Poly(vinyl chloride) Ionic Liquid Polymer Electrolyte Based on Bis(fluorosulfonyl)Amide for Sodium Secondary Batteries

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Non-flammable electrolytes have been extensively studied to improve the safety of energy storage devices. In this study, a new ionic liquid polymer electrolyte (ILPE) prepared by a cast technique using poly(vinyl chloride) (PVC) as the host polymer was examined for sodium secondary batteries. The ILPE containing 50 wt% of 1-ethyl-3-methylimidazolium bis(fluorosulfonyl)amide ([C2C1im][FSA]) showed an ionic conductivity of 5.6 mS cm−1 at 318 K. It remains stable up to 517 K based on 5 wt% loss. Stable sodium metal electrodeposition/dissolution was observed at the cathodic limit of the electrochemical window for the ILPE containing Na[FSA] ([C2C1im][FSA]; Na[FSA]; PVC = 2:0:1:0.1 w/w). The anodic limit was observed at around 4.7 V vs. Na+/Na on a Pt working electrode, while on an Al working electrode a higher anodic stability owing to passivation was observed. In the Na/[C2C1im][FSA]-NaFSA-PVdF-P2O5-cell with the theoretical capacity of 97 mAh g−1, a reversible capacity of 92 mAh g−1 was obtained at 363 K for the NaFSA-PVdF positive electrode. These results suggest great potential of this PVC-based ILPE for constructing very safe sodium secondary batteries.

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Tetrahydrofuran (THF; Wako Chemicals) was used as supplied. Sodium iron pyrophosphate, Na$_2$FeP$_2$O$_7$, was synthesized according to the previous report.\(^{39}\)

**Preparation of ILPE.**—The ILPE films were prepared by a solution casting technique. PVC (1 g) was dissolved in 40 mL of THF, and the mixture was stirred vigorously until a clear homogenous solution was formed. The two salts of [C$_2$C$_1$im][FSA] and Na[FSA], in appropriate ratios (see Table I) were added into the solution, and stirred at room temperature for 24 hours until a transparent and homogenous solution was formed. The viscous solution was cast into a petri dish and left in open air to allow the THF to evaporate. The film was then dried under vacuum at 333 K for 48 hours to form the flexible and self-standing polymer electrolyte. All films were stored in the glove box until analysis. Attempt to prepare ILPE with a higher content of [C$_2$C$_1$im][FSA] IL (>50 wt%) resulted in segregation of the IL phase, and the film was not self-standing.

**Analysis.**—The ionic conductivity ($\sigma$) of the synthesized ILPEs was measured by an impedance analyzer (3520-80, Hioki E.E. Corp). The ILPE was placed between a pair of stainless steel blocking electrodes. The data were collected in the frequency range between 1.0 \(\times\) 10\(^{-2}\) and 4.0 Hz with the amplitude of 10 mV at the open circuit potential. $\sigma$ was calculated from the resistance of the bulk value ($R_b$) found in the complex impedance diagram according to Eq. 1:

$$\sigma = \frac{d}{R_b A}$$

The ILPE was punched into a disk with the electrode area (A) of 0.4 cm\(^2\). Its thickness ($d$) was measured to be \(\sim\)0.45 mm. Thermal decomposition of the ILPEs was analyzed by a Netzsch thermogravimetric analyzer (STA409EP) from 308 to 823 K under dry nitrogen flow at a heating rate of 5 K min\(^{-1}\). Scanning electron microscopy (SEM) (Cambridge, Leica) was used to observe the morphology of the samples. For cross sectional views, the sample was immersed in liquid nitrogen for 180 s and mechanically divided into pieces. Differential scanning calorimetric (DSC) measurements were carried out on a DSC-8230 Thermo Plus EVO II Series (Rigaku) instrument under a nitrogen atmosphere. Samples were hermetically sealed in Al cells in a glove box and then heated from 233 to 423 K at a heating rate of 5 K min\(^{-1}\). Cyclic voltammetry was performed in a two-electrode cell (2032-type coin cell), with the ILPE placed between Cu, Al or Pt working electrodes and the Na counter electrode. Charge-discharge test of the Na/ILPE/Na$_2$FeP$_2$O$_7$ cell was performed with a Bio-Logic VSP potentiostat or a Hokuto Denko charge-discharge unit (HJ1001SD8) using 2032-type coin cells assembled in an Al foil. The discharge sheet typically has a thickness of \(\sim\)10 \(\mu\)m, and pressed onto Al current collector. The Na$_2$FeP$_2$O$_7$ electrode was impregnated with the ILPE in the form of THF solution prior to the cell construction, and the THF solvent was removed under vacuum.

