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# Steric effect on Li<sup>+</sup> coordination and transport properties in polyoxetane-based polymer electrolytes bearing nitrile groups†

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Polymer electrolytes (PEs) that consist of polyoxetane with nitrile side chains and lithium bis(trifluoromethanesulfonyl)amide were studied as electrolytes for Li secondary batteries. Our previous study showed that Li<sup>+</sup> ion coordination with the polar nitrile groups tethered to the main chain plays a crucial role in enhancing the Li<sup>+</sup> ion transport properties in poly(3-(2-cyanoethoxymethyl)-3-ethyloxetane) (PCEO). Herein, we report the effects of the absence of ethyl groups on the main chain of PCEO on Li<sup>+</sup> ion coordination, thermal properties, and ionic transport, by employing a structural analog, poly(3-(2-cyanoethoxymethyl)-oxetane). We found that the steric hindrance derived from the ethyl groups in PCEO resulted in more-pronounced Li<sup>+</sup> coordination with the nitrile side chains, and thereby more effective Li<sup>+</sup> ion transport was achieved. We also demonstrated successful charge/discharge cycling of a Li/LiFePO<sub>4</sub> cell using nitrile-functionalized PE.

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## 1. Introduction

There has been much effort to develop solid-state electrolytes, including inorganic and polymeric electrolytes, with high ionic conductivities as alternatives to liquid electrolytes in electrochemical devices.<sup>1,2</sup> Recent breakthroughs in inorganic solid electrolytes have remarkably improved the conductivity, which is now comparable to or even higher than that of liquid electrolytes.<sup>3</sup> This has led to a burgeoning field of study for all-solid-state lithium-ion batteries with high energy and power densities, long cycle lives, and safety for use in automotive and other large-scale energy storage.<sup>4</sup> Meanwhile, the ionic conductivities of polymer electrolytes (PEs) are less than those of liquid electrolytes by orders of magnitude, and they are still insufficient for practical battery applications despite numerous studies.<sup>5</sup> Alternatively, PEs have several advantageous properties over inorganic solid electrolytes.<sup>6</sup> Their inherent flexibility and processability enable formation of more effective electrode/electrolyte interfaces in the composite electrodes of batteries,

which is a challenge in all-solid-state batteries that use solid ceramic electrolytes.<sup>7</sup> Flexible PEs would be more tolerant to electrode volume changes during charge/discharge (especially for conversion reactions). Moreover, PEs generally possess higher stabilities than many of the solid ceramic electrolytes at low potentials for negative electrodes, such as lithium metal.

The most well-studied lithium-conductive PEs have been based on a binary mixture of poly(ethylene oxide) (PEO) and lithium salts since ionic conduction was first reported for alkali metal salts dissolved in PEO,<sup>8</sup> whereby polyether chains form a complex with metal cations.<sup>9</sup> The migration of metal cations is strongly coupled with the segmental motion of the polyether chains; thus, PEO-based PEs generally show low ionic conductivities. To improve the ionic conduction in PEs, many types of modified polymer matrices, such as random copolymer, block copolymer, comb-type copolymer, and polymer blends, have been studied.<sup>6</sup> Polyoxetanes are polyethers that contain trimethylene oxide units and can also be used as a polymer matrix for PEs.<sup>10–12</sup> PEs based on polyoxetanes with polar side chains, such as nitrile groups and phosphate ester groups, were reported.<sup>13–15</sup> The increase in glass transition temperature (*T<sub>g</sub>*) associated with complexation with Li<sup>+</sup> ions, which is a typical behavior for PEs, does not occur in poly(3-(2-cyanoethoxymethyl)-3-ethyloxetane) (PCEO); rather, *T<sub>g</sub>* decreases with increasing salt concentration.<sup>16</sup> This could be caused by steric hindrance of the ethyl groups on the main chain and preferential Li<sup>+</sup> ion coordination with the nitrile side chains. We confirmed that Li<sup>+</sup> ion coordination with the nitrile groups in PCEO is responsible for improving the ionic transport properties of the PEs.<sup>17</sup>

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In this study, poly(3-(2-cyanoethoxymethyl)-oxetane) (PCHO) was newly synthesized. The only difference between PCEO and PCHO is the absence of an ethyl group on the polyoxetane main chain. To clarify the contribution of the ethyl group to the electrolyte properties such as the ionic conductivity ( $\sigma$ ) and lithium transference number ( $t_{\text{Li}^+}$ ), PCHO complexed with lithium bis(trifluoromethanesulfonyl)amide (LiTfSA) were evaluated and were compared with previously reported PCEO electrolytes.<sup>17</sup> Here, we verified that subtle changes in the chemical structure of the repeating monomer unit of the polyoxetane-based PEs (*i.e.*, the presence or absence of the ethyl group on the main chain) greatly affected the thermal properties and ionic transport, which were well correlated with different  $\text{Li}^+$  ion coordination structures studied by Raman spectroscopy. A Li/LiFePO<sub>4</sub> cell was fabricated and its charge/discharge behavior was examined to demonstrate the applicability of the polyoxetane-based PEs to lithium secondary batteries.

## 2. Experimental section

### 2.1 Preparation of the monomer

An oxetane derivative, 3-(2-cyanoethoxymethyl)-oxetane (CHO), was synthesized by Michael addition. 3-Oxetanemethanol (5.64 mL, 70.0 mmol) and acrylonitrile (5.24 mL, 80.0 mmol) were mixed with a 20% tetraethylammonium hydroxide solution (0.6 mL) as a catalyst in pure water (3 mL), then stirred at room temperature overnight. The reaction mixture was extracted with chloroform, and the organic phase was washed with a large amount of water. After removal of chloroform by a rotary evaporator, the obtained liquid was applied to a silica column (eluent = ethyl acetate : hexane, 7 : 3). The product was obtained by removing the eluent and vacuum drying at 60 °C (yield: 3.54 g, 35.9%). The synthesized CHO was characterized using time-of-flight mass spectrometry, and <sup>1</sup>H and <sup>13</sup>C nuclear magnetic resonance (NMR) spectroscopy. The density of the monomer was 1.068 g cm<sup>-3</sup>.

