv Funct Mater*. 2008;18:3936–40.
38. Iseda K, Ohta M, Ono T, Sada K. High swelling ability of polystyrene-based polyelectrolyte gels at low temperature. *Soft Matter*. 2011;7:5938–40.
39. Ohta M, Boddu VM, Uchimiya M, Sada K. Thermal response and recyclability of poly(stearyl-acrylate-co-ethylene glycol dimethacrylate) gel as a VOCs absorbent. *Polym Bull*. 2011;67:915–26.
40. Ono T, Ohta M, Iseda K, Sada K. Counter anion dependent swelling behaviour of poly(octadecyl acrylate)-based lipophilic polyelectrolyte gels as superabsorbent polymers for organic solvents. *Soft Matter*. 2012;8:3700–4.
41. Ono T, Sada K. Toward the design of superabsorbent materials for non-polar organic solvents and oils: Ionic content dependent swelling behavior of cross-linked poly(octadecyl acrylate)-based lipophilic polyelectrolytes. *J Mater Chem*. 2012;22:20962–7.
42. Nishikori Y, Iseda K, Kokado K, Sada K. Mesogenic polyelectrolyte gels absorb organic solvents and liquid crystalline molecules. *Polymers*. 2016;8:148.
43. Ono T, Ohta M, Sada K. Ionic polymers act as polyelectrolytes in nonpolar media. *ACS Macro Lett*. 2012;1:1270–3.
44. Nishi K, Tochioka S, Hiroi T, Yamada T, Kokado K, Kim T-H, Gilbert EP, Sada K, Shibayama M. Structural analysis of lipophilic polyelectrolyte solutions and gels in low-polar solvents. *Macromolecules*. 2015;48:3613–21.
45. Ohta M, Ono T, Sada K. Layer-by-layer deposition of ionomers with lipophilic ion-pairs dissociated in less-polar media. *Chem Lett*. 2011;40:648–50.
46. Yamada T, Kokado K, Higaki Y, Takahara A, Sada K. Preparation and morphology variation of lipophilic polyelectrolyte brush functioning in nonpolar solvents. *Chem Lett*. 2014;43:1300–2.
47. Krossing I, Raabe I. Noncoordinating anions -fact or fiction? A survey of likely candidates. *Angew Chem Int Ed*. 2004;43:2066–90.
48. Türp D, Wagner M, Enkelmann V, Müllen K. Synthesis of nanometer-sized, rigid, and hydrophobic anions. *Angew Chem Int Ed*. 2011;50:4962–5.
49. Mpoukouvalas K, Türp D, Wagner M, Müllen K, Butt H-J, Floudas G. Dissociation and charge transport in salts of dendronized ions in solvents of low polarity. *J Phys Chem B*. 2011;115:5801–6.
50. Roy SW, Haldar U, De P. Remarkable swelling capability of amino acid based cross-linked polymer networks in organic and aqueous medium. *ACS Appl Mater Interfaces*. 2014;6:4233–41.
51. Chen J, Wang S, Peng J, Li J, Zhai M. New lipophilic polyelectrolyte gels containing quaternary ammonium salt with superabsorbent capacity for organic solvents. *ACS Appl Mater Interfaces*. 2014;6:14894–902.
52. Zhang Y, Wang B, Elageed EHM, Qin L, Ni B, Liu X, Gao G. Swelling poly(ionic liquid)s: Synthesis and application as quasi-homogeneous catalysts in the reaction of ethylene carbonate with aniline. *ACS Macro Lett*. 2016;5:435–8.
53. Roy D, Cambre JN, Sumerlin BS. Future perspectives and recent advances in stimuli-responsive materials. *Prog Polym Sci*. 2010;35:278–301.
54. Schattling P, Jochum FD, Theáto P. Multi-stimuli-responsive polymers – the all-in-one talents. *Polym Chem*. 2014;5:25–36.
55. Zhuang J, Gordon MR, Ventura J, Li L, Thayumanavan S. Multi-stimuli responsive macromolecules and their assemblies. *Chem Soc Rev*. 2013;42:7421–35.
56. Guragain B, Prasad B, Malgras BV, Nakashima K, Yamauchi Y. Multi-stimuli-responsive polymeric materials. *Chem Eur J*. 2015;21:13164–74.
57. Roy D, Brooks WLA, Sumerlin BS. New directions in thermo-responsive polymers. *Chem Soc Rev*. 2013;42:7214–43.
58. Heskins M, Guillet JE. Solution properties of poly(N-isopropylacrylamide). *J Macromol Sci Chem*. 1968;2:1441–5.
59. Firman P, Kahlweit M. Phase behavior of the ternary system H<sub>2</sub>O - oil - polypropyleneglycol (PPG). *Colloid Polym Sci*. 1986;264:936–42.

60. Uyama H, Kobayashi S. A novel thermo-sensitive polymer. Poly (2-*iso*-propyl-2-oxazoline). *Chem Lett*. 1992;21:1643–6.
61. Tager AA, Safronov AP, Berezyuk EA, Galaev IY. Lower critical solution temperature and hydrophobic hydration in aqueous polymer solutions. *Colloid Polym Sci*. 1994;272:1234–9.
