

Advanced Applications of Ionic Liquids in Polymer Science

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1. Introduction

During past few years, ionic liquids have kept attracting much attention as “green and designer” media for chemical reactions. Room-temperature ionic liquids have emerged as a potential replacement for organic solvents in catalytic processes on both laboratory and industrial scales (Holbrey & Seddon, 1999b). Literature reports on a wide range of reactions including advances in alkylation reactions (Earle et al., 1998), Diels-Alder cyclizations (Earle et al., 1999; Jaeger & Tucker, 1989), and the development of commercially competitive processes for dimerization, oligomerization, and polymerization of olefins (Abdul-Sada et al., 1995a; 1995b; Ambler et al., 1996; Chauvin et al., 1988; 1989). Effectively, Ionic liquids, among a unique set of chemical and physical properties (Chauvin, 1996; Chauvin & Mussmann 1995; Seddon, 1997), have no measurable vapor pressure, which lends them as ideal replacements for volatile, conventional organic solvents. The wide and readily accessible range of room-temperature ionic liquids with corresponding variations in physical properties, prepared by simple structural modifications to the cations (Gordon et al., 1998; Holbrey & Seddon, 1999a) or changes in anions (Bonho`te et al., 1996; Wilkes & Zaworotko, 1992), offers the opportunity to design an ionic liquid-solvent system optimized for particular processes. In other words, these ionic liquids can be considered as “designer solvents” (Freemantle, 1998).

Applications of ionic liquids as solvents for polymerization processes have widely been reviewed in literature (Kubisa, 2004; Shen & Ding, 2004; Lua et al., 2009). Ionic liquids have been used in polymer science, mainly as polymerization media in several types of polymerization processes, including conventional free radical polymerization (Sarbu, & Matyjaszewski, 2001), living/controlling radical polymerizations (such as atomtransfer radical polymerizations (ATRP) (Ding et al., 2005; Shen & Ding., 2004; Biedron & Kubisa., 2001; Biedron & Kubisa., 2002; Biedron & Kubisa., 2003), reversible addition-fragmentation transfer (RAFT) (Perrier & Davis, 2002), as well as in ionic and coordination polymerizations (Chiefari et al., 1998; Vijayaraghavan & MacFarlane et al., 2004). When radical polymerizations are conducted in an ionic liquid, a significant increase of k_p/k_t ratio is normally observed in comparison to those carried out in other polar/coordinating solvents. As solvents for ATRP and RAFT, ionic liquids facilitate separation of the polymer from residual catalyst and reduce the extent of side-reactions.

The use of ionic liquids in polymer science is not limited to their application as solvents. Ionic liquids are also used as additives, including plasticizers, components of polymer electrolytes, and porogenic agents) to polymers. More recently, properties of polymers containing chemically bound ionic liquid moiety (polymeric ionic liquids) are studied and the possibilities of their applications are being explored. Ionic liquids are also investigated as components of the polymeric matrixes (such as polymer gels), templates for porous polymers, and novel electrolytes for electrochemical polymerizations (Przemysław & Kubisa, 2009). This chapter focuses on the recent developments and achievements gained from applications of ionic liquids in the preparation of functional polymers as well as properties modification of polymers caused by ionic liquids.

2. Radical polymerization

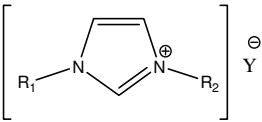
2.1 Radical polymerization (ATRP) of acrylates in ionic liquids

It is known, that properties of ILs commonly depend on the structure of the cation (the symmetry and the length of alkyl substituents, the presence of hydrophobic groups, etc.) as well as on the degree of anion charge delocalization. To elucidate the influence of the nature of ILs on the yield and molecular weight of vinyl polymers, the radical polymerization of appropriate monomers (MMA) in different ionic liquids has been studied (Yakov et. al, 2007). For the MMA polymerization, the dependence between polymer η_{inh} and the length of alkyl substitute in asymmetrical 1-methyl-3-alkylimidazolium ILs was examined (Table 1). The results presented in Table 1 (entries 1-9) show, that increase of carbon chain length of imidazolium ILs leads to the reduction of polymer molecular weight, especially in the case of tetrafluoroborate ILs (Table 1, entries 5-9). Table 1 (entries 10, 11) shows, that a polymer having relatively high η_{inh} value was obtained in both tetrafluoroborate IL: [1,3-Bu₂Im]BF₄ and [1-Bu-3-(*iso*-Bu)Im]BF₄, but in the case of 1,3-di-*n*-butylimidazolium tetrafluoroborate (entry 10) the η_{inh} value of the polymer is higher (3.13 and 2.30 dl g⁻¹, respectively).

The influence of the anion nature on the radical polymerization of MMA can be revealed by comparison of the data, obtained in ILs with ordinary used [1-Me-3-BuIm] cation (Table 1, High values of polymer molar mass and an increase in the rate of free radical polymerization of MMA in ILs can be assigned to the strong effect of ionic media on the chain propagation (activation energy decrease) and chain termination, for the reason of high viscosity of the reaction system, the so-called gel effect. (Yakov et. al, 2007).

2.2 Polymerized ionic liquids: synthesis and applications

Recently, much attention has been paid to polymerized ionic liquids or polymeric ionic liquids, which are macromolecules obtained from polymerizing ionic liquid monomers (Lu et. al, 2009). Their potential applications involve polymeric electrolytes (Galiński et. al, 2006; Ricks-Laskoski & Snow, 2006; Sato et. al, 2007; Susan et. al, 2005), catalytic membranes (Carlin & Fuller 1997), ionic conductive materials (Hirao et. al, 2000; Washiro et. al, 2004; Matsumi et. al, 2006), CO₂ absorbing materials (Tang et. al, 2005a; Tang et. al, 2005b; Tang et. al, 2005c; Tang et. al, 2005d), microwave absorbing materials (Tang et. al, 2008; Amajjahe, & Ritter 2009), and porous materials (Yan & Texter, 2006; Yan et. al, 2007).

Entry ^a				Yield (%)	η_{inh}^b (dl g ⁻¹)
	R ₁	R ₂	Y		
1	CH ₃	C ₂ H ₅	(CF ₃ SO ₂) ₂ N	98	3.06
2	CH ₃	C ₄ H ₉	(CF ₃ SO ₂) ₂ N	98	2.81
3	CH ₃	C ₂ H ₅	CF ₃ SO ₃	96	4.09 ^c
4	CH ₃	C ₄ H ₉	CF ₃ SO ₃	94	2.97
5	CH ₃	C ₃ H ₇	BF ₄	93	3.00
6	CH ₃	C ₄ H ₉	BF ₄	92	2.70
7	CH ₃	C ₅ H ₁₁	BF ₄	91	2.86
8	CH ₃	C ₆ H ₁₃	BF ₄	90	1.58
9	CH ₃	C ₇ H ₁₅	BF ₄	95	1.55
10	C ₄ H ₉	C ₄ H ₉	BF ₄	92	3.13
11	C ₄ H ₉	<i>i</i> -C ₄ H ₉	BF ₄	96	2.30
12	CH ₃	C ₄ H ₉	PF ₆	97	3.89
13	CH ₃	C ₄ H ₉	SbF ₆	98	2.92
14	CH ₃	C ₆ H ₁₃	(CF ₃ CF ₂) ₃ PF ₆	98	3.29
15		[P ⁺ (C ₆ H ₁₃)C ₁₄ H ₂₉]	BF ₄ ⁻	96	3.01
16		[P ⁺ (C ₆ H ₁₃)C ₁₄ H ₂₉]	PF ₆ ⁻	98	3.31
17		[P ⁺ (C ₆ H ₁₃)C ₁₄ H ₂₉]	C ⁻	98	3.48 ^d
18		[P ⁺ (C ₈ H ₁₇) ₄]	B ⁻	95	3.32
19		Benzene ^e		41	0.36

^a Polymerization parameters: [AIBN] = 0.5 wt%, [MMA] = 50 wt%, reaction time = 4 hr, reaction temperature, T = 60 °C.