CHO <sup>1</sup>H NMR ( $\delta$ , ppm from tetramethylsilane (TMS) in CDCl<sub>3</sub>): 2.62 (t, 2H,  $J$  = 6.00 Hz, -CH<sub>2</sub>-CN), 3.24 (sep., 1H,  $J$  = 5.8 Hz, -(CH<sub>2</sub>)<sub>3</sub>-CH), 3.70 (t, 2H,  $J$  = 6.0 Hz, -CH<sub>2</sub>-CH<sub>2</sub>-CN), 3.75 (d, 2H,  $J$  = 7.0 Hz, -CH-CH<sub>2</sub>-O-), 4.46 (t, 2H,  $J$  = 6.3 Hz, ring, -CH<sub>2</sub>-O-CH<sub>2</sub>-), 4.81 (dd, 2H,  $J$  = 1.0 Hz, 6.0 Hz, ring, -CH<sub>2</sub>-O-CH<sub>2</sub>-).

CHO <sup>13</sup>C NMR ( $\delta$ , ppm from TMS in CDCl<sub>3</sub>): 18.52 (-CH<sub>2</sub>-CN), 34.45 ((CH<sub>2</sub>)<sub>2</sub>-CH<sub>2</sub>-CH<sub>3</sub>), 65.39 (-CH<sub>2</sub>-CH<sub>2</sub>-CN), 72.34 (-CH-CH<sub>2</sub>-O-), 74.03 (-CH<sub>2</sub>-O-CH<sub>2</sub>-), 117.61 (-CN).

### 2.2 Preparation of the polymer

CHO was polymerized by a ring-opening cationic polymerization using BF<sub>3</sub>·Et<sub>2</sub>O as a cationic initiator. CHO (2.42 mL, 18.3 mmol) and the initiator (50.2  $\mu$ L, 0.400 mmol) were dissolved in dichloroethane (total volume: 5 mL). The polymerization was performed under an Ar atmosphere at 0 °C for 6 h in a salt ice bath. The reaction was quenched with the addition of aqueous 4 M NaCl/1 M NaOH (5 mL). The reaction mixture was added to chloroform, and the solution was washed with water. After

removing chloroform using a rotary evaporator, the mixture was poured into a large amount of 2-propanol to precipitate the polymerized CHO (PCHO). The resulting polymer was collected by filtration and dried at 100 °C under vacuum (yield: 2.17 g, 84.1%). The chemical structures of PCEO (reported in our previous study) and PCHO are shown in Fig. 1.

PCHO <sup>1</sup>H NMR ( $\delta$ , ppm from TMS in CDCl<sub>3</sub>): 2.15 (quin., 1H,  $J$  = 5.9 Hz, (CH<sub>2</sub>)<sub>3</sub>-CH), 2.61 (t, 2H,  $J$  = 6.3 Hz, -CH<sub>2</sub>-CN), 3.43 (m, 4H, -O-CH<sub>2</sub>-CH-), 3.53 (d, 2H,  $J$  = 6.0 Hz, -CH-CH<sub>2</sub>-O-), 3.64 (t, 2H,  $J$  = 6.0 Hz, -CH<sub>2</sub>-CH<sub>2</sub>-CN).

PCHO <sup>13</sup>C NMR ( $\delta$ , ppm from TMS in CDCl<sub>3</sub>): 18.85 (-CH<sub>2</sub>-CN), 40.20 ((CH<sub>2</sub>)<sub>3</sub>-CH), 65.63 (-CH<sub>2</sub>-CH<sub>2</sub>-CN), 69.29 (-CH-CH<sub>2</sub>-O-), 69.38 (-CH<sub>2</sub>-O-CH-), 118.13 (-CN).

### 2.3 Preparation of polymer electrolytes

The PEs were prepared using a solvent casting method. PCHO and 1 M LiTfSA in a tetrahydrofuran (THF) solution were mixed and then heated under vacuum to completely remove THF. In this report, the molar ratio of the repeating monomer unit to LiTfSA is represented as "a" ( $a$  = 40, 30, 20, 10, 5, and 3) for PCHO<sub>a</sub>LiTfSA. The concentrations of LiTfSA ( $c_{\text{Li}}$ ) in PCHO<sub>a</sub>-LiTfSA were estimated using the corresponding monomer density (1.068 g cm<sup>-3</sup>) and the reported density of molten LiTfSA (1.970 g cm<sup>-3</sup>).<sup>18</sup> The high temperature data for the density of molten LiTfSA were extrapolated to room temperature. We assumed the additivity of the volumes of the monomers and LiTfSA when calculating the density of the PEs.

### 2.4 Measurements

<sup>1</sup>H and <sup>13</sup>C NMR spectra of the synthesized substances were recorded using a Fourier transform NMR spectrophotometer (JNM-LA500, JEOL). The molecular weight of the polymer was measured using a gel permeation chromatography (GPC) system (SCL-10AVP, LC-10ADVP, DGU-12A, CTO-10AVP, and RID-10A, Shimadzu). GPC was performed using THF as the elution solvent and polystyrene standards to calibrate the columns.

A differential scanning calorimeter (DSC7020, HITACHI) was used to determine the glass transition temperature ( $T_g$ ). A small amount of the PEs (~10 mg) was hermetically sealed in an aluminum differential scanning calorimetry (DSC) pan. The samples were heated to 120 °C, cooled to -120 °C, and heated again to 120 °C at a heating/cooling rate of 10 °C min<sup>-1</sup>. The second heating scan was recorded as the DSC thermogram of the samples.  $T_g$  was determined as the onset of the heat flow step.

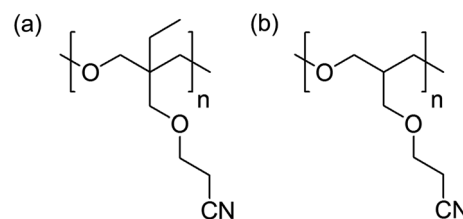


Fig. 1 Structures of the matrix polymers: (a) PCEO and (b) PCHO.



The ionic conductivity of the PEs was measured by ac impedance spectroscopy using a potentio/galvanostat (SP-150, BioLogic). The PE was placed between two stainless steel electrodes and separated by a polytetrafluoroethylene ring spacer; the conductivity cell (swagelok cell) was thermally equilibrated in a temperature cabinet (LU-14, ESPEC) at each temperature (temperature range: 20–90 °C) for 1 h before the measurements. The conductivity values were calculated using the thickness and inner diameter of the ring spacer filled with the PEs.