**Results and Discussion**

**Thermal behavior.**—Figure 1 shows thermogravimetric curves for ILPE-5 (the sample with the highest IL ratio), PVC polymer, and [C$_2$C$_1$im][FSA] IL. The decomposition temperature of ILPE-5 reached up to 517 K based on the 5 wt% loss criterion. The thermal stability of the ILPE depends on the PVC polymer, since the IL used here is more stable than the host polymer. The ILPE has sufficient thermal stability for the battery tests in the present study below 373 K.

In comparison with ILPEs using other host polymers such as PEO\(^{25}\) or PVdF-HFP,\(^{23,43}\) the PVC-based ILPEs did not display any first-order phase transition in the temperature between 298 and 423 K according to the DSC measurements, suggesting that the IL phase remains a liquid within the host polymer network, and that the PVC host polymer retains its form. The same behavior has been observed for methyl cellulose (MC)-based polymer electrolyte.\(^{40}\)

** Ionic conductivity.**—Figure 2 shows the Arrhenius plots of ionic conductivities for the ILPEs in the temperature range between 298 and 363 K. The ionic conductivity increases with increasing amount of IL, a trend that is in good agreement with a previous study of the ILPE containing N-butyl-N-methylpyrrolidinium bis(trifluoromethylsulfonyl)amide ([C$_4$C$_1$pym][TFSA]) for lithium ion batteries.\(^{43}\) The sample ILPE-1 (0 wt% IL) shows the lowest conductivity of 5.26 \(\times\) 10\(^{-6}\) mS cm\(^{-1}\), at 318 K, suggesting this system does not work without IL. The addition of the IL is believed to weaken the interaction between the polymer chains and hence enhance movements of the ions in the matrix. The sample with 50 wt% IL (ILPE-5) displayed the maximum ionic conductivity of 1.69 mS cm\(^{-1}\) at 298 K. The 1.0:2.0 weight ratio of Na[FSA] and [C$_2$C$_1$im][FSA] in ILPE-5 corresponds to the molar ratio of 0.42:0.58. The ionic conductivity of the Na[FSA]-[C$_2$C$_1$im][FSA] binary IL system at this ratio is 2.6 mS cm\(^{-1}\) at 298 K. The ionic conductivity increases with increasing amount of IL, a trend that is in good agreement with a previous study of the ILPE containing N-butyl-N-methylpyrrolidinium bis(trifluoromethylsulfonyl)amide ([C$_4$C$_1$pym][TFSA]) for lithium ion batteries.\(^{43}\) The sample ILPE-1 (0 wt% IL) shows the lowest conductivity of 5.26 \(\times\) 10\(^{-6}\) mS cm\(^{-1}\), at 318 K, suggesting this system does not work without IL. The addition of the IL is believed to weaken the interaction between the polymer chains and hence enhance movements of the ions in the matrix. The sample with 50 wt% IL (ILPE-5) displayed the maximum ionic conductivity of 1.69 mS cm\(^{-1}\) at 298 K. The 1.0:2.0 weight ratio of Na[FSA] and [C$_2$C$_1$im][FSA] in ILPE-5 corresponds to the molar ratio of 0.42:0.58. The ionic conductivity of the Na[FSA]-[C$_2$C$_1$im][FSA] binary IL system at this ratio is 2.6 mS cm\(^{-1}\) at 298 K by linear approximation from a previous work.\(^{10}\) Comparison of these two values suggests that the ionic conductivity is reduced to 65% when the IL is packed into the polymer electrolyte. According to previous report,\(^{29}\) the transport number of Na\(^{+}\) in the Na[FSA]-[C$_2$C$_1$im][FSA] was 0.27. By multiplying this value by the Na[FSA]-[C$_2$C$_1$im][FSA] transport number of Na\(^{+}\) in the Na[FSA]-[C$_2$C$_1$im][FSA] was 0.27. By multiplying this value by the Na\(^{+}\) ion conductivity in ILPE-5 is estimated to be 0.46 mS cm\(^{-1}\) at 298 K under the assumption that the transport number does not change in the ILPE. Because of its high ionic conductivity, ILPE-5 is used for further electrochemical analysis below.

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**Table I. Composition of the [C$_2$C$_1$im][FSA]-Na[FSA]-PVC ILPE samples.**

<table>
<thead>
<tr>
<th>Weight ratio</th>
<th>Fraction of [C$_2$C$_1$im][FSA] (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[C$_2$C$_1$im][FSA]</td>
<td>Na[FSA]</td>
</tr>
<tr>
<td>ILPE-1</td>
<td>0</td>
</tr>
<tr>
<td>ILPE-2</td>
<td>0.5</td>
</tr>
<tr>
<td>ILPE-3</td>
<td>1.0</td>
</tr>
<tr>
<td>ILPE-4</td>
<td>1.5</td>
</tr>
<tr>
<td>ILPE-5</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Figure 2. Arrhenius plots of ionic conductivity of the ILPEs with different ratios of [C2C1im][FSA] ionic liquid in the temperature range between 298 and 363 K.

