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Improved performance of carbon nanotube buckypaper and ionic-liquid-in-Nafion actuators for rapid response and high durability in the open air

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ABSTRACT

The fabrication and electromechanical performance of three layer actuators (carbon nanotube/Nafion/carbon nanotube) with doped Nafion were studied. The Nafion actuators were doped with 1-butyl-3methylimmidazolium tetrafluoroborate ($BMI^+BF_4^-$) ionic liquid, which was verified by electrochemical impedance spectroscopy analysis. The three layer actuators were fabricated using a simple method involving a doping and hot-pressing process. Carbon nanotube thin films (buckypaper or BP) were used as the electrode layers for fabricating the actuators. The actuators doped with the ionic liquid generated electromechanical strains up to 0.4%, which was ten times higher than when testing the neat Nafion three layer actuators. The results were promising for manufacturing lightweight, low power smart structures.

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1. Introduction

Achieving lightweight, rapid response, high durability, large displacement and low driving voltage electroactive polymer (EAP) actuators would offer great potential for applications ranging from micro-electromechanical systems to mimicking artificial muscles [1]. EAP based actuators typically lack in durability or responsiveness since the actuation is faradaically driven via ions and electro-osmotic movements going through the polymers to the electrodes. When the actuator is subjected to an electric field, ions can be reduced and electrolyzed at the interface between electrode and polymer films, which dramatically decreases the performance of the actuation. Developing a method for high performance actuation that provides efficient charge transport should avoid the unwanted ions reduction/oxidization occurrence. This would ensure the functioning of tailored actuators that could overcome the disadvantages of EAP actuators. Typical EAP actuator designs function only in electrolyte solutions. In 2003, the first dry actuator was developed by Wallace and co-workers, who used ionic liquids as a mix-in organic electrolyte [2]. For designing high performance ionic actuators, two apparent parameters govern the actuation performance [2]: (1) the effects of interfacial bonding strength for charge transport and (2) the ion type and density that are doped in the polymer film. Several techniques have been used for improving actuator interfacial bonding, such as electroless plating [3,4], spraying [5,6] and hot-pressing [7,8]. Typically, a stronger interfacial bonding ensures a better pathway for charge transport through heterogeneous interface since the cation mobility would induce swelling at the cathode side and consequently bend the strip toward the anode side. Doping inorganic metal ions [3,9,10] or organic ions [2,11,12] into polymer films could be an effective way to enhance bending displacement. Specifically, Nafion, a sulfonated tetrafluoroethylene based fluoropolymer–copolymer doped with metal, would bend to 5 mm [13] in an electrolyte solution environment due to the deformation generated by diffused ions causing the swelling at the cathode side [3,14,15]. For this study, a homologous series of buckypaper and Nafion-based actuator combinations using an ionic liquid doping method and a simple fabrication process were explored to improve durability and increase displacement, while using a low activating voltage.

Single-walled carbon nanotubes (SWCNTs) would appear to provide a promising choice for electrodes in various devices and for energy storage applications [16] due to their high electrical conductivity and exceptional mechanical properties. These SWCNTs can be used to make porous nanotube sheets or buckypapers (BP). Baughman et al. demonstrated that a SWCNT BP electrochemical actuator system could effectively be used for the direct conversion of electrochemical energy to mechanical energy [17,18]. At low electric fields, CNT BP demonstrated expansion and contraction with the electron injection and hole injection, respectively [19]. However,

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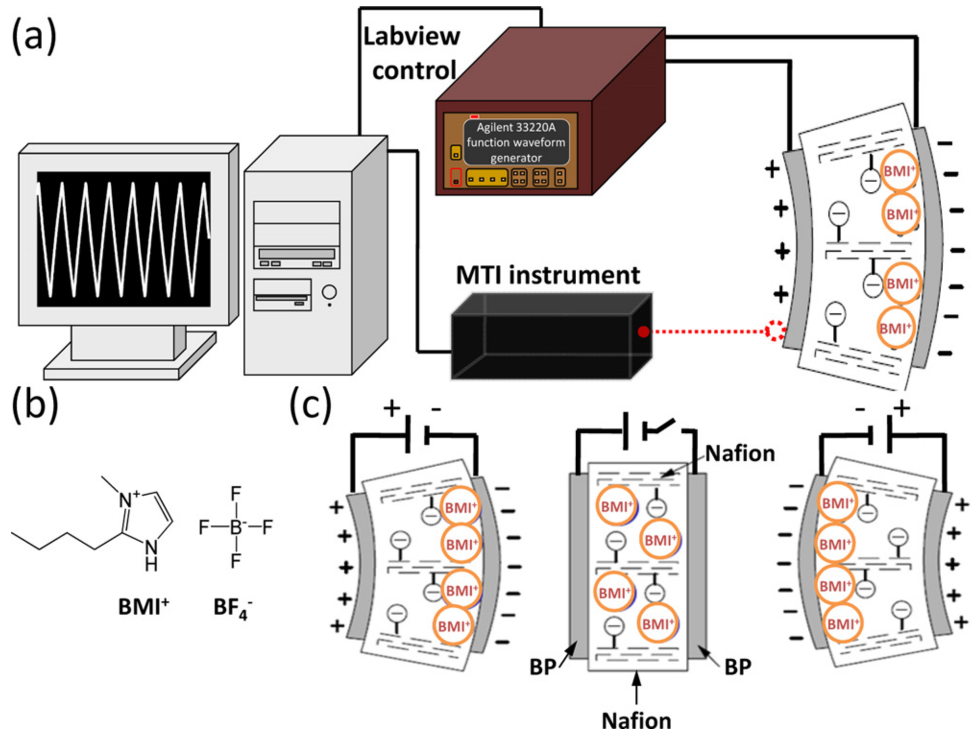