Raman spectra of the PEs were measured using a laser Raman spectrophotometer (NRS-3100, JASCO) with a 532 nm laser. The PE was sealed between two glass plates with a rubber spacer (thickness: 5 mm) in an Ar-filled glove box to avoid moisture adsorption. Raman spectra of PCHO<sub>a</sub>LiTFSA were measured from 500–2400 cm<sup>−1</sup> with a resolution of 4 cm<sup>−1</sup>. The obtained spectra were normalized with respect to the methylene vibration of polyoxetanes (1390–1520 cm<sup>−1</sup>) and were analyzed using commercial software for peak fitting (PeakFit™ version 4.12, SYSTAT). A pseudo-Voigt function was used for peak deconvolution.

The transference numbers of Li ions ( $t_{Li^+}$ ) in PCHO<sub>5</sub>LiTFSA and PCEO<sub>5</sub>LiTFSA (the sample reported in the previous report,<sup>17</sup>  $M_n = 4.56 \times 10^4$  g mol<sup>−1</sup>) were determined using the electrochemical method proposed by Bruce and Vincent.<sup>19</sup> The required parameters were obtained using potentiostatic polarization and ac impedance spectroscopy with a potentio/galvanostat (SP-150, BioLogic). The PE was placed between two lithium foil electrodes that were separated by a polypropylene spacer, and the cell was stored in a temperature cabinet (LU-114, ESPEC) at 50 °C for several days to stabilize the symmetric cell. Then, impedance spectra were measured prior to the potentiostatic polarization. The current was monitored while a potentiostatic polarization was applied to the cell with a potential step of 10 mV. After a steady current was observed, impedance spectra were measured again. The following equation gives the transference number,

$$t_{Li^+} = [I_{ss}(\Delta V - I_0 R_0)]/[I_0(\Delta V - I_{ss} R_{ss})] \quad (1)$$

where  $\Delta V$  is the applied potential ( $\Delta V = 10$  mV),  $I_0$  is the initial current of the potentiostatic polarization,  $I_{ss}$  is the steady state current of the polarization,  $R_0$  is the interfacial resistance before the polarization, and  $R_{ss}$  is the steady state interfacial resistance during the polarization.

## 2.5 Charge/discharge test of the Li/PCEO<sub>5</sub>LiTFSA/LiFePO<sub>4</sub> cell

The Li|PCEO<sub>5</sub>LiTFSA|LiFePO<sub>4</sub> cell was prepared using the previously reported PE based on PCEO.<sup>17</sup> Lithium metal foil (diameter: 10 mm, Honjo Metal Co., Ltd.) was used as the negative electrode. The positive electrode was composed of LiFePO<sub>4</sub> as the active material (theoretical capacity: 170 mA h g<sup>−1</sup>), acetylene black (AB) as the conductive supporting agent, polyvinylidene fluoride (PVdF), and PCEO<sub>5</sub>LiTFSA as the binder at a weight ratio of LiFePO<sub>4</sub> : AB : PVdF : PCEO<sub>5</sub>LiTFSA = 75 : 15 : 10 : 1. The materials were suspended in *N*-methylpyrrolidone, and the slurry was coated onto a stainless steel

(SUS) foil. After drying at 60 °C for 4 h, the electrode was cut into a circular shape (10 mm in diameter) and compressed at 2 kN for 15 min. LiFePO<sub>4</sub> was loaded on the electrode (2 mg cm<sup>−2</sup>). A porous glass filter paper (GA-55, ADVANTEC) was used as a mechanical electrolyte support because the PE used in this study was not self-standing (it was not crystalline and had a low  $T_g$ ). PCEO<sub>5</sub>LiTFSA was heated to 130 °C and infiltrated into the glass filter paper under vacuum. A 2032-type coin cell was assembled using the above electrodes and the PE in the Ar-filled glove box.

A charge/discharge test was performed with a charge-discharge unit (HJ1020mSD8, Hokuto Denko). The temperature of the cell was maintained at 70 °C in an aluminum bath during the charge/discharge test. The rate capability of the cell was investigated by changing the charge-discharge rate (0.05, 0.1, 0.2, 0.5, 1, and 2C). The charging cutoff voltage was set to 3.9 V to avoid electrolyte oxidation, while the discharging cutoff voltage was 2.5 V.

## 3. Results and discussion

### 3.1 Thermal properties

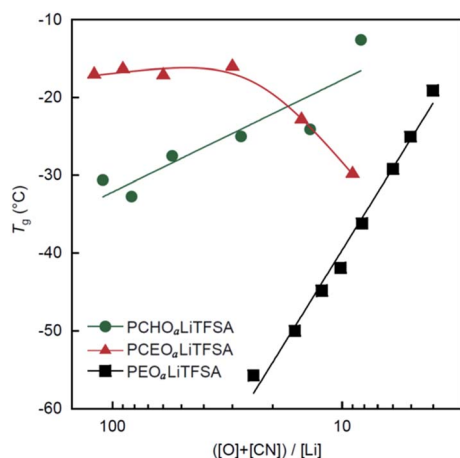
Table 1 summarizes the molecular weights ( $M_n$  and  $M_w$ ), polydispersity index ( $M_w/M_n$ ), and  $T_g$  of pure PCHO, as determined from the GPC and DSC measurements. The reported data for PCEO are also listed for comparison. PCEO is a semi-crystalline polymer with a small melting peak at 55 °C and  $T_g$  at −18.3 °C.<sup>17</sup> Although one may expect that the ethyl group on the main chains of PCEO would sterically hinder chain packing to form a crystalline phase, it rather assisted the formation of a small crystalline domain in PCEO. In contrast, the DSC thermogram of PCHO did not contain an endothermic peak corresponding to the melting of the crystalline domain, suggesting that PCHO is amorphous. The  $T_g$  of PCHO is lower than that of PCEO (−18.3 °C), but higher than the reported  $T_g$  of plain poly(trimethyl oxide),  $-(CH_2CH_2CH_2O)_n-$ , (−71 °C).<sup>20</sup> The presence of side chains could increase  $T_g$ , and PCEO having the nitrile and ethyl side chains showed higher  $T_g$  values because of enhanced intermolecular interactions. Considering the thermal behavior, PCHO is expected to be more favorable than PCEO for ion transport because of its non-crystallinity and lower  $T_g$ .

