The effects of alkaline and alkaline earth metal salts on the performance of a polymer actuator based on single-walled carbon nanotube-ionic liquid gel

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Abstract

We investigated an effect for alkaline metal salts or an alkaline earth metal salt on electrochemical and electromechanical properties of an actuator using a single-walled carbon nanotube (SWCNT)-ionic liquid (IL) gel electrode, and much better performance of the actuator containing the metal salt/IL. The actuator containing the alkaline metal salt /IL or alkaline earth metal salt/IL performed much better than that containing only the IL. It is considered that the higher ionic conductivity of the gel electrolyte layer containing the alkaline metal salt /IL or alkaline earth metal salt/IL produces the quick response actuator, and that the large capacitance gives the large generated strain.

Keywords: Alkaline metal salt; Alkaline earth metal salt; Polymer actuator; Single-walled carbon nanotube; Ionic liquid gel

1. Introduction

Recently, much attention has been focused on soft materials that can directly transform electrical energy into mechanical work, because they allow a wide range of applications including robotics, tactile and optical display, prosthetic devices, medical devices, micro-electromechanical systems and so forth [1]. Especially, low-voltage electroactive polymer (EAP) actuators, which can work quickly and softly driven are very useful, since they can be used as artificial muscle-like actuators for various bio-medical and human affinity applications [2-3]. In previous papers [4-6], we have reported the first dry actuator that can be fabricated using ‘bucky-gel’ [7], a gelatinous room-temperature ionic liquid (IL) containing single-walled carbon nanotubes (SWCNTs). Our actuator has a bimorph configuration with a polymer-supported IL electrolyte layer sandwiched by polymer-supported bucky-gel electrode layers, which allow the quick and long-lived operation in the air at low applied voltages. ILs are less-volatile and show high ionic conductivities and wide potential windows, which are advantageous for the quick response in the actuation and the high electrochemical stability of the components, respectively [8].

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In our previous reports, the dependence of IL species on the electromechanical and electrochemical properties of the actuator composed of the bucky-gel electrode and the gel electrolyte layer have been reported [6, 9, 10]. We measured the frequency dependence of the displacement response of the actuator and it can be successfully simulated by the electrochemical kinetic model. Both the steric repulsion effects due to the transfer of ions to the electrode and ‘the charge injection’ [11] gives the bending motion of the actuator. The generated strain of the polymer-supported bucky-gel electrode of the actuator is considered to be attributed to the volume-change for polymer-IL gel of the cathode and that of the anode [9]. In addition to that, we show that the polymer-IL gel of the electrolyte is the important factor in the field of the low-voltage EAP actuator, and we are considered that these results become the important design principle of the low-voltage EAP actuator [12].

While, rechargeable Li batteries are a ubiquitous energy device that is being used worldwide in many types of a portable electronic equipment. In the state-of-the-art technologies of 4V-class rechargeable Li batteries, a mixture of organic aprotic solvents and a lithium hexafluorophosphate (Li[PF_6]) of a conducting salt is generally used as a non-aqueous electrolyte. Moreover, the high-energy and rechargeable for Li storage in the Li battery based on SWCNT technology is reported [13], much attention has been focused on a polymer battery using a Li ion polymer gel electrolyte [14]. We pay attention to the electrode and electrolyte for the high-energy density device, such as the EAP actuator and the electrochemical capacitor using a Li salt/IL. Furthermore, it is paid attention to that rechargeable alkaline earth metal batteries are higher-energy density devices than rechargeable Li batteries [15]. Therefore, we pay attention to an electrode and electrolyte for a high-energy density device, such as an EAP actuator and an electrochemical capacitor using a Mg salt/IL. It is expected that the ionic conductivity of the gel electrolyte layer containing the alkaline metal (Li) salt/IL or the alkaline earth metal salt (Mg) salt/IL is higher than that containing only the IL, and that the double-layer capacitance of the polymer-supported bucky-gel electrode containing Li salt/IL or Mg salt/IL is larger than that containing only the IL. Furthermore, it is expected that the higher ionic conductivity of the gel electrolyte layer containing Li salt/IL or Mg salt/IL produces the quick response actuator, and that the large capacitance gives the large generated strain in the actuator.