^b For the solutions of 0.05 g of PMMA in 10.0 ml of CHCl₃ at 25.0 °C.

^c M_w = 5,770,000 g/mol (determined by static light scattering in acetone).

^d M_w = 4,100,000 g/mol (determined by static light scattering in acetone).

^e For comparison. (Reproduced from Vygodskii I, et al (2007) *Polym. Adv. Technol.* 3, 18, 50–63, Copyright (2007), with permeation from John Wiley & Sons)

Table 1. IL's nature effect upon the radical polymerization of MMA

A variety of polymers having imidazolium moieties in the side chains have been reported, including poly (meth) acrylate (Washiro et. al, 2004; Ding et. al, 2004; Nakashima et. al, 2007; Juger et. al, 2009), polystyrene (Tang et. al, 2005c; Tang et. al, 2005e), and poly(*N*-vinylimidazolium) derivatives (Amajjahe, & Ritter 2009; Leddet et. al, 2001; Marcilla et. al, 2004; Marcilla et. al, 2005), and most of these poly(ionic liquid)s were prepared by conventional radical polymerizations. Free radical polymerizations of various *N*-vinylimidazolium derivatives were reported to proceed in the presence of conventional radical initiator, and various copolymers involving the imidazolium group were also synthesized by this method (Mu, et. al, 2005; Sugimura et. al, 2007).

2.2.1 Microwave-absorbing ionic liquid polymer

Microwave-absorbing materials are applicable to reducing electromagnetic interference from personal computers, stealth aircraft technology, microwave cookware, and microwave darkroom protection (Petrov & Gagulin, 2001; Bregar, 2004; Yoshihiro et. al, 2002; Saib et. al, 2006; Zou et. al, 2006). Microwave absorption is usually achieved by combining dielectric and magnetic loss. Most microwave absorbing materials are polymer composites with conductive fillers, such as graphite, carbon black, and metals, or magnetic fillers, such as ferrites and carbonyl iron powders. These fillers make the microwave-absorbing materials black and hard to fabricate, for example, into precise parts or thin films (Peng et. al, 2005; Bosman et. al, 2003). Conductive polymers such as polyaniline, polypyrrole, polyalkylthiophenes, and poly(4,4'-diphenylene diphenylvinylene) were also reported as microwave-absorbing materials (Truong et. al, 2003; Chandrasekhar & Naishadham, 1999; Olmedo et. al, 1995; Wan, et. al, 2001; Phang, et. al, 2005). The structures of poly(ionic liquid)s studied by Tang and coworker are shown in Fig. 1.

Since the poly(ionic liquid)s exhibit no magnetic loss and are insulators (the reported ionic conductivity of a poly(ionic liquid) with a similar structure to the polymers reported here is about 10^{-8} s m^{-1}), their microwave absorptions are solely due to the dielectric loss.

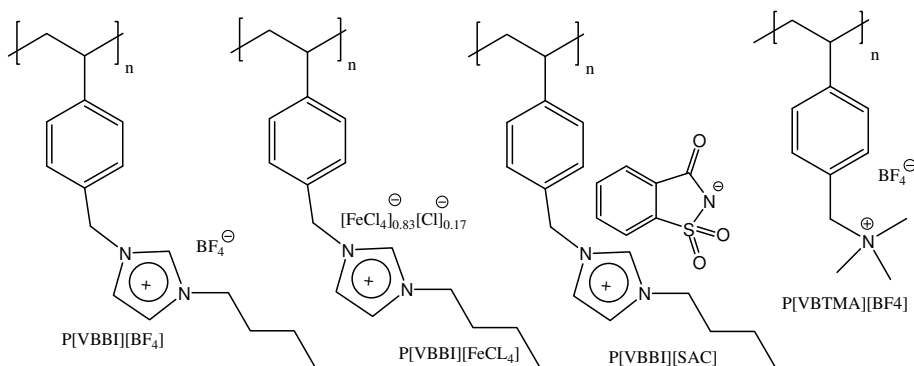


Fig. 1. Structures of poly(ionic liquid)s: poly[1-(*p*-vinylbenzyl)-3-butylimidazolium tetrafluoroborate] (P[VBBI][BF₄]), poly[1-(*p*-vinylbenzyl)-3-butylimidazolium tetrachloroferrate] (P[VBBI][FeCl₄]), poly[1-(*p*-vinylbenzyl)-3-butylimidazolium o-benzoic sulphimide] (P[VBBI][SAC]), and poly[*p*-vinylbenzyltrimethylammonium tetrafluoroborate] (P[VBTMA][BF₄]).

(Reproduced from Tang et. al, (2008) *Macromolecules*, 41, 2, 493-496, Copyright (2008) with permission from American Chemical Society)

The dielectric constant ϵ' is shown in Fig. 2 as a function of frequency. At frequencies lower than 1 GHz, the ϵ' decreases with increasing frequency. At higher frequencies, the ϵ' remains essentially constant. The poly(ionic liquid)s with the imidazolium cations have similar dielectric constants ($\epsilon' \approx 4$). In contrast, P[VBTMA][BF₄] with the ammonium cations has a higher dielectric constant ($\epsilon' \approx 5.2$). This is not surprising because this material is more polar than poly(ionic liquid)s with imidazolium cations, which is in line with results of other ionic liquids (Tokuda et. al, 2006).

To probe the effect of anion on the dielectric loss, the dielectric losses of three poly(ionic liquid)s, P[VBBI][Sac], P[VBBI][BF₄], and P[VBBI][FeCl₄], with the same backbone and cations but different anions are compared. Sac⁻ is a mostly used organic anion while BF₄⁻ is a widely used inorganic anion in ionic liquids. A poly(ionic liquid) with FeCl₄⁻ anions containing transition metal ions Fe³⁺ is also synthesized to test whether such kinds of anions can further increase the loss factor (Tang et. al, 2008).