Figure 3. (a) Surface and (b) cross sectional SEM images of ILPE-5.

Figure 4. Cyclic voltammograms of Cu (negative potential region), Pt (positive potential region), and Al (positive potential region) plate electrodes at 363 K with the ILPE-5 electrolyte. The two-electrode test cell was used with the Na metal counter electrode. Scan rate: 5 mV s⁻¹.

SEM image.—Figure 3 shows the surface and cross sectional SEM images of the ILPE-5 film. SEM observation of the ILPE sample without any special pretreatment is possible owing to the low vapor pressure of the ILs. The surface of the ILPE-5 film was rough and some inhomogeneity was observed. On the other hand, no obvious porous structure was observed in the cross sectional view suggesting homogenous impregnation of the Na[FSA]-[C2C1im][FSA] IL into the host polymer. The inhomogeneity at the surface is attributed to the removal of the solvent, and it does not extend to the interior. A similar observation has been reported for other ILPEs.42,44,45

Electrochemical window.—Figure 4 shows the cyclic voltammograms of Cu (negative potential region), Pt (positive potential region), and Al (positive potential region) plate electrodes with the ILPE-5 electrolyte at 363 K. For the Na[FSA]-[C2C1im][FSA] IL system, it was reported that Na metal deposition/dissolution occurs at 0 V vs. Na⁺/Na.10 In this experiment, the cyclic voltammogram indicates that Na metal deposition/dissolution occurs for ILPE-5 at the cathodic limit with the Coulombic efficiency of 57%. It should be noted this electrochemical reaction occurs at around −0.1 V vs. the Na metal counter electrode under the present condition. Although the deposition overpotential is observed, the dissolution should occur at or above the Na⁺/Na redox potential. This observation suggests that the Na metal counter electrode only worked as a quasi-reference electrode, it did not correctly indicate the potential of the Na⁺/Na redox couple, most likely owing to the surface film formation. Similar behavior was observed for the gelled IL Na⁺ conductors for sodium batteries.46 The deposition overpotential observed in the Na[FSA]-[C2C1im][FSA] IL was not observed for this ILPE, suggesting that the interfacial process occurs more smoothly in the solid state than in the liquid state, which may be related to the difference in the properties of surface film. Unfortunately, surface analysis of the Na metal electrode after cycle was difficult in this study because the bad condition of the electrode surface. The anodic decomposition occurs around 4.7 V, which is comparable to the case of the Na[FSA]/PEO polymer electrolyte.26 Although the voltammogrammetric data on a flat Pt electrode provides only preliminary anodic stability, the present result indicates the possible compatibility of ILPE-5 to many of the known positive electrode materials for Na secondary batteries. The Al working electrode
exhibits the highest anodic stagnation with ILPE-5 without showing the onset of anodic current, suggesting the validity of AI current collector for positive electrodes. This is similar to the observation for the Na[FSA]-[C2C1im][FSA] IL system, and indicates the formation of passivation film on the electrode surface.

**Charge-discharge behavior of Na2FeP2O7**—Figure 5 shows the galvanostatic charge-discharge curves of the Na/ILPE-5/Na2FeP2O7 cell at 10 mA g⁻¹ and 363 K. The curves show a stair-case shape with a small plateau at 2.4 V followed by a large plateau at 2.9 V. However, the discharge capacity below 2.3 V is significantly larger than the charge capacity in the same voltage region. This difference seems to be supplemented in the voltage region 2.4–2.9 V, which shows a stair-case shape with a large plateau at 2.9 V. However, the increase in discharge capacity probably arises from a greater extraction of Na⁺ from the cathode during the consecutive cycles and reaches 91.2 mAh g⁻¹ at the 5th cycle, with the Coulombic efficiency of 97.3%.

**Conclusions**

This study reported the first PVC-based ILPE [C2C1im][FSA]-Na[FSA]-PVC for sodium secondary batteries. Its ionic conductivity increases with the content of IL, reaching a maximum at [C2C1im][FSA]-Na[FSA]-PVC = 2.0:1.0:1.0 in w/w (ILPE-5). The combined thermogravimetry and differential scanning calorimetry analyses indicated that the ILPE thermally decomposes without melting at above 500 K. Stable electrodeposition/dissolution of sodium metal occurred at the cathodic limit for ILPE-5, and the anodic limit on a Pt electrode was around 4.7 V vs. Na⁺/Na⁺. The discharge capacity of 92 mAh g⁻¹ was obtained at 363 K with a Na2FeP2O7 positive electrode in the Na/ILPE-5/Na2FeP2O7 cell. These results suggest the potential of the PVC-based ILPE as a solid-state electrolyte for safe, reliable sodium secondary batteries.

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**References**