Fig. 1. (a) Schematic of the BP/BMI$^+$-Nafion/BP composite actuator and actuation measurement setup using an MTI laser displacement sensor; (b) molecular structure of $BMI^+BF_4^-$; (c) actuation mechanism of BP/BMI$^+$-Nafion/BP composite actuator.

their BP actuation system had to be placed in an electrolytic solution to provide the charge concentration on the SWCNTs surface. Since Nafion films act as a solid electrolyte, coupling SWCNT BP should provide a novel actuating system that takes advantage of the EAPs and SWCNT materials [17].

This paper reports on the successful implementation of $BMI^+BF_4^-$ doping into Nafion and buckypaper that resulted in a high performance actuation behavior of the composite actuators. We also report on a relatively simple, reliable fabrication method to incorporate the BP and the $BMI^+BF_4^-$-in-Nafion film through a simple layer-by-layer stacking and hot-pressing process. Our designated actuators adopt bimorph configurations that demonstrate a rapid response and high durability in an atmosphere environment.

2. Experimental

2.1. Material and actuator fabrication

The ionic liquid used in this study was 1-butyl-3methylimmidazolium tetrafluoroborate ($BMI^+BF_4^-$; Fig. 1b) (Supplier Sigma–Aldrich ID: 24889490), which remained fluid over a wide temperature range and demonstrated a greater electrochemical potential window. When compared with other electrolytes used for actuator systems, ionic liquids demonstrated that they could be sustained in a very dry state and wide potential window. These features would make them particularly useful for applications in EAP actuator systems from which moisture must be excluded over long periods of operation.

Fig. 1a shows the configuration of the BP composite actuator. By combining the BP with a BMI$^+$ doped Nafion layer, we fabricated an actuator strip with a tri-layers configuration using a hot-pressing process. The BP was made using a stable suspension of carbon nanotubes, which is typically produced with surfactant and ultrasonication. The surfactant Triton X-100 was chosen to aid in dispersion, and the suspension underwent ultra-sonication for 1 h to make stable suspension. The suspension was filtered through a buckner funnel (flask, filter paper and pump) to make a thin film of BP with 15–20 μm in thickness and area density of 20–30 g/m^2 [20,21]. The SWCNTs used in this research were purified SWCNTs purchased from Carbon Nanotechnologies Inc. (CNI). Fig. 2 shows the doping process of Nafion built-in-BMI$^+$ materials. A 5 cm × 5 cm Nafion-117 was heated to 120 °C in a vacuum chamber for 2 h to remove the water molecules in the Nafion. The dried Nafion was soaked in $BMI^+BF_4^-$ for 2 h to allow time for total saturation.

When electric voltage was applied to the BP/BMI$^+$-Nafion/BP actuator, the BMI$^+$ cations were transported and accumulated to the cathodic side (Fig. 1c). The BMI$^+$ doped Nafion film 30 mm long × 5 mm wide was sandwiched between two 30 mm × 5 mm BPs, which were placed in a hot-press set at 120 psi at 120 °C for 10 min to combine the three layers, as shown in Figs. 3 and 4a.

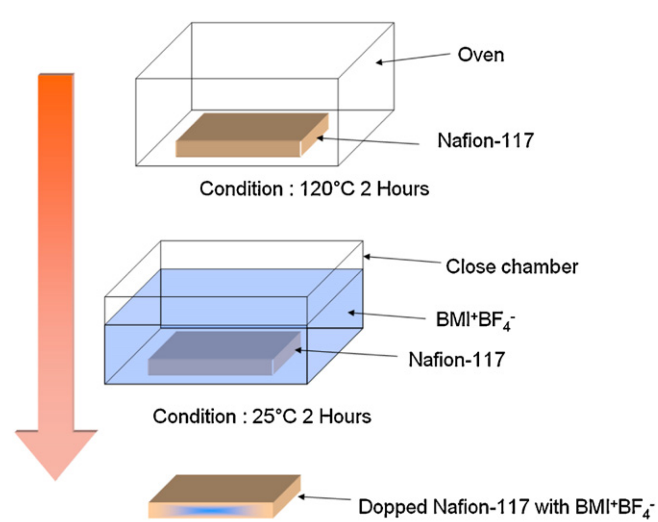

Fig. 2. BMI$^+$-Nafion doping process.