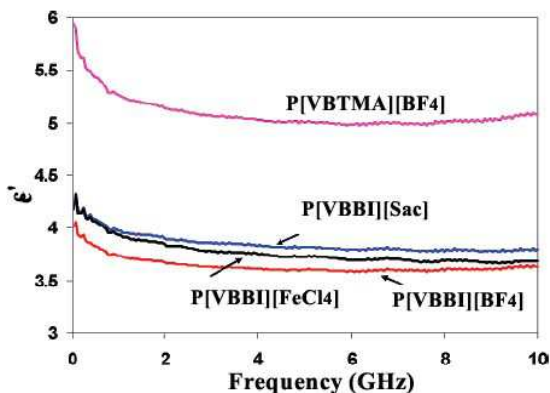


Fig. 2. Dielectric constant ϵ' (the real part of complex permittivity) as a function of frequency (Reproduced from Tang et. al, (2008) *Macromolecules*, 41, 2, 493-496, Copyright (2008), with permission from American Chemical Society)

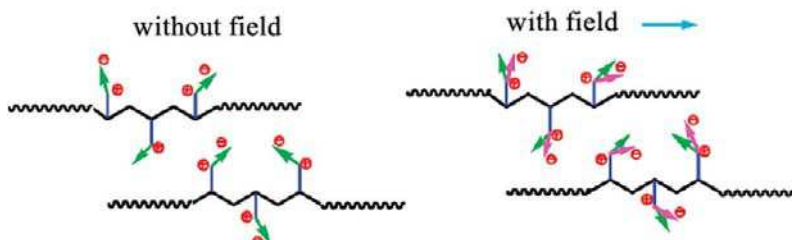


Fig. 3. Orientation of ion-pair dipoles in poly(ionic liquid) without and with an electric field (green vector vs purple vector). (Tang et. al, (2008) *Macromolecules*, 41, 2, 493-496, reprinted with permission from American Chemical Society)

As sketched in Fig. 3, poly(ionic liquid)s have strong dipole moments created by the permanent ion pairs. In the absence of an external field, these dipoles are randomly oriented (randomly point in different directions) and continually jump from one orientation to another as a result of thermal agitation. In an external field, these dipoles orient themselves in the direction of the applied field (Fig. 3). (Tang et. al, 2008)

2.2.2 Electrowetting of a new ionic liquid monomer and polymer system

Synthesis and electrowetting of a new ionic liquid monomer and polymer system was reported by Holly and coworkers (Holly et. al, 2008). The formation of the monomeric ionic liquid salt and its polymerization is depicted in Fig. 4.

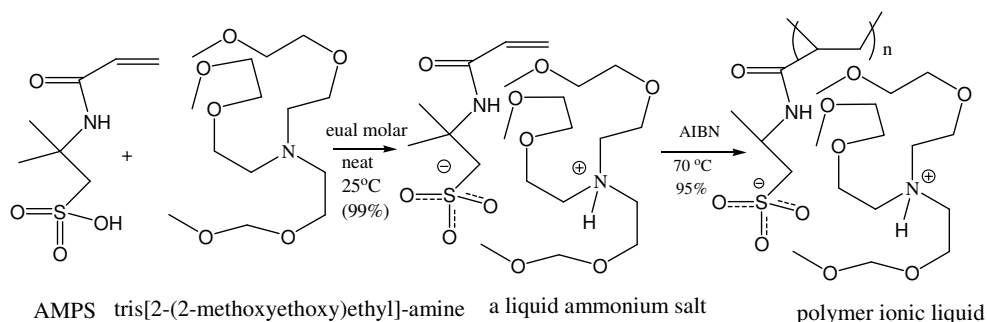


Fig. 4. Reaction Scheme for AMPS oxyethylene ammonium salt monomer and polymer (Reproduced from Ricks-Laskoski & Snow (2006) *J. Am. Chem. Soc.* 128, 38, 12402-12403, Copyright (2006), with permeation from American Chemical Society)

The uniqueness of the oxyethylene amine in the formation of the ammonium cationic species contributes to both the ionic and liquid nature of the monomer and polymer. Even more remarkable is the ability of this polymer to maintain its liquid nature as a macromolecule and to wet a substrate, showing preference for one polarity based upon the makeup of the ionic backbone of the polymer formed (Ricks-Laskoski & Snow, 2006).

Polymerizable ionic liquids and their actuation in an electric field are a combination of material and properties with unique potential to display structural and fluid dynamics above that found for small molecule ionic liquids.

Electrowetting is an electrostatically driven surface effect where a liquid droplet's spreading on a hydrophobic surface is modulated by application of a voltage to the droplet and an underlying conducting substrate (Quilliet & Berge 2001). A schematic of this effect is illustrated in Figure 5.

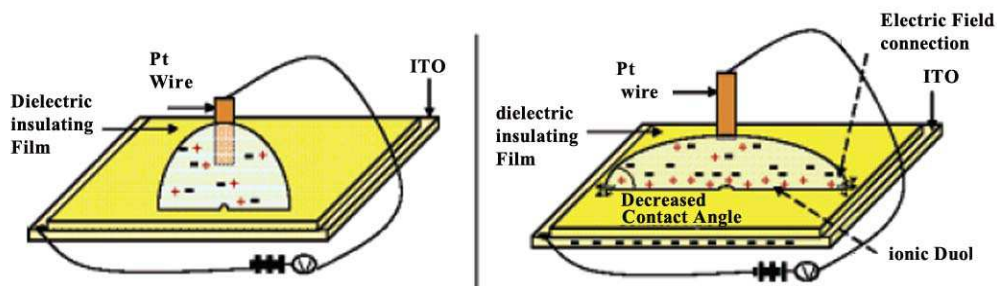


Fig. 5. Depiction of an electrowetting actuation electrode setup with (right) and without (left) an induced electric field (Reproduced from Ricks-Laskoski & Snow (2006) *J. Am. Chem. Soc.* 128, 38, 12402-12403, Copyright (2006), with permeation from American Chemical Society)

The droplet rests on a very thin low-dielectric insulating film (Teflon AF) which is supported on a conducting substrate and is contacted at the top by a very fine wire contact. Application of a voltage builds up a layer of charge on both sides of the interface with the dielectric film and decreases the interfacial energy.

2.2.3 Polymerized ionic liquids: solution properties and electrospinning

The solution properties and electrospinning of a polymerized ionic liquid was explored by Chen and Elabd (Chen & Elabd, 2009). Polymerized ionic liquids are synthesized from polymerizing ionic liquid monomers, where ionic liquids are of great interest due to their unique physiochemical properties. Compared to other polyelectrolyte solutions, this polymerized ionic liquid solution exhibits similar viscosity scaling relationships in the semidilute unentangled and semidilute entangled regimes. However, the electrospinning-electrospinning transition occurs at similar polymer solution concentrations compared to neutral polymers, where electrospinning produced beaded fibers and defect free fibers at ~ 1.25 and ~ 2 times the entanglement concentration, respectively. Due to high solution conductivities, electrospinning produces fibers approximately an order of magnitude smaller than neutral polymers at equivalent normalized solution concentrations. In addition, a high ionic conductivity of the solid-state fiber mat was observed under dry conditions and even higher conductivities were observed for polyelectrolyte fiber mats produced from electrospinning polyelectrolyte-ionic liquid solutions, where both anion and cation are mobile species. Structure of polymerized ionic liquid poly(MEBIm-BF₄) is shown in Fig. 6.

Fig. 7 shows the morphology of the fibers at various ionic liquid contents. Instead of reduced fiber sizes, the existence of ionic liquid results in larger fibers with a ribbon structure. This can be attributed to the nonvolatility of ionic liquid that hinders the solidification of fibers to smaller sizes. Moreover, the liquid component in the fiber collapses the fiber into a ribbon structure.

