High Strain Low Voltage Induced Densified Vertically Aligned Carbon Nanotube Ionic Actuators

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M A T S

Abstract:

Electroactuation materials that can generate high strain under low voltages are crucial components in artificial muscles, robotics applications, and micro- and nano- electromechanical (MEMs and NEMs) devices. This project developed ultra-high volume density carbon nanotube (CNT)-based ionic actuators that would increase the actuation strain from a current < 1% to 20% under low voltages (< 4 volts). Using a biaxial mechanical densification (BMD) process increased the volume fraction (V_f) of the vertically aligned carbon nanotubes (VA-CNT) from 1% to 40% [1]. The densification process maintained the vertically aligned morphology of the CNTs, providing non-tortuous pathways for ion transportation. This characteristic is crucial to creating fast, efficient, and high strain actuation devices. One percent V_fCNT forests were densified to 40%V_f, infiltrated with 40%wt Nafion polymer, and immersed in two separate ionic liquids, 1-ethyl-3-methylimidazolium trifluoromethanesulfonate ($[EMI^+][Tf^-]$) and 1-butyl-3-methylimidazolium tetrafluoroborate ($[BMI^+][BF_4^-]$), for strain testing. Experimentation revealed $[BMI^+][BF_4^-]$ showed largest strains of 13% under 0-3V triangular wave signals, while using $[EMI^+][Tf^-]$ showed ~ 5% strains under the same conditions. These results indicated that the size difference between the cations and anions in the ionic liquid was one critical factor that drove the actuation of the device.

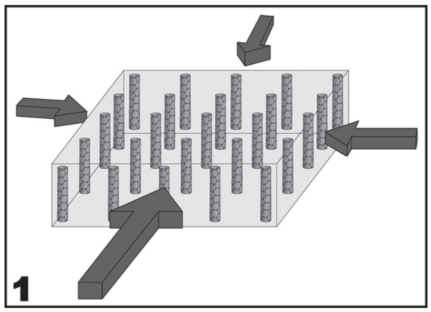


Figure 1, top: Biaxial densification process of CNT forest.

Introduction:

Electroactuation materials are simple devices that perform energy conversion between electrical and mechanical forms. Creating electroactuation devices that can generate large movement under low voltages is one key component to advancing the prominence of actuators in everyday life. VA-CNT based ionic actuators are a proven concept with the potential to produce high strain under low voltages [2]. By densifing the VA-CNTs, it has been theoreticized that the actuation efficiency can be significantly increased.

Fabrication and Experimental Procedure:

One percent V_f VA-CNTs were grown, 500 μm thick, on a silicon substrate using a modified chemical vapor deposition process with a Fe-on-alumina catalyst system [3]. After removal from the substrate, samples were put through a BMD process (Figure 1) to decrease the spacing between the CNTs and increase the density from 1% V_f (10 mm^2) to 40% V_f (1.6 mm^2). CNT samples were then placed in 3D metal cages with a metal mesh on the top side and were infiltrated with a 2.5% Nafion (NR-211) dispersion in DMF to contain 40% wt of NR-211. Samples were placed under vacuum at 5 mmHg for 5-7 days or until the solvent had completely dissolved. The samples were then annealed at 110°C for one hour and immersed in ionic liquid under vacuum at 5 mmHg for one day.

Various waveforms were applied to the CNT actuators in an actuation testing station and their actuation (Figure 2) was characterized with a fiber optic displacement sensor. Both ionic liquids, $[EMI^+][Tf^-]$ and $[BMI^+][BF_4^-]$, were utilized separately in the testing process and triangular waveforms ranging from -3-3V were tested under a 5 mv sec^{-1} scan rate.