Fig. 2 shows the salt concentration dependence of  $T_g$  for PCEO<sub>a</sub>LiTFSA and PCHO<sub>a</sub>LiTFSA:  $T_g$  of the PEs values were plotted as a function of the molar ratio of possible interaction sites and LiTFSA,  $([O] + [CN])/[Li]$ . For comparison, the reported  $T_g$  data of PEO<sub>a</sub>LiTFSA,<sup>21</sup> which is the most widely studied PE for lithium secondary batteries, are also shown in Fig. 2. In PEO-based electrolytes,  $T_g$  increases as the salt concentration increases. This is due to ionic cross-linking formed by multi-dentate coordination of the main chain ether groups to Li<sup>+</sup> ions, in which the polymer segmental motion is highly restricted. In contrast, we report that the  $T_g$  value of PCEO decreases as the salt concentration increases.<sup>16,17</sup> This plasticizing effect is due to relaxation of dipole-dipole interactions between the nitrile groups of PCEO in the presence of the Li salt. This plasticization with the addition of Li salt is not limited to PCEO, but has also been reported for polyacrylonitrile,<sup>22</sup> and



**Table 1** Molecular weights ( $M_n$  and  $M_w$ ), polydispersity index ( $M_w/M_n$ ), and thermal characteristic ( $T_g$  and melting point,  $T_m$ ) of PCHO. Data for PCEO were obtained from ref. 17

	Molecular weight			Thermal characteristics	
	$M_n$ [g mol <sup>-1</sup> ]	$M_w$ [g mol <sup>-1</sup> ]	$M_w/M_n$ [—]	$T_g$ [°C]	$T_m$ [°C]
PCEO	$4.56 \times 10^4$	$1.08 \times 10^5$	2.37	-18.3	55.0
PCHO	$2.86 \times 10^4$	$7.94 \times 10^4$	2.78	-30.9	Not observed



**Fig. 2**  $T_g$  as a function of the molar ratio of possible interaction sites and LiTfSA in the PEs ( $[O] + [CN])/[Li]$  for PCHO<sub>a</sub>LiTfSA, PCEO<sub>a</sub>LiTfSA, and PEO<sub>a</sub>LiTfSA.  $T_g$  values for PCEO<sub>a</sub>LiTfSA and PEO<sub>a</sub>LiTfSA were obtained from ref. 17 and 21, respectively.

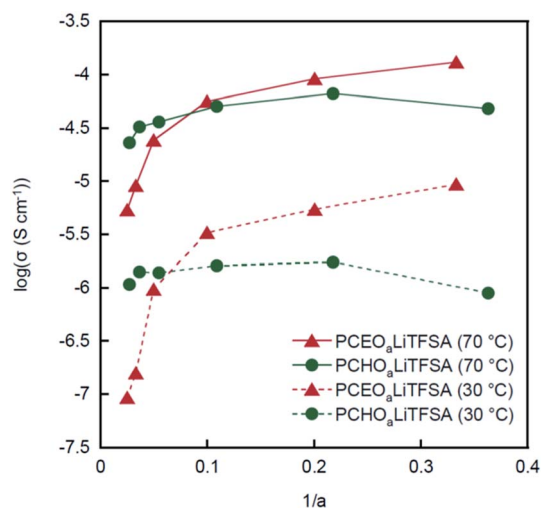
polyethylene carbonate.<sup>23</sup> In the context of free volume theory for amorphous materials,<sup>24,25</sup> the reduction in  $T_g$  by the addition of Li salt implies that the free volume in the system increases upon Li<sup>+</sup> ion coordination. This is likely the case because sterically hindered Li<sup>+</sup> coordination with the main chains and preferential Li<sup>+</sup> coordination with polar side chains would result in a more loosely-packed segmental arrangement.

For newly synthesized PCHO,  $T_g$  increases with increasing salt concentration, although the increase in  $T_g$  is gentler than that of PEO<sub>a</sub>LiTfSA. This suggests that PCHO forms an ionically cross-linked structure in the presence of LiTfSA, but the cross-linking density is not as dense as that in PEO<sub>a</sub>LiTfSA. The differences in the thermal behavior between PCEO<sub>a</sub>LiTfSA and PCHO<sub>a</sub>LiTfSA suggest that the ethyl group on the polyoxetane main chains plays an important role in the Li<sup>+</sup> ion coordination structure and the resultant thermal behavior in the PEs. The prepared PEs (PCEO<sub>a</sub>LiTfSA and PCHO<sub>a</sub>LiTfSA) were not a rubbery solid, but were a highly viscous solution due to the low crystallinity and the lower  $T_g$ . However, a self-standing membrane can be readily formed by introducing robust cross-linking points into the polymers as reported in the literature.<sup>26–28</sup>

### 3.2 Ionic conductivity

In Fig. 3, the ionic conductivities of PCHO<sub>a</sub>LiTfSA at 30 °C and 70 °C are plotted as a function of the molar ratio of LiTfSA to

the repeating monomer unit,  $1/a$  (relevant to the salt concentration). For comparison, the conductivity data for PCEO<sub>a</sub>LiTfSA are also shown in the same figure. Furthermore, the molar conductivity is also shown in the ESI (Fig. S1†). At low values of  $1/a$  (*i.e.*, low salt concentration), the ionic conductivity of PCHO<sub>a</sub>LiTfSA is higher than that of PCEO<sub>a</sub>LiTfSA. This is attributed to the high mobility of ions in PCHO<sub>a</sub>LiTfSA. As shown in Fig. 2, a lower  $T_g$  value is evidently responsible for the faster segmental motion and the lower local viscosity of PCHO<sub>a</sub>LiTfSA. The ionic conductivity increases for both PEs with increasing  $1/a$  (*i.e.*, increasing salt concentration), except for PCHO<sub>a</sub>LiTfSA at the highest  $1/a$ . However, PCHO<sub>a</sub>LiTfSA shows only a small change in conductivity and a continuous decrease in molar conductivity with increasing  $1/a$  (Fig. S1†). The contribution of the increase in the charge carrier would be negated by the increase in  $T_g$  with the addition of Li salt (as shown in Fig. 2), which would account for the marginal change in the conductivity and the decrease in the molar conductivity at higher  $1/a$ . The Li salt concentration dependence of the PCHO<sub>a</sub>LiTfSA conductivity qualitatively agrees with that for the PEO-based PEs; the change in conductivity and molar conductivity fall within one order of magnitude, which is comparable to that for PEO-based PEs.<sup>29,30</sup> Therefore, this typical change is predominantly due to a reduction in mobility by the formation of an ionically cross-linked structure. The ever-increasing conductivity for PCEO<sub>a</sub>LiTfSA suggests again that the presence of the ethyl group can inhibit the formation of the cross-



**Fig. 3** Ionic conductivity of the PEs as a function of LiTfSA content ( $1/a$ ) at 30 °C and 70 °C.





linked structures by  $\text{Li}^+$  ion coordination with the ether main chains.

