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Electromechanical actuation of buckypaper actuator: Material properties and performance relationships

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ABSTRACT

Carbon nanotubes can be assembled into macroscopic thin film materials called buckypapers. To incorporate buckypaper actuators into engineering systems, it is of high importance to understand their material property-actuation performance relationships in order to model and predict the behavior of these actuators. The electromechanical actuation of macroscopic buckypaper structures and their actuators, including single and multi-walled carbon nanotube buckypapers and aligned single-walled nanotube buckypapers, were analyzed and compared. From the experimental evidence, this Letter discusses the effects of the fundamental material properties, including Young modulus and electrical double layer properties, on actuation performance of the resultant actuators.

1. Introduction

The materials used in many branches of engineering for actuation applications are typically heavy, nonflexible and require high power, so their practicality for creating biomimetic systems is limited. For example, electromagnetic or turbine motors are excellent for producing rotary motion but are limited when recreating the complicated movements of biological systems, such as caudal pectoral fish fins that generate unsteady flows [1].

Due to their unique combination of electrical and mechanical properties, carbon nanotubes (CNTs) have attracted a great deal of interest for use as electromechanical actuators. Individual carbon nanotubes combine excellent electrical and thermal conductivities with remarkable mechanical properties, currently considered the strongest and stiffest materials known [2]. However, these properties have yet to be realized when the nanotubes are attempted to be assembled into useful macroscopic forms. A practical approach to manufacture manageable structures of carbon nanotubes for engineering applications is their assembly into buckypapers. Buckypapers are sheets of highly entangled single or multi-walled nanotubes (SWNTs or MWNTs) held together by entanglement and van der Waals interactions. These structures provide sufficient mechanical properties and good handablity to permit their evaluation for actuator applications [3].

The concept of using SWNT buckypapers (SWNT BPs) as electromechanical actuators was introduced about ten years ago [4]. This actuation was attributed to dimensional changes of the covalent bond network along the nanotube axis direction as a consequence of quantum chemical effects arising from charge injection into the nanotubes [4]. The performance of such actuators was very limited due to their material properties. To improve the buckypaper actuation performance, a better understanding the relationships between buckypaper material properties and actuation performance is essential.

As part of our ongoing investigations into manufacturing robust and reliable active devices consisting of carbon nanotubes, this Letter reports on the actuation experiments performed on SWNT BP, MWNT BP and aligned SWNT BP samples. These structures allow the comparison of actuation performance over a rather wide range of Young's modulus values of different buckypaper materials. In particular, the relationship between actuation strain and electrical capacitance of electrical double layers generated in the actuators can be assessed.

2. Experimental procedure

2.1. Actuators preparation

Three different types of buckypapers were specifically used for this study. The SWNTs and MWNTs used were produced by Southwest Nanotechnologies Inc. The buckypaper fabrication procedures are documented in detail by the research groups of Smalley [5] and Wang [6]. The procedure for fabrication is the same except

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for aligned SWNT – aqueous suspensions of nanotubes were sonicated with the aid of surfactant, Triton X-100. The suspensions were filtered through a 0.45 μm filter to develop randomly dispersed buckypaper sheets [5]. Thickness of the SWNT and MWNT buckypapers are 15 μm with an aerial density about 22–25 g/m^2. Individual SWNTs are 10–30 nm long and about 1 nm in diameter. In the case of MWNTs, the dimensions are about 50–100 μm long and 10–20 nm in diameter. The aligned buckypaper samples were produced by filtering the dispersed suspension within a 17.3 Tesla high magnetic field at the National High Magnetic Field Laboratory (NHMFL) [7]. All samples were washed repeatedly with distilled water to remove as much of the surfactant as possible, then annealed at 850 °C under argon gas for 4 h to burn off impurities and residual surfactants. All samples have the similar aerial densities (20 g/m^2) and thickness (15 μm).

As shown in Fig. 1, the buckypaper actuator is a bimorph structure fabricated with Nafion, a solid electrolyte layer capable of ion diffusion, sandwiched between two buckypaper (BP) electrode layers. Purchased from DuPont, the Nafion NRE-212 is the electrically conducting polymer membrane used as the medium between the two buckypaper strips. The electric conductivity of the Nafion NRE-212 is 10^{-2} S/cm [8]. This polymer was chosen for its proven ion mobility and environmental stability [9]. As shown in Fig. 2, the Nafion was sandwiched between two buckypaper layers and hot-pressed at 110 °C while undergoing a pressure of 120 psi for 10 minutes. Before combining the buckypaper and Nafion membrane, a Nafion solution was coated onto the two sheets of buckypapers. Approximately nine drops of the solution were spread out on each buckypaper electrode to increase the interfacial bonding before hot pressing the structure. The length (L) and width (w) of the actuator were 30 mm and 5 mm, respectively. The total thickness (t) of the sample was 80 μm, with a thickness of 50 μm for the Nafion film and 15 μm for the each BP layer.