Results, Discussion, and Conclusions:

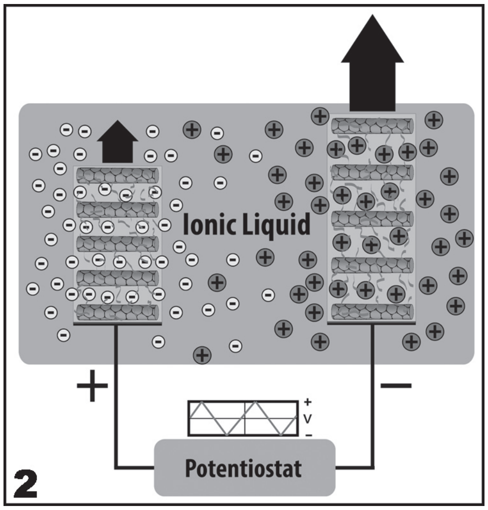
A graph from a test showing the applied voltage as a -3-3V triangular wave and the response of the actuator is shown in

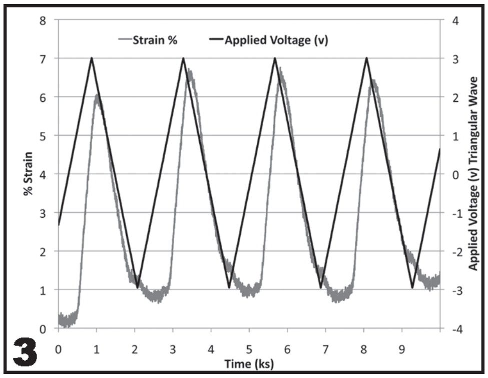
Figure 3. As voltage increased/decreased, the conductive, porous, CNT forests acted as electrodes that attracted/repelled ions of the opposite charge that filled the CNTs, causing expansion/contraction and therefore strain.

Strain is defined as the thickness difference between the initial and final states of the actuator after applying voltage. Figure 4 shows the maximum percent strain recorded from six different testing scenarios of different waveforms and ionic liquids. Phase separation in the applied voltage and response of the actuator were noted and more investigation on this topic is needed.

It was also observed that for the first 10-20 cycles of applied voltage, the actuators mostly expanded during a conditioning phase. After the conditioning phase, the actuators entered into a steady state in which the difference in sizes between the cations and anions in the ionic liquid drove the actuation process [1]. Using three different waveforms and two ionic liquids for each waveform showed that $[BMI^+][BF_4^-]$ was a more effective ionic liquid than $[EMI^+][Tf^-]$. This observation is due to the size difference between the cations and anions of the $[BMI^+][BF_4^-]$, which was greater than the difference in $[EMI^+][Tf^-]$ [4].

As higher voltage was applied, more actuation was observed. Maximum strain of 13.2% occurred under a 0-3V waveform using $[BMI^+][BF_4^-]$. These results are quite significant due to the fact that previous researchers, using undensified samples have achieved < 1% strain [5]; concluding that the densification of VA-CNTs create ionic actuators with the capability of creating higher strain than undensified samples.





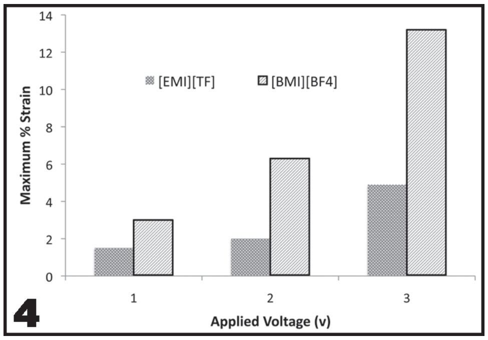


Figure 2, top: Applied voltage to CNT ionic actuators showing expansion of actuators.

Figure 3, middle: Line graph of -3-3v triangular wave being applied to actuators and response of the actuators.

Figure 4, bottom: Maximum strain percent as a function of applied voltage and ionic liquid.

Future Work:

Atomic force microscopy (AFM) measurements to obtain the elastic modulus of the CNTs will be used to calculate columbic and electromechanical efficiencies of the devices. Subsequently, a mathematic representation of the system will be formed in the sense of an electrical circuit for simulation purposes. By altering the %wt of N-211 to be added to the samples, the strain on the actuators can also be optimized.

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