With the increase of ionic liquid content, more ribbons were observed in the fiber mat (Fig 7).

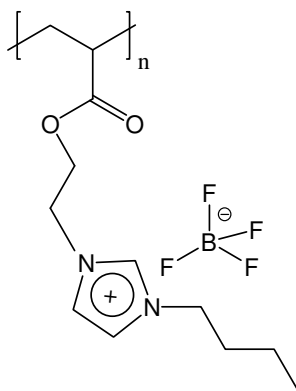


Fig. 6. Structure of polymerized ionic liquid poly(MEBIm-BF₄) (Reproduced from Chen et al., (2009) *Macromolecules* 42, 3368-3373, Copyright (2009), with permission from American Chemical Society)

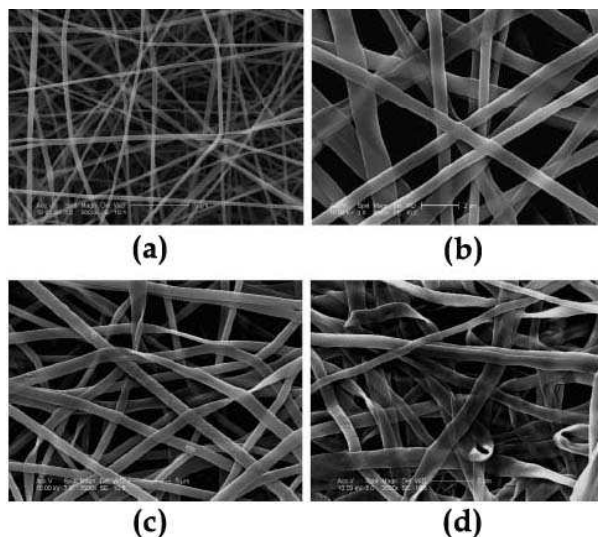


Fig. 7. Field emission scanning electron microscope images of electrospun Nafion-PAA-BMIm-BF₄ blend at ionic liquid weight fraction of (a) 0%, (b) 10%, (c) 20%, (d) 30%. The weight ratio of Nafion:PAA is 3:2 at a 10 wt % total polymer concentration (Reproduced from Chen et al., (2009) *Macromolecules* 42, 3368-3373, Copyright (2009), with permission from American Chemical Society)

2.3 Ultrasound and ionic-liquid-assisted synthesis method

Currently, the study of physical and chemical effects of ultrasound irradiation is a rapidly growing research area. When liquids are irradiated with high-intensity ultrasound irradiation, acoustic cavitations (the formation, growth, and implosive collapse of bubbles) provide the primary mechanism for sonochemical effects. During cavitation, bubble collapse produces intense local heating, high pressures, and extremely rapid cooling rates (Suslick et al. 1991, Suslick 1988). These transient, localized hot spots can drive many chemical reactions, such as oxidation, reduction, dissolution, decomposition, and promotion of polymerization (Suslick 1988). One of the most important recent aspects of sonochemistry has been its application in the synthesis of nanodimensional materials (Suslick & Price, 1999). Ultrasound irradiation offers a very attractive method for the preparation of novel materials with unusual properties and has shown very rapid growth in its application in materials science due to its unique reaction effects and ability to induce the formation of particles of much smaller sizes (Suslick 1988, Suslick & Price, 1999). The advantages of the sonochemical method include a rapid reaction rate, controllable reaction conditions, and the ability to form nanoparticles with uniform shapes, narrow size distributions, and high purity.

2.3.1 Ultrasound and ionic-liquid-assisted synthesis and characterization of polyaniline/Y₂O₃ nanocomposite with controlled conductivity

A sonochemical method has been employed to prepare polyaniline-Y₂O₃ (PANI/Y₂O₃) nanocomposite with controlled conductivity with the assistance of an ionic liquid by

Kowsari and Faraghi (Kowsari & Faraghi, 2010) Ultrasound energy and the ionic liquid replace conventional oxidants and metal complexes in promoting the polymerization of aniline monomer. Ionic liquids (with unique properties) can act as morphology templates for the synthesis of PANI/ Y_2O_3 nanocomposite with novel or improved properties. Here task specific acidic ionic liquids with different counter ions induce different template and different PANI morphology. The structures of ionic liquids studied by Kowsari Faraghi are shown in Fig. 8.

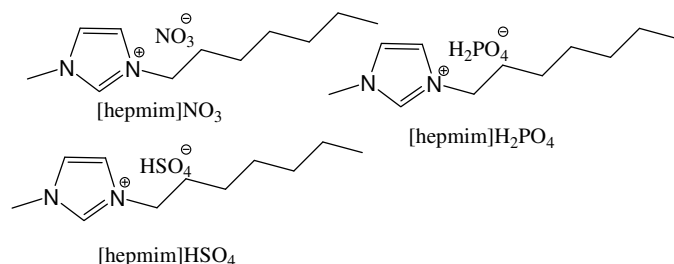


Fig. 8. The structures of ionic liquids in this study

Fig. 9a–d exhibits the morphology of PANI/ Y_2O_3 nanocomposite in the presence of different type of ionic liquid. Interesting morphologies were obtained for PANI/ Y_2O_3 nanocomposites. To compare the effects of ionic liquid additives on the properties of the resulting PANI/ Y_2O_3 nanocomposite, the monomer concentration ratio was kept constant. The differences in the structure of PANI/ Y_2O_3 nanocomposite prepared, in the presence of ionic liquids are clearly visible. At the same magnification PANI/ Y_2O_3 nanocomposite (with [hepmim]. H_2PO_4 ionic liquid) reveals an interesting ribbon structure (Fig. 9a). The nanosheet structure of PANI/ Y_2O_3 in the presence of [hepmim] HSO_4 , ionic liquid is shown in Fig. 9b. In Fig. 9b the smooth surface of PANI/ Y_2O_3 is visible. Smooth surfaces of it can be a reason for the better conductivities of these samples compared to Y_2O_3 -free PANI. The SEM study shows that the presence of ionic liquid additives in polymerization strongly affects the morphology of PANI/ Y_2O_3 . ionic liquids play a key role in tailoring the resultant conducting PANI/ Y_2O_3 structures. It was found that in the presence of [hepmim] NO_3 , the products were regular solid microspheres covered with some nanoparticles. (Fig 9c) .TEM image of Y_2O_3 is shown in Fig 9d.

The influence of three different ionic liquid counter anions, namely HSO_4^- , $H_2PO_4^-$ and NO_3^- on conductivity was investigated by preparing composites in the presence of these anions. It was observed that the conductivity was strongly influenced by the type of anion, although the yields of the respective composites were subject to variation. Since the PANI in the composite is in its emeraldine salt form irrespective of the acid used, the variation in conductivity most probably stems from the differences in the size and nature of the dopant anions.