In this paper, we investigated the effect of the alkaline metal salt (Lithium tetrafluoroborate (Li[BF_4]) or Lithium bis(trifluoromethanesulfonyl)imide (Li[TFSI]) or the alkaline earth metal salts (Magnesium bis(trifluoromethanesulfonyl)imide (Mg[TFSI]_2) on the electrochemical and electromechanical properties of the actuator using the SWCNT-IL gel electrode (viz. “using the polymer-supported bucky-gel electrode”), and much better performance of the actuator containing the metal salt/IL. The IL in the conventional actuator is advantageous for the quick response in the actuation and the high electrochemical stability of the components. In addition to that, in this system, it is a solvent, possessing with the less-volatile, for Li[BF_4], Li[TFSI] and Mg[TFSI]_2.

2. Experimental

2.1. Materials

The chemical structures of the alkaline metal salts (Li[BF_4] and Li[TFSI]) and the alkaline earth metal salt (Mg[TFSI]_2) used are shown in Fig. 1. The IL used was 1-ethyl-3-methylimidazolium tetrafluoroborate (EMI[BF_4]) and 1-ethyl-3-methylimidazolium bis(trifluoromethanesulfonyl)imide (EMI[TFSI]), of which the chemical structures are shown in Fig. 1. Li[BF_4], Li[TFSI] and Mg[TFSI]_2 were from Kishida Chemical, Co. Ltd., which were used as received. EMI[BF_4] and EMI[TFSI] were from Fluka and Merck, Co. Ltd., which were used as received. Other reagents were used as received from Carbon Nanotechnologies Inc. (high-purity HiPco™ SWCNTs), Arkema Chemicals Inc. (poly(vinylidene fluoride-co-hexafluoropropylene (PVdF(HFP)): Kynar Flex 2801), Aldrich (Methyl Pentanone (MP), Propylene Carbonate (PC)), Kishida Chemical Co. Ltd. (Dimethylacetamide) (DMAc).

2.2. Preparation of the actuator film [9]
The configuration of our bucky-gel actuator is illustrated in Fig.1. Typically, in the case of the molar ratio of Mg[TFSI]₂/EMI[TFSI]= 0.1, the polymer-supported bucky-gel electrode layer composed of 12.4 wt% of SWCNTs, 8.8 wt% of Mg[TFSI]₂, 58.9 wt% of EMI[TFSI] and 19.9 wt% of PVdF(HFP) was prepared as followed. The mixture of 50 mg of SWCNTs, 35.4 mg (0.06 mmol) of Mg[TFSI]₂, 237.2 mg (0.6 mmol) of EMI[TFSI] and 80 mg of PVdF(HFP) in 9 ml DMAc was dispersed in ultrasonic bath for more than 5 hours. Then, a gelatinous mixture composed of SWNTs, Mg[TFSI]₂, EMI[TFSI] and PVdF(HFP) in DMAc was obtained. In the case of other molar ratios and in the case of Li[BF₄] or Li[TFSI], the casting solution was obtained by mixing 0.6 mmol of EMI[BF₄] or EMI[TFSI] with the same amount of SWCNTs and PVdF(HFP) in 9 ml of DMAc. The electrode layer was fabricated by casting 1.6 ml of the electrolyte solution in the Teflon mold (an area of 2.5 x 2.5 cm²) and evaporating the solvent, finally, the solvents removed in vacuo at 80°C, perfectly. The thickness of the obtained electrode film was 70 μm - 80 μm. The gel electrolyte layers were fabricated by casting 0.5 ml of the solutions composed of Mg salts (Mg[TFSI]₂; 0.1 mmol / 59.1 mg), IL (EMI[TFSI]; 1 mmol / 395.3 mg) and PVdF(HFP) (200 mg) in a mixed solution composed of 6ml of MP and 500 mg of PC in the Teflon mold (an area of 2.5 x 2.5 cm²) and evaporating the solvent, finally, the solvents removed in vacuo at 80°C, perfectly. The thickness of the obtained gel electrolyte film was 20 μm - 30 μm. In the case of other molar ratios and in the case of Li[BF₄] or Li[TFSI], the casting solution was obtained by mixing 1 mmol of EMI[BF₄] or EMI[TFSI] with the same amount of PVdF(HFP) in 6ml of MP and 500 mg of PC. An actuator film was fabricated by hot-pressing the electrode and electrolyte layers which have the same IL (70°C, 120 N, 60 sec.). The thickness of the actuator film was 150 μm - 175 μm, which are smaller than the sum of those of two electrode and one electrolyte layers, since the thickness of each layer decreases by being hot-pressed.