The temperature dependent conductivity ( $\sigma$ ) was also measured to elucidate the ionic conduction mechanism in  $\text{PCEO}_a\text{LiTFSA}$  and  $\text{PCHO}_a\text{LiTFSA}$ , as shown in Fig. S2.† The Arrhenius plots of the conductivity show non-linear behavior with a curvature that is generally observed for amorphous PEs, and are well described by an empirical expression in relation to the Vogel–Tammann–Fulcher equation,<sup>5</sup>

$$\sigma = AT^{-1/2} \exp\left[\frac{-B}{R(T - T_0)}\right] \quad (2)$$

where  $A$  is a fitting parameter relevant to the number of charge carriers,  $B$  is the pseudo activation energy of ionic conduction,  $R$  is the gas constant, and  $T_0$  is an ideal glass transition temperature. Because  $T_0$  is typically 30–50 K below  $T_g$  for many cases, we defined  $T_0 = T_g - 50$  K for fitting the conductivity data according to the previous report.<sup>31</sup> Table 2 shows the obtained parameters for  $\text{PCEO}_a\text{LiTFSA}$  and  $\text{PCHO}_a\text{LiTFSA}$ .  $\text{PCEO}_a\text{LiTFSA}$  with low Li salt concentrations ( $a = 20, 30$ , and  $40$ ) are crystalline; therefore, these compounds are not included in the fitting analysis.

The  $A$  parameter tends to increase with increasing salt concentration in each PE, indicating that the number of effective charge carriers increases with the addition of the Li salt. The  $A$  value of  $\text{PCHO}_a\text{LiTFSA}$  was higher than that of  $\text{PCEO}_a\text{LiTFSA}$  at the same  $a$  value. The absence of ethyl groups in  $\text{PCHO}$  may result in a higher polarity in the PE, which can promote ionic dissociation of the Li salt, leading to the higher  $A$  value for  $\text{PCHO}_a\text{LiTFSA}$ .  $\text{PCHO}_a\text{LiTFSA}$  shows slightly larger values of  $B$  than  $\text{PCEO}_a\text{LiTFSA}$ , indicating that  $\text{PCHO}_a\text{LiTFSA}$  has a little higher activation barrier for ion exchange between the coordination sites in the PEs. This implies that  $\text{Li}^+$  ion coordination is more stabilized in  $\text{PCHO}$  than in  $\text{PCEO}$ , and  $\text{Li}^+$  ions are more tightly trapped by the multi-dentate polyether groups in  $\text{PCHO}_a\text{LiTFSA}$ .

In our previous work, we reported that the parameters  $A$  and  $B$  for  $\text{PCEO}_a\text{LiBF}_4$  and  $\text{PCEO}_a\text{LiBF}_4$  show smaller  $A$  and larger  $B$  values than those of  $\text{PCEO}_a\text{LiTFSA}$  at the same  $a$  value.<sup>15</sup> It seems that the more associative character and smaller size of  $\text{LiBF}_4$  are responsible for the smaller  $A$  value and larger  $B$  value. The  $B$  value of the PEO-based PEs dramatically changes with respect to the salt concentration and anion species,<sup>32</sup> and  $B = 24$

$\text{kJ mol}^{-1}$  was reported for  $\text{PEO}_{12}\text{LiTFSA}$ .<sup>33</sup> Hence, the smaller  $B$  values of  $\text{PCEO}_a\text{LiTFSA}$  and  $\text{PCHO}_a\text{LiTFSA}$  than that of the PEO-based PEs suggest that ion migration is promoted more in  $\text{PCEO}$  and  $\text{PCHO}$  by preferential  $\text{Li}^+$  ion coordination with the nitrile side chains.

### 3.3 Coordination structure of $\text{Li}^+$ ions

Raman spectroscopic measurements were carried out to investigate the coordination structure formed in PEs. The Raman spectra of the nitrile group ( $2200\text{--}2320\text{ cm}^{-1}$ ) is shown in Fig. 4. A symmetric peak that can be assigned to the stretching vibration of nitrile groups is observed at  $2249\text{ cm}^{-1}$  for pure  $\text{PCHO}$ . However, another peak emerges at higher wavenumber in the presence of  $\text{LiTFSA}$ . This is indicative of  $\text{Li}^+$  ion coordination with the nitrile groups in  $\text{PCHO}_a\text{LiTFSA}$ . The Raman spectra in this region show an isosbestic point at  $2255\text{ cm}^{-1}$  (except that for  $\text{PCHO}_3\text{LiTFSA}$ ), indicating that two species (*i.e.*, free and bound nitrile groups) co-exist. Here, each spectrum was further analyzed using the same procedure as that in our previous report,<sup>17</sup> and each was deconvoluted into four bands at  $2249$ ,  $2253$ ,  $2264$ , and  $2277\text{ cm}^{-1}$ , as shown Fig. 4b. The peaks at  $2249$  and  $2253\text{ cm}^{-1}$  are assigned to vibrations of uncoordinated (free) nitrile groups, whereas the peaks at  $2264$  and  $2277\text{ cm}^{-1}$  are due to nitrile groups bound to  $\text{Li}^+$  ions. The intensity of a peak at  $x\text{ cm}^{-1}$  is given as  $I_{x(\text{CN})}$ . To quantitatively determine the coordination number of the nitrile group ( $n_{\text{CN}}$ ), the relationship between the slope and intercept of the linear function plotted as  $I_{\text{f(CN)}}/c_{\text{Li}}$  vs.  $a$  was analyzed using the following relationship,