As can be seen in Fig. 10, the conductivities may be classified in the decreasing order $NO_3^- < HSO_4^- < H_2PO_4^-$

The effect of the concentration of ionic liquid = [hepmim] HSO_4) on PANI- Y_2O_3 morphology is shown in Fig 11. As is vivid, at 0.2 M concentration morphology is a mixture of fibers and plates. When the concentration increases to 0.4, fibers gradually disappear and change into plates. Also, when the concentration reaches 0.6, the plates become thin in terms of

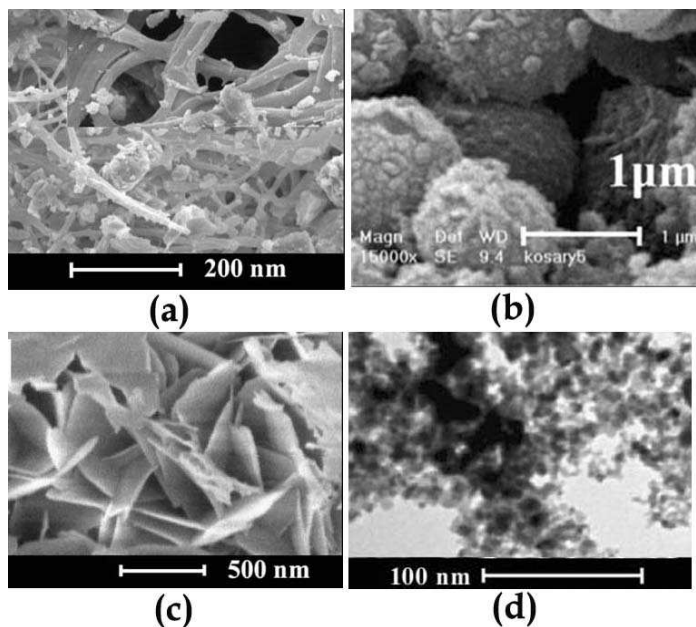


Fig. 9. SEM images of PANI/ Y_2O_3 composite at different type of IL: (a) PANI/ Y_2O_3 composite ($Y_2O_3 = 30\%$, aniline = 0.2 M, and IL = [hepmim] $\cdot H_2PO_4 = 0.6$ M), (b) PANI/ Y_2O_3 composite ($Y_2O_3 = 30\%$, aniline = 0.2 M, and IL = [hepmim] $\cdot HSO_4 = 0.6$ M), (c) PANI/ Y_2O_3 composite ($Y_2O_3 = 30\%$, aniline = 0.2 M, and IL = [hepmim] $\cdot NO_3 = 0.6$ M). (d) TEM image of Y_2O_3 (Reproduced from Kowsari & Faraghi (2010) *Ultrason. Sonochem.* 17, 4, 718-725, Copyright (2010), with permeation from Elsevier)

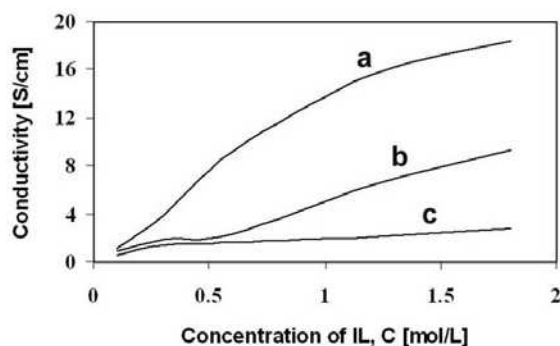


Fig. 10. The conductivities of PANI/ Y_2O_3 composites at different concentrations of ILs: (a) PANI/ Y_2O_3 composite ($Y_2O_3 = 30\%$, aniline = 0.2 M, and IL = [hepmim] $\cdot H_2PO_4 = 0.6$ M), (b) PANI/ Y_2O_3 composite ($Y_2O_3 = 30\%$, aniline = 0.2 M, and IL = [hepmim] $\cdot HSO_4 = 0.6$ M), (c) PANI/ Y_2O_3 composite ($Y_2O_3 = 30\%$, aniline = 0.2 M, and IL = [hepmim] $\cdot NO_3 = 0.6$ M). (Reproduced from Kowsari & Faraghi (2010) *Ultrason. Sonochem.* 17, 4, 718-725, Copyright 2010), with permeation from Elsevier)

thickness. As for both mentioned ionic liquids, increase in concentration brings about higher conductivity and yield, as well.

In the present study, when there is an increase in a frequency from 20 to 40 kHz, the morphology evolves as sphere shapes. In additions, the yield would be 55 wt %, 76 wt %, and 80 wt % at 20, 30, and 40 kHz for frequency.

Ultrasonic irradiation at 40 kHz, yields constantly higher degradation efficiencies compared with that at 20 kHz for all ionic liquids. Since, in the present study, the ionic liquid replaces conventional oxidant and metal complexes for polymerization, the increase of ionic liquids degradation leads to the increase of the concentration of alkyl radicals and the increase of aniline polymerization and, therefore, the increase of yield of product.

2.4 Ziegler-Natta polymerisation of ethylene

Ziegler-Natta polymerisation is used extensively for the polymerisation of simple olefins (e.g. ethylene, propene and 1-butene) and is the focus of much academic attention, as even small improvements to a commercial process operated on this scale can be important. Ziegler-Natta catalyst systems, which in general are early transition metal compounds used in conjunction with alkylaluminium compounds, lend themselves to study in the chloroaluminate(III) ionic liquids, especially the ones with an acidic composition.

During studies into the behaviour of titanium(IV) chloride in chloroaluminate(III) ionic liquids Carlin *et al* carried out a brief study to investigate if Ziegler-Natta polymerisation was possible in an ionic liquid (Carlin *et. al* 1990)

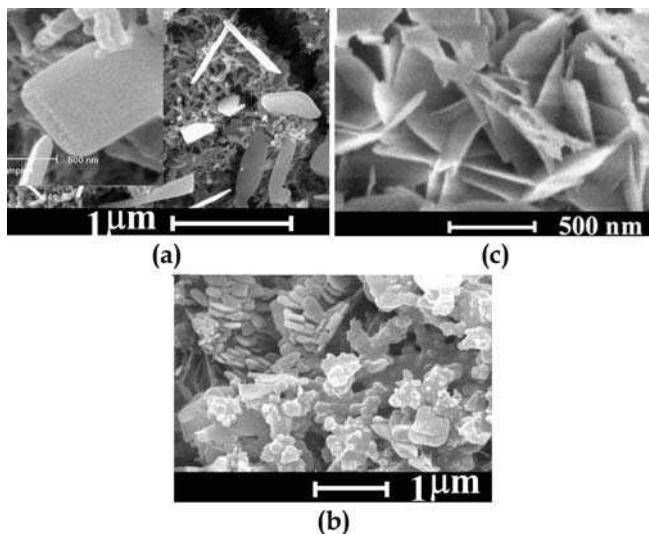


Fig. 11. SEM images of PANI/ Y_2O_3 composite ($Y_2O_3 = 30\%$, aniline = 0.2 M, and IL = [hepmim] HSO_4) at different concentrations of ILs (a) [IL] = 0.2 M, (b) [IL] = 0.4 M, (c) [IL] = 0.6 M (Reproduced from Kowsari & Faraghi (2010) *Ultrason. Sonochem.* 17, 4, 718-725, Copyright (2010), with permeation from Elsevier)