2.3. Displacement measurement [12]

The actuator experiments were conducted by the applied triangle voltages to a 10 x 1 mm² sized actuator strip clipped by two gold disk electrodes; the displacement at a point 5 mm away (free length) from the fixed point was continuously monitored from one side of the actuator strip by using a laser displacement meter (KEYENCE model LC2100/2220). A Hokuto Denko Potentio/Galvanostat model with a YOKOGAWA ELECTRIC model FC 200 waveform generator was used for activating the bucky-gel actuator. The electric parameters were simultaneously measured. The measured displacement \( \delta \) was transformed into the strain difference between two bucky electrode layers (\( \varepsilon \)) by using the following equation on the assumption that the cross sections are plane at any position along the actuator: there is no distortion of the cross sections:

\[
\varepsilon = 2d\delta / (L^2 + \delta^2) \quad (1)
\]

where \( L \) is the free length and \( d \) is the thickness of the actuator strip [16].

2.4 Characterization of the electrode and electrolyte film

The double layer capacitance of the bucky-gel electrode was estimated by cyclic voltammogram, which was measured by two-electrode configuration using a Hokuto Denko Model HSV-100. The conductivity of the gel electrolyte layer was measured by impedance measurement, which was measured by Solatron 1250 Impedance Analyzer.

3. Results and discussion

Fig. 2 shows the ionic conductivity \( \kappa \) (= (thickness/(R x Area)) against Li or Mg salt/IL. The ionic conductivity of the gel electrolyte layer depended on the molar ratio of Li or Mg salt/IL. Furthermore, the ionic conductivities of the gel electrolyte layers with the molar ratios of Li[BF₄]/EMI[BF₄]=0.1 and 0.5, Li[TFSI]/EMI[TFSI]=0.1 and 0.3, and Mg[TFSI]₂/EMI[TFSI]= 0.05, 0.1 and 0.25 were higher than those containing only EMI[BF₄] and only EMI[TFSI], respectively. These results are considered to attribute that the van der Waals volume of Li or Mg cation is smaller than that of [EMI] cation. However, the ionic conductivities of the gel electrolyte layers with the molar ratios of Li[BF₄]/EMI[BF₄] = 1.0 and Li[TFSI]/EMI[TFSI] = 0.5 and 1.0 are lower than those containing only EMI[BF₄] and only EMI[TFSI], respectively. These results are considered that the ionic conductivity of the gel electrolyte depends on other factors (e.g. the diffusion coefficient of the gel electrolyte).
It is well-known that the SWCNTs have extraordinary mechanical [17] and electrochemical [18, 19] properties. Due to these properties, SWCNTs are promising materials for electrochemical actuators based on the double-layer electrostatic mechanism [20]. In this respect, the bucky-gels are soft composite materials of SWCNTs in imidazolium ion-based ILs, where the heavily entangled nanotube bundles are exfoliated by the cation-π interaction on the SWCNT surfaces to give much finer bundles [21]. Hence, the bucky-gel electrode layer prepared by the ultrasonic dispersion method has the large electric double layer capacitance, which gives the large actuation. Moreover, a high-energy, a rechargeable for a Li storage in a Li battery based on a SWCNT technology is reported [13], we pay attention to the electrode for a high-energy density device, such as the electrochemical capacitor using the alkaline or alkaline earth metal salt/IL. It is expected that double-layer capacitance of the bucky-gel electrode containing the alkaline or alkaline earth metal salt/IL is larger than that containing only the IL.