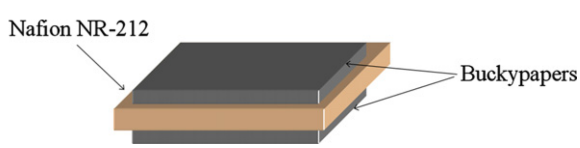

Fig. 1. Schematic illustration of buckypapers actuators.

2.2. Experimental set-up

BP/Nafion actuators were tested in a cantilevered configuration and would bend when stimulated by an applied voltage. One end was fixed by a rigid clamp fitted with copper foil electrodes that were connected to buckypaper surface of the sample, and the deflection of the free end was measured with a displacement laser sensor, as shown in Fig. 3(a).

The tip displacement was converted into strains (S_1) using simple geometry and Eq. (1), where δ was the tip displacement (zero-to-peak), t was the sample thickness and L was the free length of the sample. This equation assumes that the actuator deforms with a uniform curvature [10,11]

$$S_1 = \frac{\delta . t}{L^2} \tag{1}$$

The displacement of the buckypaper/Nafion actuators was measured using a laser displacement sensor (MICROTRAK II; MTI Instrument, Inc.). Test cells were produced for characterizing the electrochemical properties of BP/Nafion. As shown in Fig. 3(b), the sinusoidal wave potentials were applied between the working and counter electrodes using a function generator (Agilent 2310A). The clamp that held the actuators was mounted to a breadboard from ThorLabs. The breadboard was in a Plexiglas enclosure with a door mounted on top to prevent air flow from disturbing the results. The breadboard was mounted on an Iso-Plate Passive Isolation System to dampen any vibrations in the room. The time history of the tip displacement and input voltage was measured with an oscilloscope.

3. Results and discussion

SEM images (FE-SEM JSM-7401F, JOEL) revealed the morphology of the randomly dispersed SWNT and MWNT buckypapers in Fig. 4 (A) and (B), as well as the aligned SWNT sample (Fig. 4(C)). All samples displayed a distinctly fibrillar structures due to small diameter nanotubes assembled into bundles or ropes.

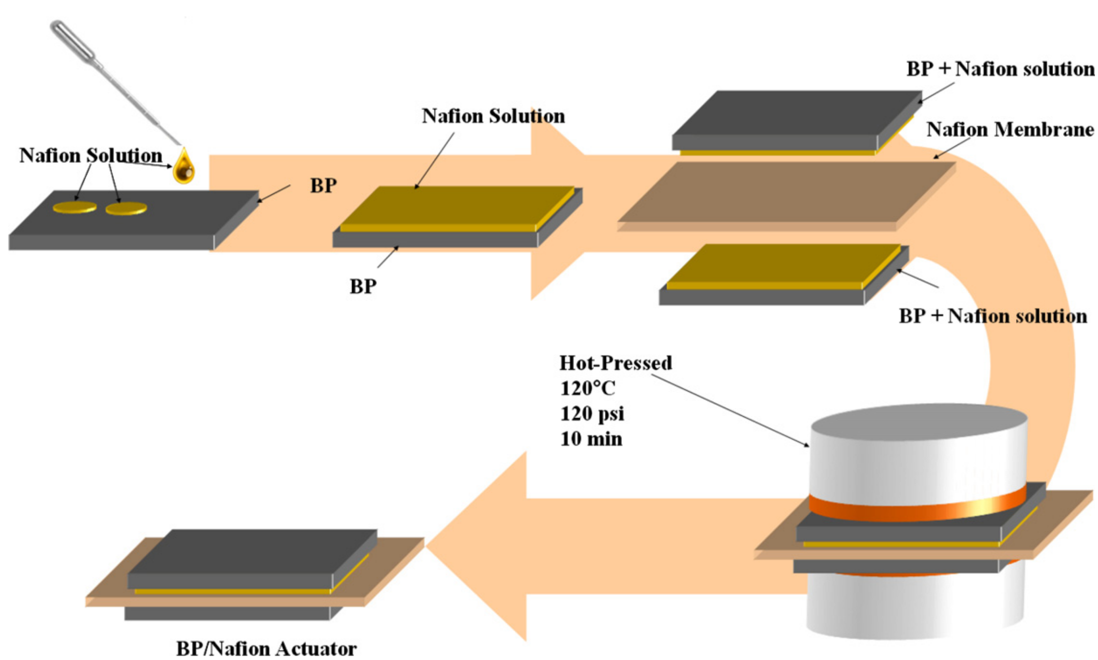

Fig. 2. Buckypapers actuators fabrication process.