2.5 Microemulsion polymerization by ionic liquids

Microemulsions are thermodynamically stable dispersions containing two immiscible liquids stabilized by surfactants at the liquid-liquid interface. Compared with "classic" water-in-oil microemulsions, ionic liquid-in-oil microemulsions, in which an ionic liquid dispersed in an oil-continuous phase by suitable surfactants, are of great interest due to the unique features of both ionic liquid and microemulsion system (Eastoe et al., 2005; Binks et al., 2003; He et al., 2006; Atkin et al., 2007; Gao et al., 2004; Li et al., 2007). Microemulsions composed of a room temperature ionic liquid, 1-butyl-3-methylimidazolium tetrafluoroborate ([Bmim][BF₄]), cyclohexane, and a surfactant, Triton X-100, have been recently studied by Han (Gao et al., 2004) and Eastoe (Eastoe et al., 2005). Small angle neutron scattering data clearly demonstrated the formation of ionic liquid nanodroplets dispersed in cyclohexane (Eastoe et al., 2005). More recently, microemulsions composed of an ionic liquid dispersed in a variety of organic oils, such as toluene, (Li et al., 2007; Gao et al., 2006) xylene (Gao et al., 2006b) and benzene, (Gao et al., 2007) have been investigated by several groups. These microemulsions behaviors are consistent with water-in-oil microemulsions and provide nanosized ionic liquid domains as reaction or extraction media which should avoid contacting with water. However, potential uses of these ionic liquid - based microemulsions have not been intensively studied so far.

2.5.1 Microemulsions with an ionic liquid surfactant

The formation of amphiphilic association structures in and with ionic liquids, such as micelles, vesicles, microemulsions and liquid crystalline phases has been reviewed recently (Hao & Zemb, 2007, Qiu, & Texter, 2008). The formation of micelles formed by common surfactants in EAN was first documented in 1982 by Evans and coworkers (Evans et al, 1982, 1983), whereas the formation of liquid crystals of lipids in ethyl ammonium nitrate (EAN) (Evans, & Kaler, 1983) as well as lyotropic liquid crystals of non-ionic surfactants were observed in the same room temperature ionic liquid (Araos & Warr, 2005). The formation of liquid crystalline phases of binary mixtures of [C₁₆mim][Cl] and EAN has also been described lately (Zhao et al, 2009). The self-aggregation of common ionic and non-ionic surfactants in imidazolium based RTIL was also reported. (Anderson et al, 2003; Patrascu et al, 2006; Hao et al, 2005)

As imidazolium based ionic liquids (ILs) with long-chain hydrocarbon residues exhibit surfactant properties in water (Thomaier& Kunz, 2007; (Bowers et al, 2004; Miskolczy et al, 2004; Sirieix-Plenet et al, 2004; Kaper & Smarsly, 2006; Seoud et al, 2007), Thomaier and coworkers could recently demonstrate that the surfactant like ionic liquid (SLIL) 1-hexadecyl-3-methylimidazolium chloride ([C₁₆mim][Cl]) forms colloidal structures in EAN as well. They found a critical aggregation concentration (cac) approximately ten times higher than the critical micelle concentration (cmc) in the corresponding aqueous system. (Thomaier & Kunz, 2007) This gap is in accordance with the results of Evans *et al.*, who found that the cacs of classical surfactants in EAN are between 5 and 10 times higher than in water. (Evans et al, 1982)

2.5.2 Polymerization of ionic liquid-based microemulsions: The synthesis of polymer electrolytes

S. Yu and coworkers (Yu et al, 2008) reported the first example of polymerization of microemulsions comprising surfactant stabilized ionic liquid nanodomains. Polymerization of these ionic liquid-based microemulsions yielded free-standing, flexible, and transparent

polymer electrolytes even though the resulting vinyl polymers are incompatible with ionic liquid cores. The obtained ionic liquid/ polymer composites show high conductivity at both room temperature and elevated temperature. This facile yet and effective method provides a versatile platform for the preparation of semisolid polymer electrolytes containing ionic liquids. Although they only demonstrated this method with vinyl monomers of styrene, methyl methacrylate, vinyl acetate, and *N,N*-dimethylacrylamide and only one surfactant as examples, they believe that this method should be extendable to other liquid monomers with similar polarity and ionic liquids with desirable properties. The elucidation of interaction between the polymeric matrix and ionic liquids need to be further explored in future work.

2.6 Aqueous/ionic liquid interfacial polymerization

Interfacial polymerization (IP) involves step polymerization of two reactive monomers or agents, which are dissolved respectively in two immiscible phases and the reaction takes place at the interface of the two liquids. IP has been used to prepare various polymers, such as poly(urea), poly(amide), and poly(ester) capsules.

It allows the synthesis of polymers at low temperature with limited side reactions, and can avoid the use of catalysts or phase transfer agents. The relative ease of IP has made it the preferred technique in many fields, ranging from microencapsulation of pharmaceutical products to preparing conducting polymers. IP is commonly done with volatile organic solvents as the organic phase, such as benzene (Chu et al, 2002), chloroform (Ashgarian et al, 1999), and toluene (Lu et al, 2002). The nonvolatile nature of ionic liquids gives them significant advantage in minimizing solvent consumption. They are good solvents for organic, inorganic, and polymeric compounds, and have been used as media for chemical reactions (Dupont et al, 2002), including polymerization (Harrisson et al, 2003) and ionic liquid/CO₂ biphasic reactions. Poly aniline (PANI) has been synthesized with water/ionic liquid IP by Kowsari and Yavari (Kowsari & Yavari, 2009). This method has some obvious advantages, such as PANI nanofiber can be fabricated and both solvents used are environmentally benign.

3. Polycondensation processes in ionic liquids

Polycondensation is typically conducted at relatively high temperature thus non-volatile and thermally stable ionic liquids seem to be suitable solvents for polycondensation processes. Research in this area has mainly been directed towards synthesis of polyamides, polyimides and polyesters. On the other hand, in some studies of polycondensation catalytic effect of ionic liquids was observed. More recently, two step procedures (involving post polycondensation in ionic liquid) was applied to polycondensation of sebacic, adipic, and succinic acid with aliphatic diols. Aliphatic polyesters with Mw up to 6×10⁴ were obtained and once more it was noted that solubility of polyesters in ionic liquid was a limiting factor. Solubility depends on structure of IL (nature of cation and anion) and correlation was found between the miscibility of aliphatic polyester/ionic liquid system and the extent to which their solubility parameters matched (Kubisa, 2009).

3.1 Ionic liquids as novel solvents and catalysts for the direct polycondensation

The direct polycondensation of *N,N'*-(4,4'-oxydiphtaloyl)- bis-L-phenylalanine diacid with various aromatic diamines was performed in ionic liquid media by Mallakpour and Kowsari

(Mallakpour & Kowsari, 2005). The influence of various reaction parameters, including the nature of the ionic liquid cations and anions, the monomer structures, the reaction temperature, and the reaction time, on the yields and inherent viscosities of the resulting optically active poly(amide imide)s (PAIs) were investigated. Direct polycondensation preceded in ionic liquids and triphenyl phosphite (a condensing agent) without any additional extra components, such as LiCl and pyridine, which are used in similar reactions in ordinary molecular solvents. Therefore, ionic liquids can act as both solvents and catalysts. Various high-molecular weights, optically active PAIs were obtained in high yields with inherent viscosities ranging from 0.54 to 0.88 dL/g. This method was also compared with three other classical methods for the polycondensation of the aforementioned monomers.