62. Aoshima S, Oda H, Kobayashi E. Synthesis of thermally-induced phase separating polymer with well-defined polymer structure by living cationic polymerization. I. Synthesis of poly(vinyl ethers) with oxyethylene units in the pendant and its phase separation behavior in aqueous solution. *J Polym Sci, Part A: Polym Chem*. 1992;30:2407–13.
63. Kohno Y, Saita S, Men Y, Yuan J, Ohno H. Thermoresponsive polyelectrolytes derived from ionic liquids. *Polym Chem*. 2015;6:2163–77.
64. Chung JE, Yokoyama M, Yamato M, Aoyagi T, Sakurai Y, Okano T. Thermo-responsive drug delivery from polymeric micelles constructed using block copolymers of poly(*N*-isopropylacrylamide) and poly(butylmethacrylate). *J Control Release*. 1999;62:115–27.
65. Freeman PI, Rowlinson JS. Lower critical points in polymer solutions. *Polym (Guildf)*. 1960;1:20–6.
66. Saeki S, Kuwahara N, Konno S, Kaneko M. Upper and lower critical solution temperatures in polystyrene solutions. *Macromolecules*. 1973;6:246–50.
67. Kuwahara N, Saeki S, Chiba T, Kaneko M. Upper and lower critical solution temperatures in polyethylene solutions. *Polym (Guildf)*. 1974;15:777–81.
68. Seno K-i, Kanaoka S, Aoshima S. Synthesis and LCST-type phase separation behavior in organic solvents of poly(vinyl ethers) with pendant imidazolium or pyridinium salts. *J Polym Sci, Part A: Polym Chem*. 2008;46:5724–33.
69. Sato E, Masuda Y, Kadota J, Nishiyama T, Horibe H. Dual stimuli-responsive homopolymers: Thermo- and photo-responsive properties of coumarin-containing polymers in organic solvents. *Eur Polym J*. 2015;69:605–15.
70. Halperin A, Kröger M, Winnik FM. Poly(*N*-isopropylacrylamide) phase diagrams: Fifty years of research. *Angew Chem, Int Ed*. 2015;54:15342–367.
71. Crespo Colin A, Cancho SM, Rubio RG, Compostizo A. Equation of state of aqueous polymer systems: poly(propylene glycol) + water. *Phys Chem Chem Phys*. 1999;1:319–22.
72. Lau ACW, Wu C. Thermally Sensitive and Biocompatible Poly (N-vinylcaprolactam): Synthesis and characterization of high molar mass linear chains. *Macromolecules*. 1999;32:581–4.
73. Men Y, Schlaad H, Yuan J. Cationic poly(ionic liquid) with tunable lower critical solution temperature-type phase transition. *ACS Macro Lett*. 2013;2:456–9.
74. Kohno Y, Ohno H. Key factors to prepare polyelectrolytes showing temperature-sensitive lower critical solution temperature-type phase transitions in water. *Aust J Chem*. 2012;65:91–4.
75. Kohno Y, Deguchi Y, Ohno H. Ionic liquid-derived charged polymers to show highly thermoresponsive LCST-type transition with water at desired temperatures. *Chem Commun*. 2012;48:11883–5.
76. Men Y, Li X-H, Antonietti M, Yuan J. Poly(tetrabutylphosphonium 4-styrenesulfonate): a poly(ionic liquid) stabilizer for graphene being multi-responsive. *Polym Chem*. 2012;3:871–3.
77. Mano JF. Stimuli-responsive polymeric systems for biomedical applications. *Adv Eng Mater*. 2006;10:515–27.
78. Ward MA, Georgiou TK. Thermoresponsive polymers for biomedical applications. *Polymers*. 2011;3:1215–42.
79. Allen G, Baker CH. Lower critical solution phenomena in polymer-solvent systems. *Polym (Guildf)*. 1965;6:181–91.
80. Imre A, Van Hook WA. Liquid-liquid demixing from solutions of polystyrene. 1. A review. 2. Improved correlation with solvent properties. *J Phys Chem Ref Data*. 1996;25:637–61.
81. Yoshimitsu H, Kanazawa A, Kanaoka S, Aoshima S. Well-defined polymeric ionic liquids with an upper critical solution temperature in water. *Macromolecules*. 2012;45:9427–34.
82. Montolio S, González L, Altava B, Tenhu H, Burguete ML, Garcia-Verdugo E, Luis SV. LCST-type polymers based on chiral-polymeric ionic liquids. *Chem Commun*. 2014;50:10683–6.
83. Amemori S, Kokado K, Sada K. Fundamental molecular design for precise control of thermoresponsiveness of organic polymers by using ternary systems. *J Am Chem Soc*. 2012;134:8344–7.
84. Amemori S, Kokado K, Sada K. LCST behavior driven by charge-transfer interaction. *Angew Chem Int Ed*. 2013;52:4174–8.
85. Gharib DH, Amemori S, Naya M, Kokado K, Sada K. Gel thermoresponsiveness driven by switching of the charge-transfer interaction. *RSC Adv*. 2015;5:89319–22.