Fig. 3 shows the double-layer capacitance \( C \) (the gravimetric capacitance of the SWCNT, \( C_{SWCNT} = C/(the \ weight \ of \ SWCNT) \)) of the bucky-gel electrode containing Li[BF_4]/EMI[BF_4], Li[TFSI]/EMI[TFSI] and Mg[TFSI]_2/EMI[TFSI]. At a slow sweep rate 1 mV s\(^{-1}\), we found large capacitance value 68-94 Fg\(^{-1}\) in the case of the Li[BF_4]/EMI[BF_4], 65-82 Fg\(^{-1}\) in the case of the Li[TFSI]/EMI[TFSI] and 52-89 Fg\(^{-1}\) in the case of Mg[TFSI]_2/EMI[TFSI]. The double-layer capacitance depends on the molar ratio of Li[BF_4]/EMI[BF_4], Li[TFSI]/EMI[TFSI] and Mg[TFSI]_2/EMI[TFSI] in the electrode layer. It is found that the double-layer capacitance of the gel electrode layer containing M[X]/EMI[X] is larger than that containing only the IL, and that the alkaline or alkaline earth metal salt produces the large electrochemical capacitor. This is considered to be attributed to the intercalation into the SWNT bundles as Li storage site [13].

Fig. 4 shows the generated strains of the polymer-supported bucky-gel electrodes of the actuators containing Li[BF_4]/EMI[BF_4] on the frequency of the applied triangle voltage (±2 V). As shown in Fig. 4 (left), the generated strains depend on the measuring frequency. For low frequencies (0.05 - 0.005 Hz) of the applied triangle voltage, it is considered that the SWCNTs dispersed in the electrode layer is fully charged. On the contrary, for higher frequencies, it is considered that there is not enough time for the dispersed SWCNTs to be fully charged [6]. As shown in Fig. 4 (right), for high frequencies (1 - 0.05 Hz), the generated strains of the actuators with molar ratios of Li[BF_4]/EMI[BF_4] = 0.1 and 0.5 are larger than that containing only EMI[BF_4]. This result is considered to be attributed that the ionic conductivity of the gel electrolyte layer with molar ratios of Li[BF_4]/EMI[BF_4] = 0.1 and 0.5 is higher than that containing only EMI[BF_4]. In addition to that, for low frequencies (0.01 - 0.005 Hz), the generated strain of the actuator with molar ratio of Li[BF_4]/EMI[BF_4] = 1.0 is larger than that containing only EMI[BF_4]. This result is considered that the large capacitance gives the very large generated strain. While, at a slow sweep rate 1 mV s\(^{-1}\), the double-layer capacitances of the bucky-gel electrode with molar ratios of Li[BF_4]/EMI[BF_4] = 0.1 and 0.5 are larger than that containing only EMI[BF_4], however, for low frequencies (0.01 - 0.005 Hz), the generated strains of the actuators with the molar ratios of Li[BF_4]/EMI[BF_4] = 0.1 and 0.5 are about the same as that containing only EMI[BF_4]. These results may be considered to be attributed to other factors (e.g. the young’s modulus).
Fig. 4 The strain calculated from the peak-to-peak value of the displacement of the polymer-supported SWCNT-IL gel actuator with various ratios of Li[BF₄]/EMI[BF₄] at the frequency of the applied triangle voltage (±2 V).