3.2 Polycondensation processes in ionic liquid under microwave irradiation

Application of ionic liquids as media to microwave-assisted reactions offers several advantages. Typical organic solvents are frequently flammable and volatile, which is a safety hazard for high-temperature and closed-vessel applications using microwaves. In contrast, ionic liquids have high boiling-points, low vapor pressures, and high thermal stabilities. In addition, typical ionic liquids have moderately high dielectric constants (in the range of 10–15), and relatively low heat capacities (in the range of 1–2 J/g K). This combination allows ionic liquids to absorb microwaves efficiently. Owing to these advantages, ionic liquids have been investigated as solvents in a number of microwave-mediated reactions. Microwave heating in ionic liquids was used also for polycondensation reactions leading to polyamides (Mallakpour & Kowsari, 2006). Certain advantages have been indicated, but until now only slight improvement of reactions conditions (more efficient heating, higher rates) has been achieved.

4. Ionic polymerization

4.1 Cationic polymerization

Ability of ionic liquids to dissolve wide range of inorganic compounds was exploited in the study in which organoborate acids (HBOB) (bisoxalatoboric acid, bisuccinatoboric and bisglutaratoboric acids) were used as initiators of the cationic polymerization of styrene in pyrrolidonium, imidazolium and phosphonium bis (trifluoromethanesulfonyl) amide ionic liquids. In another study, cationic polymerization of styrene initiated with $AlCl_3$ in ionic liquid ([bmim][PF₆]), supercritical CO₂ and organic solvent (CH₂Cl₂) was investigated. The only conclusion was that in ionic liquids rates and molecular weights are higher than in organic solvent (Kubisa, 2009).

Studies on the dimerisation and hydrogenation of olefins with transition metal catalysts in acidic chloroaluminate(III) ionic liquids report the formation of higher molecular weight fractions consistent with cationic initiation (Chauvin et. al 1990; Ellis et. al 1999). These studies ascribe the occurrence of the undesired side reaction to both the Lewis acid and the proton catalysed routes. Their attempts to avoid these side reactions led to the preparation of alkylchloroaluminate(III) ionic liquids and buffered chloroaluminate(III) ionic liquids (Chauvin et. al 1990; Ellis et. al 1999).

Attempts to bring the benefits of ionic liquid technology by drawing on the inherent ability of the chloroaluminate(III) ionic liquids to catalyse cationic polymerisation reactions, as

opposed to minimising them, were patented by Ambler et al of BP Chemicals Ltd in 1993 (Ambler, 1993). They used acidic [EMIM][Cl-AlCl₃] ($X(\text{AlCl}_3) = 0.67$) for the polymerisation of butene to give products that find application as lubricants. The polymerisation can be carried out by bubbling butene through the ionic liquid. The product formed a separate layer that floats upon the ionic liquid and was isolated by a simple process. Alternatively, the polymerisation was carried out by injecting the ionic liquid into a vessel charged with butene. After a suitable settling period the poly(butene) was isolated in a similar fashion. The products from these reactions must be best described as oligomers as opposed to polymers as the product is still in the liquid form. Chain transfer to impurities, ionic liquid, monomer and polymer will terminate the propagation reaction resulting in the low-mass products.

4.1.1 Cationic polymerization of styrene in scCO₂ and [bmim][PF₆]

Bueno and coworkers (Bueno et. al 2009) presented a study on the cationic polymerization of styrene in different reaction media, supercritical CO₂ (scCO₂), [bmim][PF₆], dichloromethane, and scCO₂ plus [bmim][PF₆] using AlCl₃ as initiator at temperatures from 273 to 333 K. The reactions were analyzed in relation to the monomer conversion rate, polymer structures, average molecular weights and molecular weight distribution. In all cases, the styrene polymerization produced oligomers. Reactions using ionic liquid as a solvent led to higher molecular weight and monomer conversion rate. Monomer conversion rates of about 100% and weight average molecular weight (*M_w*) of 2400 at 298 K were obtained. Reactions with scCO₂ as a solvent yielded low monomer conversion rates (around 50%) and a *M_w* = 2000 at 298 K. The oligolystyrenes presented *rr* syndiotactic-rich sequences in the microstructure in all reaction conditions. The use of ionic liquid and scCO₂ results in better yields than the use of the other organic solvents.

4.2 Anionic polymerization

4.2.1 Anionic polymerization of methyl methacrylate in an ionic liquid

Anionic polymerization reactions of methyl methacrylate (MMA) in ionic liquids were carried out by utilizing alkyl lithium initiators such as *n*-butyl lithium (*n*-BuLi) and diphenylhexyl lithium (DPHLi) by H. Kokubo and Watanabe (Kokubo & Watanabe, 2008). The polymerization in ionic liquids having bis(trifluoromethyl sulfonyl)amide ([NTf₂]) anion did not yield poly(MMA) (PMMA), because of the deactivation of the initiator due to an attack on the trifluoromethyl group. By using 1-butyl-3-methylimidazolium hexafluorophosphate ([C₄mim][PF₆]), the polymerization reactions proceeded. The PMMA prepared in [C₄mim][PF₆] gave low yields (5–9%), as compared with those (15–62%) obtained for PMMA prepared in tetrahydrofuran (THF), and the prepared PMMA had large polydispersity indices (≈ 2.0). The results obtained can be attributed to the high reaction temperature (0 °C), in comparison to the common anionic polymerization temperature of MMA, -78 °C, and the reaction between the initiator and the imidazolium cation. The initiator was considered to be deactivated because the hydrogen atom at the 2-position of the imidazolium ring was withdrawn by the alkyl lithium initiator. The tacticity of the obtained PMMA, prepared in [C₄mim][PF₆] by utilizing DPHLi, was rich in *mm* triads, similar to that polymerized in toluene

5. Miscellaneous application of ionic liquids in polymer chemistry

5.1 Polymer electrolytes: Compatible system between polymers and ionic liquids (ion gels)

Polymer electrolytes containing room temperature ionic liquids were first reported on such a system by Noda & Watanabe (Noda & Watanabe, 2000). Successively, the study was expanded to polymer electrolytes containing chemically stable ionic liquids (Noda & Watanabe, 2000; Watanabe et. al 1993; Watanabe et. al 1995; Watanabe & Mizumura 1996; Ogata et. al 1995; Susan et. al 2005). Watanabe and coworkers found that common vinyl monomers were widely soluble in common ionic liquids and that they could be polymerized by free radical polymerization (Noda & Watanabe 2000; Susan et. al 2005). In certain cases, surprisingly good compatibility of the resulting polymers with the ionic liquids could be achieved irrespective of the polymer concentration and temperature (Fig. 12).

