Ultrafine Sensing Using Carbon Nanotube Arrays

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ABSTRACT

Arrays of Carbon Nanotubes (CNTs) have shown the ability to react as foam-like structures and display local buckling within the bulk. The arrays, or turfs, are high aspect ratio CNT fibers that extend up to 1 mm in height. The material has great promise for engineering and sensing applications, though an understanding of the material response is still at infancy. Here, we perturb CNT array turfs by uniform compressive contact and measure the electrical resistance change in two directions, normal and transverse to the tubes. Resistance changes as a function of strain exhibit a sensitivity increase of 7 times in the transverse versus normal directions. The increase is hypothesized to be to the localized buckling induced reorganization of the individual CNTs at the surface, which results in tube densification. Characterization of the buckling region by nanoindentation has shown an increase in the contact stiffness. Micro-Raman spectroscopy corroborates the results where a measured increase in tube interactions provides a denser fiber network. The results give fundamental insight into the resistivity of the CNT arrays and their application as high-resolution contact sensors, microscale electrical contacts, and chemical sensors.

Keywords: Carbon Nanotubes, Sensors, Conductivity

1 INTRODUCTION

The use of carbon nanotubes (CNTs) in the form of vertically aligned arrays or films has been of interest due to the super-compressible response [1] and the ability to be used as electrical [2] and thermal [3] contacts. Because of the high elastic modulus, tensile and flexural strengths [4-10], CNTs provide many exceptional features for mechanical applications. The mechanical properties of individual CNTs have been characterized in compression [11, 12] and in tension [13], as well as mechanical characterization of composites made of dispersed CNTs at low loadings [14-17]. Also, CNT arrays have been shown to provide a durable means to enhance electrical switching lifetime and have been measured for both electrical [18] and thermal contact resistance [19], demonstrating an improved performance due to the array compliance. The viscoelastic nature and fatigue resistance has been measured under cyclic compression where the CNT arrays react mechanically similar to soft-tissue, and have been able to withstand high cycle fatigue [20].

2 BACKGROUND

A fundamental understanding of the compressive response of VACNT arrays contributes to the design of CNT-based sensing systems, for the use in tactile, contact, and potentially gas sensing applications. CNT arrays may be utilized as strain gage sensors which have high gage factors due to good piezoresistive properties of CNTs. The electrical response of CNT arrays has been used in electromechanical switches where the effect of a mechanical perturbation drives the electrical response. Thus, the electrical responses of the array under compressive strain are of great importance and interest to study fundamentals of the electro-mechanics. The electrical conductivity of compressed CNT arrays has shown reversible conductivity and compressive strain responses in the elastic range of the array for both perpendicular and parallel tube directions [2]. However, for sensing and control purposes, localized plastic deformation of the array occurs when loaded cyclically. Here the electrical response of the CNT array under compressive strain is measured to determine relationships between the resistance changes with respect to the array deformation. The low-cycle compression of bulk vertically aligned CNT arrays has observed initiation and growth of the local buckling as a function of compressive strain. A critical strain is found above which the buckling region length increased and below which it remained at or below the applied strain [21]. Resistance changes as a function of strain exhibit a sensitivity increase of 7 times in the transverse versus normal directions [22].

3 RESULTS

Two types of CNT array samples were prepared for the test to measure resistance changes under uniaxial compression; one, of which resistance is measured perpendicular to the tube growth direction (lateral measurement orientation), and another type for measurement parallel to the tube growth direction (vertical measurement orientation).

A precision loading stage was used for compression testing (Figure 1). For the lateral sample, it is mounted by a cyanoacrylate adhesive to the compression anvil. A Lithium Niobate sample was used as the counterface and adhered with cyanoacrylate to the opposite compression anvil. The initial position of the compression test is when the sample and the counterface are brought into incipient contact with one another, as observed by the digital microscope mounted above the loading stage. Six compression cycles, with prescribed displacements of 100µm to 600µm, with and increment of 100µm, were performed on the sample at a loading rate of 10µm/sec and unloading rate of 1mm/sec. Resistance of the sample before and during the compression test was measured using an electrical amplification circuit and DAQ system.