Fig. 5 The strain calculated from the peak-to-peak value of the displacement of the polymer-supported SWCNT-IL gel actuator with various ratios of Li[TFSI]/EMI[TFSI] at the frequency of the applied triangle voltage (±2 V).

Fig. 5 shows the generated strains of the polymer-supported bucky-gel electrodes of the actuators containing Li[TFSI]/EMI[TFSI] on the frequency of the applied triangle voltage (±2 V). As shown in Fig. 5 (left), the generated strains also depend on the measuring frequency. For low frequencies (0.05 - 0.005 Hz) of the applied triangle voltage, it is considered that the SWCNTs dispersed in the electrode layer is fully charged. On the contrary, for higher frequencies, it is considered that there is not enough time for the dispersed SWCNTs to be fully charged [6]. As shown in Fig. 5 (right), the generated strains of the actuators with molar ratios of Li[TFSI]/EMI[TFSI] = 0.1 (in the high frequency range; 10 - 0.05 Hz) and 0.3 (in the high frequency range; of 1 - 0.05 Hz) are larger than that containing only EMI[TFSI]. This result is considered that the ionic conductivities of the gel electrolyte layers with molar ratios of Li[TFSI]/EMI[TFSI] = 0.1 and 0.3 are higher than that containing only EMI[TFSI]. For low frequencies (0.01 - 0.005 Hz), the generated strains of the actuators with molar ratios of Li[TFSI]/EMI[TFSI] = 0.5 and 1.0 are larger than that containing only EMI[TFSI]. It is considered that the large capacitance gives the very large generated strain. While, at a slow sweep rate 1 mV s⁻¹, the double-layer capacitances of the polymer-supported bucky-gel electrodes with the molar ratios of Li[TFSI]/EMI[TFSI] = 0.1 and 0.3 are larger than that containing only EMI[TFSI], however, for low frequencies (0.01 - 0.005 Hz), the generated strains of the actuators with molar ratios of Li[TFSI]/EMI[TFSI] = 0.1 and 0.3 are about the same as that containing only EMI[TFSI]. These results may be considered to be attributed to other factors (e.g. the young’s modulus).
Fig. 6 shows the generated strain of the polymer-supported bucky-gel electrode of the actuator containing Mg[TFSI]$_2$/EMI[TFSI] on the frequency of the applied triangle voltage (±2 V). As shown in Fig. 6 (left), the generated strains depend on the measuring frequency. For low frequencies (0.05 - 0.005 Hz) of the applied triangle voltage, it is considered that the SWCNTs dispersed in the electrode layer is fully charged. On the contrary, for higher frequencies, it is considered that there is not enough time for the dispersed SWCNTs to be fully charged [6]. As shown in Fig. 6, for all frequencies (100 - 0.005 Hz), the generated strains with the molar ratio of Mg[TFSI]$_2$/EMI[TFSI] = 0.1 are larger than that containing only EMI[TFSI]. It is considered that the higher ionic conductivity of the gel electrolyte layer containing Mg[TFSI]$_2$/EMI[TFSI] produces the quick response actuator, and that the large capacitance gives the large generated strain. These results are considered to attribute that the double-layer capacitance of the gel electrode layer containing Mg[TFSI]$_2$/EMI[TFSI] is larger than that containing only EMI[TFSI] for low frequencies (0.05 - 0.005 Hz), and that the ionic conductivity of the gel electrolyte layer containing Mg[TFSI]$_2$/EMI[TFSI] was higher than that containing only EMI[TFSI] for higher frequencies. While, the ionic conductivity of the gel electrolyte layer with the molar ratio of Mg[TFSI]$_2$/EMI[TFSI]= 0.25 is about the same as that with the molar ratios of Mg[TFSI]$_2$/EMI[TFSI]= 0.1, however, as shown in Fig. 6 (right), for high frequencies (1 - 0.05 Hz), the generated strain with the molar ratio of Mg[TFSI]$_2$/EMI[TFSI] = 0.25 are smaller than that with the molar ratio of Mg[TFSI]$_2$/EMI[TFSI] = 0.1. Moreover, at a slow sweep rate 1 mV s$^{-1}$, the double-layer capacitances of the gel electrode layers with the molar ratios of Mg[TFSI]$_2$/EMI[TFSI] = 0.25 and 0.5 are larger than that with the molar ratio of Mg[TFSI]$_2$/EMI[TFSI] = 0.1, however, for low frequencies (0.05 - 0.005 Hz), the generated strains with the molar ratios of Mg[TFSI]$_2$/EMI[TFSI] = 0.25 and 0.5 are smaller than that with the molar ratios of Mg[TFSI]$_2$/EMI[TFSI] = 0.1. These results may be considered to be attributed to other factors (e.g. the young’s modulus).