Typically, the polymerization of methyl methacrylate (MMA) in a common ionic liquid, 1-ethyl-3-methyl imidazolium bis(trifluoromethane sulfone)imide ($[\text{C}_2\text{mim}][\text{NTf}_2]$) in the presence of a small amount of a cross-linker gives self standing, flexible, and transparent polymer gels. The polymer and ionic liquid composite gels, which they term "ion gels", show a single T_g for a given range of $[\text{C}_2\text{mim}][\text{NTf}_2]$ composition, and the T_g decreases with an increase in the mole fraction of $[\text{C}_2\text{mim}][\text{NTf}_2]$ (Fig 13) (Susan et. al 2005; Ueki & Watanabe 2008).

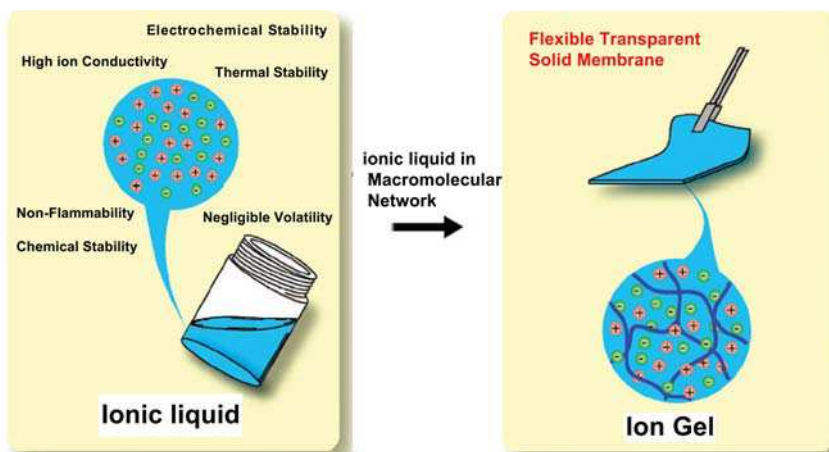


Fig. 12. Preparation of ion gels (compatible binary systems between polymer networks and ionic liquids) by a variety of methods such as in situ radical polymerization of vinyl monomers in ionic liquids and sol-gel transition of macromolecules in ILs. The flexibility of molecular design of ionic liquids can facilitate various interesting applications of ion gels, particularly as ion-conducting polymer electrolytes (Reproduced from Ueki & Watanabe (2008) *Macromolecules*, 41, 11, 3739-3748, Copyright (2008), with permission from American Chemical Society)

5.2 Ion gel gated polymer thin-film transistors

Lee and coworkers (Lee et. al 2007) demonstrate that a gel electrolyte (a so-called "ion gel") based on a mixture of an ionic liquid and a block copolymer can provide both large specific

capacitance ($>10 \mu\text{F}/\text{cm}^2$) and greatly improved polarization response times (1 ms) when used as the gate dielectric in a polymer TFT (thin-film transistor). The improved properties allow transistor operation at frequencies greater than 100 Hz, significantly faster than what has been demonstrated previously and opening the door to a broader range of applications. Furthermore, the ion gel material is solution processible, making it potentially compatible with high throughput patterning methods (e.g., ink jet printing). Unlike traditional solid polymer electrolytes, which are obtained by the dissolution of salts by ion-coordinating polymers, the ion gel electrolyte is formed by gelation of poly(styrene-block-ethylene oxide-block-styrene) (SOS) triblock copolymer in 1-butyl-3-methylimidazolium hexafluorophosphate ([BMIM][PF₆]), a room temperature ionic liquid; the structures of these materials are shown in Fig. 14.

6. Conclusions

Further progress in the area of ionic liquids and specifically polymerization mechanisms is inevitable. Due to distinctive features and "green" applications of ionic liquids in industry, researchers have found this research topic an interesting and promising one. Very attractive initial applications for the incorporation of ionic liquids monomers into polymers have been reported, but the range of possible ionic liquid structures is much larger than has so far been explored. What seems to be necessary and needed is careful selection of the systems studied where real synthetic advantages of applying ionic liquids are offered or new insights into polymerization mechanisms are provided. These research requirements are opposed to mere mentioning, although new, examples of processes that can be carried out with regard to ionic liquids. This way, achievements in the field can be foreseen.

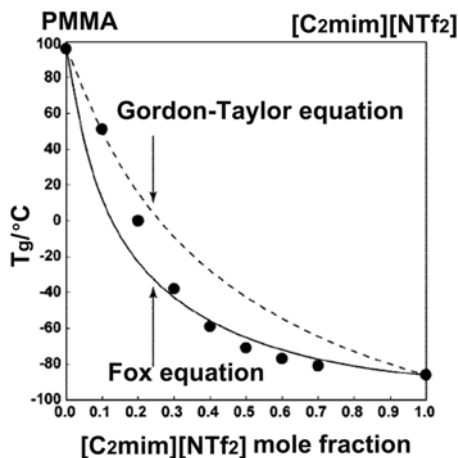


Fig. 13. Glass transition temperatures (T_g) of PMMA network polymers with dissolved [C₂mim][NTf₂] as a function of [C₂mim][NTf₂] mole fraction. The points denote experimental T_g results, the broken lines denote the fitted profiles by the Gordon-Taylor equation, and the solid lines denote those by the Fox equation. (Reproduced from Susan et. al (2005) *J Am. Chem. Soc.* 2005, 127, 4976, Copyright (2005), with permeation from American Chemical Society)

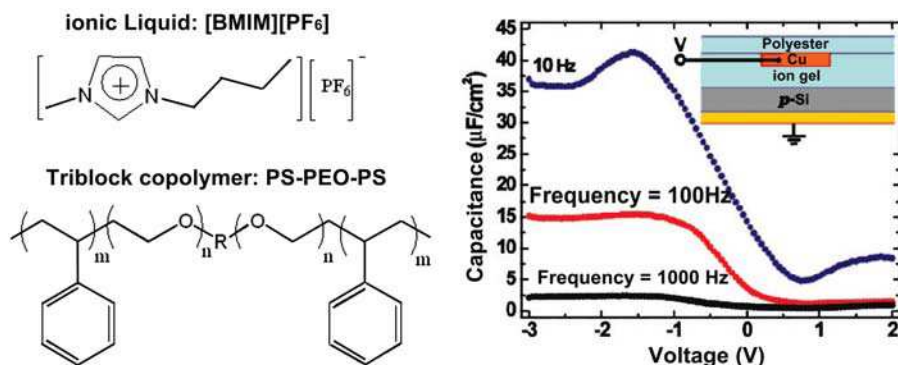


Fig. 14. Structure of the ionic liquid and triblock copolymer ion gel components (left) and C-V characteristics of a p-Si/ion gel/Cu test structure (see inset) at three frequencies (right). The C-V curves indicate large frequency-dependent hole accumulation in the Si at negative bias on the top contact (Reproduced from Lee et. al (2007) *J. Am. Chem. Soc.* 129, 4532-4533, Copyright (2007), with permeation from American Chemical Society)

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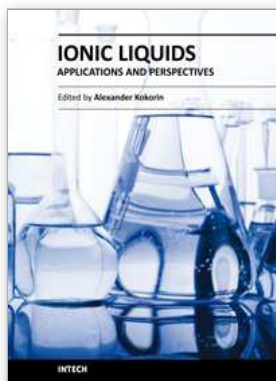
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