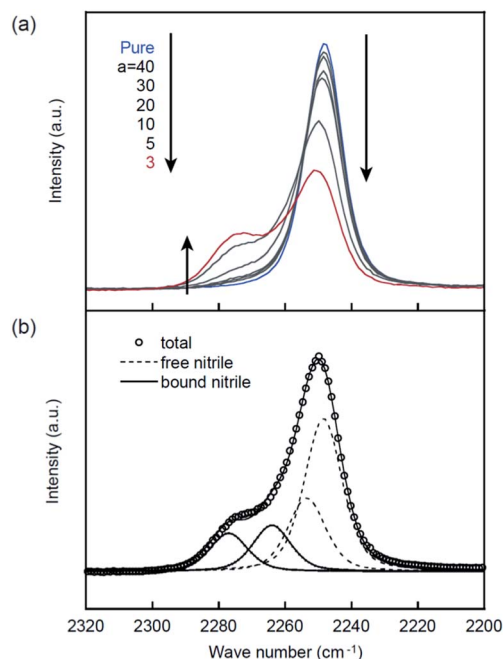


Fig. 4 Raman spectra of the nitrile group in  $\text{PCHO}_a\text{LiTFSA}$  in the frequency range of  $2200\text{--}2320\text{ cm}^{-1}$  at room temperature. (a) Dependence on Li salt concentration (pure and  $a = 3\text{--}40$ ) and (b) typical result upon deconvolution of the spectrum for  $a = 5$ .

Table 2 The fitting parameters for  $\text{PCEO}_a\text{LiTFSA}$  and  $\text{PCHO}_a\text{LiTFSA}$

Polymer	$a$	$A$ ( $\text{S cm}^{-1} \text{ K}^{1/2}$ )	$B$ ( $\text{kJ mol}^{-1}$ )
PCEO	10	1.21	7.96
	5	3.19	8.84
	3	5.75	9.49
PCHO	40	2.21	10.7
	30	4.97	11.5
	20	4.88	10.9
	10	9.34	11.1
	5	11.9	11.6
	3	9.86	10.2



$$I_{\text{f(CN)}}/c_{\text{Li}} = J_{\text{f(CN)}}(a - n_{\text{CN}}) \quad (3)$$

where  $I_{\text{f(CN)}}$  is the sum of the integrated intensities of the lower two bands ( $I_{\text{f(CN)}} = I_{2249(\text{CN})} + I_{2253(\text{CN})}$ ), and  $J_{\text{f(CN)}}$  is the molar Raman scattering coefficient of the free nitrile moieties. For highly concentrated  $\text{PCHO}_3\text{LiTFSA}$  ( $a = 3$ ), the Raman spectrum deviates from the isosbestic point and shifts to a lower wave-number, suggesting that the  $\text{Li}^+$  ion coordination structure is different from that of the others. Therefore, the data for  $\text{PCHO}_3\text{LiTFSA}$  are excluded from the fitting analysis.

Fig. 5 shows the result of the linear least-square fitting to eqn (3) for the nitrile group in  $\text{PCHO}_a\text{LiTFSA}$ . From the good linear relationship in Fig. 5, we could determine the coordination number of the nitrile group in  $\text{PCHO}_a\text{LiTFSA}$  ( $n_{\text{CN}} = 0.81 \pm 0.40$ ), which is smaller than the reported  $n_{\text{CN}}$  of  $\text{PCEO}_a\text{LiTFSA}$  ( $0.93 \pm 0.7$ ).<sup>17</sup> Thus,  $\text{Li}^+$  ion coordination with the nitrile groups is less pronounced in  $\text{PCHO}_a\text{LiTFSA}$ . The  $\text{Li}^+$  ion was probably more preferentially coordinated with the ether groups by the absence of the steric hindrance of the ethyl groups on the main chains in  $\text{PCHO}_a\text{LiTFSA}$ .

The Raman spectra corresponding to the  $\text{CF}_3$  bending vibration coupled with the S–N stretching vibration of the TFSA anion are shown in Fig. 6. To investigate the  $\text{Li}^+$  ion coordination with the TFSA anions, these Raman spectra were further deconvoluted into two peaks at 739 and 745  $\text{cm}^{-1}$  using the same method as that used in the previous work.<sup>17</sup> The peak at 739  $\text{cm}^{-1}$  can be assigned to TFSA in the form of a free or solvent separated ion pair, whereas the peak at 745  $\text{cm}^{-1}$  corresponds to TFSA directly bound to  $\text{Li}^+$  ions in the form of a contact ion pair or aggregates. The respective peak intensities ( $I_{739(\text{TFSA})}$  and  $I_{745(\text{TFSA})}$ ) were used to determine the coordination number of TFSA anions ( $n_{\text{TFSA}}$ ) according to the following equations,<sup>34</sup>

$$0.9I_{739(\text{TFSA})} + I_{745(\text{TFSA})} = J_{745(\text{TFSA})}c_{\text{Li}} \quad (4)$$

$$I_{745(\text{TFSA})} = J_{745(\text{TFSA})}n_{\text{TFSA}}c_{\text{Li}} \quad (5)$$

As shown in Fig. 7, a relatively good linear relationship is obtained for both cases, and the coordination number for  $\text{PCHO}_a\text{LiTFSA}$  is estimated as  $n_{\text{TFSA}} = 0.16 \pm 0.01$  using the two

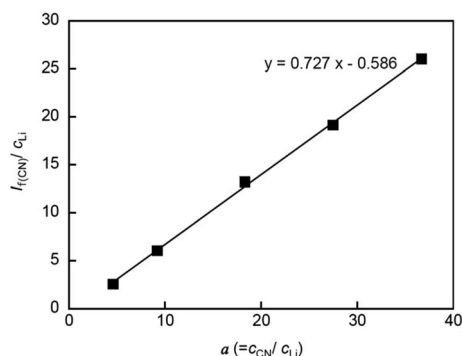


Fig. 5  $I_{\text{f(CN)}}/c_{\text{Li}}$  plotted as a function of  $a (=c_{\text{CN}}/c_{\text{Li}})$  for  $\text{PCHO}_a\text{LiTFSA}$ . The solid line represents the least-square linear fitting.