We compare the generated strain containing Mg[TFSI]$_2$/EMI[TFSI] (Fig. 6) to those containing Li[TFSI]/EMI[TFSI] and Li[BF$_4$]/EMI[BF$_4$] (Fig. 4 and 5). It is considered that the generated strain containing Mg[TFSI]$_2$/EMI[TFSI] = 0.1 is larger than that containing Li[TFSI]/EMI[TFSI] or Li[BF$_4$]/EMI[BF$_4$] in the wide frequencies (100 - 0.005 Hz). It is considered that the electrode and electrolyte for the high-energy density device (such as the EAP actuator and the electrochemical capacitor) using the Mg[TFSI]$_2$/EMI[TFSI] is better than that using Li[TFSI]/EMI[TFSI] or Li[BF$_4$]/EMI[BF$_4$] [15].

4. Conclusion

In this study, we investigated the effect of the alkaline metal salt (Li[BF$_4$] or Li[TFSI]) or the alkaline earth metal salt (Mg[TFSI]$_2$) on electrochemical and electromechanical properties of the actuator using the SWCNT-IL gel electrode. The ionic conductivity of the gel electrolyte layer depended on the ratio of M[X]/EMI[X] (M = Li$^+$ or Mg$^{2+}$, X = BF$_4^-$ or TFSI$^-$). The ionic conductivities of the gel electrolyte layers with the molar ratios of Li[BF$_4$]/EMI[BF$_4$]=0.1 and 0.5, Li[TFSI]/EMI[TFSI]=0.1 and 0.3, and Mg[TFSI]$_2$/EMI[TFSI]=0.05, 0.1 and 0.25 were higher than those containing only EMI[BF$_4$] and only EMI[TFSI], respectively. At a slow sweep rate 1 mV s$^{-1}$,
we found large capacitance value 68-96 F g⁻¹ in the case of the Li[BF₄]/EMI[BF₄], 65-82 F g⁻¹ in the case of the Li[TFSI]/EMI[TFSI] and 52-89 F g⁻¹ in the case of Mg[TFSI]₂/EMI[TFSI]. This is considered to be attributed to the intercalation into the SWNT bundles as Li storage site. The double-layer capacitance depends on the molar ratio of M[X]/EMI[X] in the electrode layer. For high frequencies (1 - 0.05 Hz), the generated strains of the polymer-supported bucky-gel electrodes of the actuators with molar ratios of Li[BF₄]/EMI[BF₄] = 0.1 and 0.5 are the quick response. In addition to that, for low frequencies (0.01 - 0.005 Hz), the generated strain of the actuator with molar ratio of Li[BF₄]/EMI[BF₄] = 1.0 is larger than that containing only EMI[BF₄]. Similarly, in the case of the actuator containing Li[TFSI]/EMI[TFSI], the generated strains with molar ratios of Li[TFSI]/EMI[TFSI] = 0.1 (in the high frequency range; 10 - 0.05 Hz) and 0.3 (in the high frequency range; 1 - 0.05 Hz) are quick response. For low frequencies (0.01 - 0.005 Hz), the generated strains with molar ratios of Li[TFSI]/EMI[TFSI] = 0.5 and 1.0 are larger than that containing only EMI[TFSI]. For all frequencies (100 - 0.005 Hz), the generated strain containing Mg[TFSI]₂/EMI[TFSI] = 0.1 is larger than that containing only EMI[TFSI]. Moreover, the generated strain containing Mg[TFSI]₂/EMI[TFSI] = 0.1 is larger than those of the actuator containing Li[TFSI]/EMI[TFSI] and Li[BF₄]/EMI[BF₄] for all frequencies (100 - 0.005 Hz).