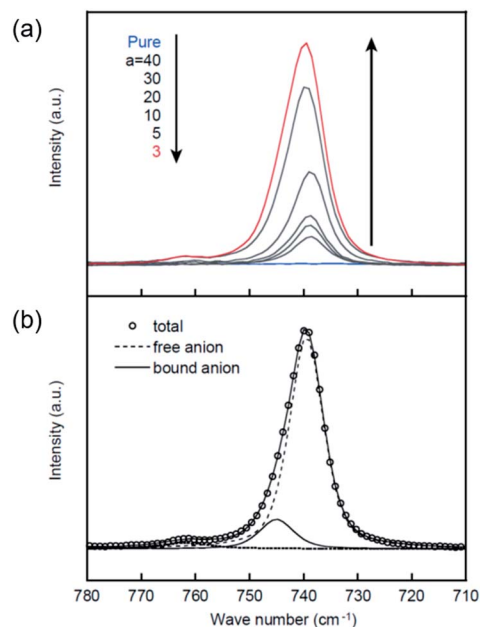


Fig. 6 Raman spectra in  $\text{PCHO}_a\text{LiTFSA}$  in the frequency range of 710–780  $\text{cm}^{-1}$  at room temperature. (a) Dependence on Li salt concentration (pure and  $a = 3$ –40) and (b) typical result upon deconvolution of the spectrum for  $a = 5$ .

linear fitting results. This value is nearly half the reported  $n_{\text{TFSA}}$  value for  $\text{PCEO}_a\text{LiTFSA}$  ( $0.30 \pm 0.04$ ).<sup>17</sup> The Raman spectra corresponding to the ether groups (800–900  $\text{cm}^{-1}$ ) are very complicated because various vibrational modes are involved in this range; therefore, the coordination number of the ether groups could not be determined from the spectroscopic analysis. Given the total coordination number of  $\text{Li}^+$  ions (generally 4–5)<sup>35,36</sup> and the values of  $n_{\text{CN}}$  and  $n_{\text{TFSA}}$ , more ether groups on the main chains can be anticipated to coordinate to  $\text{Li}^+$  ions in  $\text{PCHO}_a\text{LiTFSA}$  than in  $\text{PCEO}_a\text{LiTFSA}$ . This can form a cross-linked structure based on the main chains in  $\text{PCHO}_a\text{LiTFSA}$ , which is consistent with the experimental observations:  $T_g$  increases with the addition of Li salt (Fig. 2) and the slightly higher values for the  $B$  parameter for ionic conduction (Table 2). The ethyl groups in  $\text{PCEO}$  likely sterically hinder  $\text{Li}^+$  ion

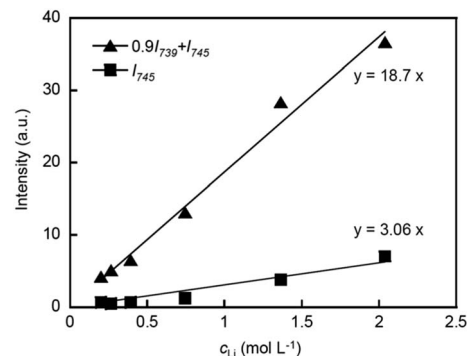


Fig. 7  $I_{\text{f(CN)}}/c_{\text{Li}}$  plotted as a function of  $a (=c_{\text{CN}}/c_{\text{Li}})$  for  $\text{PCHO}_a\text{LiTFSA}$ . The solid line represents the least-square linear fitting.



coordination with the ether groups, which promotes  $\text{Li}^+$  ion coordination with the nitrile side chains and TFSA anions, as evidenced by the larger  $n_{\text{CN}}$  and  $n_{\text{TFSA}}$  values for  $\text{PCEO}_a\text{LiTFSA}$ .

### 3.4 $\text{Li}^+$ ion transference number

To elucidate the transport properties of the  $\text{Li}^+$  ions in each PE, the transference number ( $t_{\text{Li}^+}$ ) was measured using an electrochemical method.<sup>19</sup> As this value increases beyond 0.5,  $\text{Li}^+$  migration proceeds at a faster rate relative to TFSA anions in the PEs. The experimental data are shown in the ESI (Fig. S3 and S4†).  $t_{\text{Li}^+}$  values of 0.59 and 0.40 are obtained for  $\text{PCEO}_5\text{LiTFSA}$  and  $\text{PCHO}_5\text{LiTFSA}$ , respectively. The lower  $t_{\text{Li}^+}$  value for  $\text{PCHO}_5\text{LiTFSA}$  indicates that the migration of  $\text{Li}^+$  ions is more restricted in  $\text{PCHO}_5\text{LiTFSA}$ , and corroborates the more-pronounced coordination with the ether groups, whereby the mobility of  $\text{Li}^+$  ions is coupled with the segmental motion of the ether main chains. The  $t_{\text{Li}^+}$  values for  $\text{PCEO}_5\text{LiTFSA}$  and  $\text{PCHO}_5\text{LiTFSA}$  are much larger than those for typically studied PEs, such as  $\text{PEO}_a\text{LiTFSA}$  (typically  $< 0.2$ ).<sup>37,38</sup>  $\text{Li}^+$  ion exchange occurs more frequently between the mono-dentate nitrile side chains and the counter anions than between the multidentate polyethers on the main chains; therefore, the  $\text{Li}^+$  ion can travel more effectively *via* side chain coordination and site exchange.

### 3.5 Charge/discharge tests

Based on the comparative study shown above, we found that  $\text{PCEO}_5\text{LiTFSA}$  exhibits higher  $\text{Li}^+$  ion transport properties. Here, we assembled a lithium-ion half-cell,  $\text{Li}|\text{PCEO}_5\text{LiTFSA}|\text{LiFePO}_4$ , with  $\text{PCEO}_5\text{LiTFSA}$  as an electrolyte to study whether the polyoxetane-PEs are indeed applicable to Li secondary batteries. No capacity was observed at 30 °C even at very low charge-discharge rate (0.05C), probably due to low ionic conductivity of  $\text{PCEO}_5\text{LiTFSA}$ . The preliminary charge/discharge test from 2.5–4.0 V at 70 °C causes an unexpected charging plateau and an apparent overcharge is observed around 3.95 V (Fig. S5†). We previously reported that the electrochemical window of  $\text{PCEO}_5\text{LiTFSA}$  is  $\sim 4.0$  V vs.  $\text{Li}/\text{Li}^+$  on stainless steel electrodes.<sup>17</sup> This indicates the oxidative decomposition of  $\text{PCEO}_5\text{LiTFSA}$  on the cathode at this potential. Therefore, a further charge/

discharge test was performed in the range of 2.5–3.9 V at 70 °C. The charge–discharge curves and cycle performance with different charge–discharge rates are shown in Fig. 8. The obtained capacities are approximately  $100 \text{ mA h g}^{-1}$ , even with a low charge–discharge current density at 0.05C, and are much lower than the theoretical capacity of  $\text{LiFePO}_4$  ( $170 \text{ mA h g}^{-1}$ ). This is predominantly due to the insufficient electrode/electrolyte interface in the composite cathode, even though  $\text{PCEO}_5\text{LiTFSA}$  is combined with the composite cathode as the co-binder. To construct better electron/ion pathways, the material composition and the fabrication procedure of the cathode must be further optimized. With an increasing charge–discharge rate, the capacity drastically decreases and the over-voltage increases. In particular, almost no capacity is delivered at rates above 1C. This is probably caused by the low ionic conductivity of  $\text{PCEO}_5\text{LiTFSA}$ . However, the cell shows a relatively stable cycle performance with only a slight capacity loss at the same rate and high coulombic efficiency of  $\sim 99.5\%$ , suggesting that the electrochemical reaction at the positive electrolyte ( $\text{LiFePO}_4 \rightleftharpoons \text{FePO}_4 + \text{Li}^+ + \text{e}^-$ ) is highly reversible in  $\text{PCEO}_5\text{LiTFSA}$ . Thus, these results suggest that the polyoxetane-based PEs with nitrile functionality are applicable to Li secondary batteries.

## 4. Conclusions

The steric effect of the ethyl group of polyoxetane-based PEs with nitrile side chains was clarified by comparing the thermal properties,  $\text{Li}^+$  ion coordination, and ion transport properties of  $\text{PCHO}_a\text{LiTFSA}$  and  $\text{PCEO}_a\text{LiTFSA}$ . As the Li salt concentration increased,  $T_g$  increased for  $\text{PCHO}_a\text{LiTFSA}$ ; this behavior is analogous to that of well-studied PEO-based PEs. Conversely,  $T_g$  decreased with increasing salt concentrations for  $\text{PCEO}_a\text{LiTFSA}$ . Correspondingly, the ionic conductivity of  $\text{PCHO}_a\text{LiTFSA}$  was lower than that of  $\text{PCEO}_a\text{LiTFSA}$  in the high salt concentration region, mainly because of the higher microviscosity. The  $\text{Li}^+$  ion coordination structure was investigated using Raman spectroscopy, which revealed that the mixed coordination with ether groups, nitrile side chains, and TFSA anions occurred in both  $\text{PCHO}_a\text{LiTFSA}$  and  $\text{PCEO}_a\text{LiTFSA}$ ;

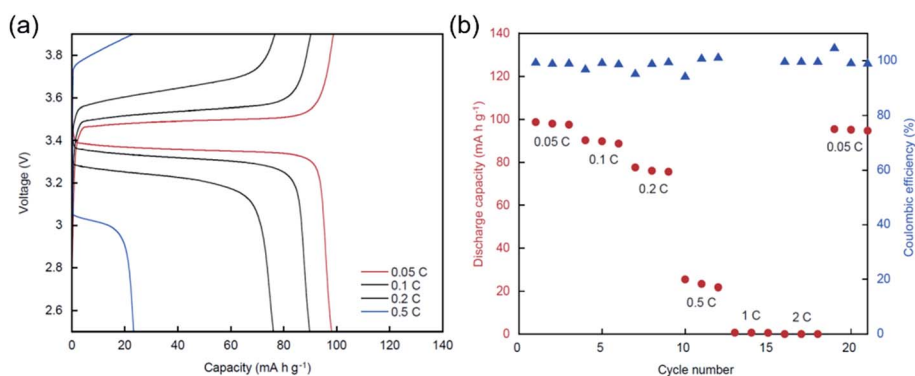


Fig. 8 (a) Charge/discharge curves and (b) cycle properties of the  $\text{Li}/\text{PCEO}_5\text{LiTFSA}/\text{LiFePO}_4$  cell at 70 °C. The measurements were carried out in the range of 2.5–3.9 V ( $1\text{C} = 356 \text{ mA g}^{-1}$ ). Coulombic efficiencies exceeded 110% at 1C and are not shown in the figure because of the negligible discharge capacities that were higher than the charge capacities recorded in the charge–discharge unit.



however, the ether groups were more prone to coordinating with  $\text{Li}^+$  ions in  $\text{PCHO}_a\text{LiTFSA}$ . The more preferential  $\text{Li}^+$  ion coordination with the ether groups resulted in a more pronounced cross-linking of the main chains with  $\text{Li}^+$  ions, leading to an increase in  $T_g$  and less effective  $\text{Li}^+$  ion transport (i.e., lower conductivity and  $t_{\text{Li}^+}$ ) in  $\text{PCHO}_a\text{LiTFSA}$ . In other words, the ethyl group played a pivotal role in enhancing the  $\text{Li}^+$  ion transport by sterically inhibiting  $\text{Li}^+$  ion coordination with the ether main chains of the polyoxetanes. In addition, the  $\text{Li-LiFePO}_4$  cell using  $\text{PCEO}_5\text{LiTFSA}$  showed a reversible charge-discharge with a relatively stable cycle ability and high coulombic efficiency. Although the conductivity values of  $\text{PCHO}_a\text{LiTFSA}$  and  $\text{PCEO}_a\text{LiTFSA}$  (on the order of  $10^{-6}$  to  $10^{-5}$   $\text{S cm}^{-1}$  at 30 °C) were not sufficient for practical applications in solid-state Li secondary batteries, this work could provide insight into the molecular design of PEs for pursuing a high ionic conductivity at a level comparable to that of liquid electrolytes, in association with a high  $\text{Li}^+$  ion transference number that rivals that of inorganic solid electrolytes.

## Conflict of interest

There are no conflicts to declare.

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