Therefore, it is found that the electrode containing Li[BF₄]/EMI[BF₄], Li[TFSI]/EMI[TFSI] or Mg[TFSI]₂/EMI[TFSI] produces the large capacitor. The actuator containing Li[BF₄]/EMI[BF₄], Li[TFSI]/EMI[TFSI] and Mg[TFSI]₂/EMI[TFSI] performed much better as the actuator using polymer-supported bucky-gel electrode containing only EMI[BF₄] and EMI[TFSI], respectively. It is considered that higher ionic conductivity of the gel electrolyte layer containing Li[BF₄]/EMI[BF₄], Li[TFSI]/EMI[TFSI] or Mg[TFSI]₂/EMI[TFSI] produces the quick response actuator, and that the larger capacitance gives the large generated strain for the bucky-gel electrode in the actuator. The actuator containing Mg[TFSI]₂/EMI[TFSI] performed much better than the actuator containing Li[TFSI]/EMI[TFSI] or Li[BF₄]/EMI[BF₄] for the wide frequencies (100 - 0.005 Hz). These results are considered to be the actuator enough to apply actual applications (e.g. tactile display).

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Fig. 1 Configuration of a polymer-supported bucky gel actuator and a molecular structure of an ionic liquid, alkaline and alkaline earth metal salts and a polymer used.
Fig. 2 Compare to the ionic conductivities of the gel electrolyte layers with various ratios of Li[BF₄]/EMI[BF₄], Li[TFSI]/EMI[TFSI] and Mg[TFSI]₂/EMI[TFSI]. (The data of Li[BF₄]/EMI[BF₄], Li[TFSI]/EMI[TFSI] = 0 and Mg[TFSI]₂/EMI[TFSI] = 0 were quoted from ref. [9].)
Fig. 3 Compare to gravimetric capacitance $C_{\text{swCNT}}$ in the polymer-supported bucky gel electrode with various ratios of Li[BF$_4$]/EMI[BF$_4$], Li[TFSI]/EMI[TFSI] and Mg[TFSI]$_2$/EMI[TFSI]. (The applied triangle voltage: ±0.5 V, Sweep rate = 1 mV/s) (The data of Li[BF$_4$]/EMI[BF$_4$], Li[TFSI]/EMI[TFSI] and Mg[TFSI]$_2$/EMI[TFSI] =0 were quoted from ref. [9].)
Fig. 4 The strain calculated from the peak-to-peak value of the displacement of the polymer-supported SWCNT-IL gel actuator with various ratios of Li[BF₄]/EMI[BF₄] at the frequency of the applied triangle voltage (±2 V).
Fig. 5 The strain calculated from the peak-to-peak value of the displacement of the polymer-supported SWCNT-IL gel actuator with various ratios of Li[TFSI]/EMI[TFSI] at the frequency of the applied triangle voltage (±2 V).
Fig. 6 The strain calculated from the peak-to-peak value of the displacement of the polymer-supported SWCNT-IL gel actuator with various ratios of Mg[TFSI]/EMI[TFSI] at the frequency of the applied triangle voltage (±2 V).