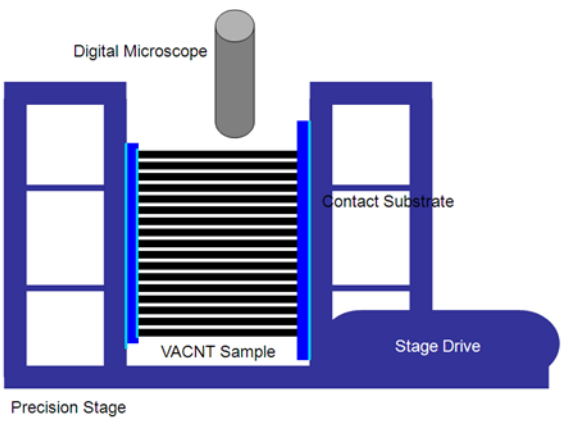
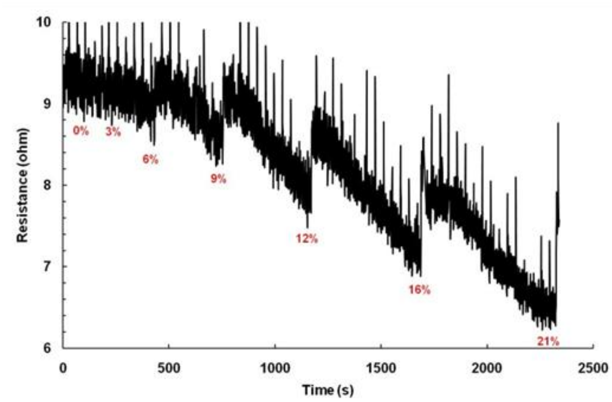


Figure 1. Testing apparatus showing the CNT arrays mounted to the stage on the left side with a free surface towards the right of the figure.

Figure 2 shows the plots of electrical resistance versus time on varying the applied compressive strain for lateral and vertical samples, respectively. The spikes in the data are found due to the experimental setup and not the sample, and need to be addressed in future experiment. Removal of the compressive strain from the CNT array results in a partial recovery of its original shape and buckling forming at the free surface. Likewise, the electrical resistance regained a portion of the initial value. This indicates that the electrical resistance and compressive strain responses of the CNT array are partially reversible. The larger resistance values for the lateral orientated sample are due to the electrical current passing through the sample solely due to nanotube-nanotube interactions, but for the vertical sample, electrical current can also transmit through the nanotubes themselves acting as conduction pathways.

4 CONCLUSIONS

With an increase of the applied compressive strain, electrical resistance of the CNT array (both in the vertical and lateral orientations) will decrease correspondingly because of sample geometry changes and structural changes causing resistivity decreases. Resistance changes of 60% for the lateral sample and ~27% for the vertical sample were measured. Also, electrical resistance of the CNTs array is partially reversible with releasing of the load, though because of plastic deformation occurring in the array, resistance will not return to its original value. Multiple loading cycles to the sample resulted in the overall decrease of the electrical resistance.



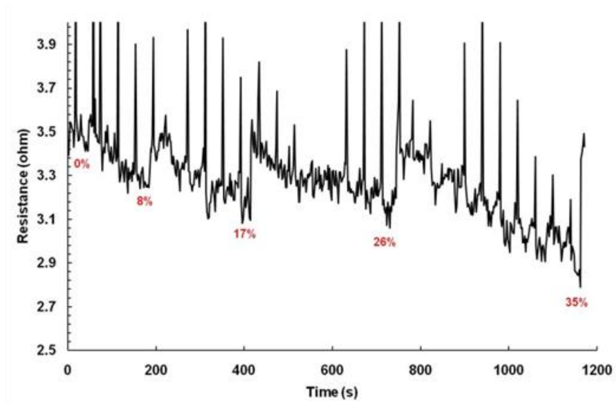


Figure 2. Resistance versus time curves for successive applied strains (red numbers). Lateral orientated sample (top) and vertical orientated sample (bottom).

REFERENCES

[1] Cao A, Dickrell PL, Sawyer WG, Ghasemi-Nejhad MN, Ajayan PM. Super-compressible foamlike carbon nanotube films. Science 2005;310:1307-1310.

[2] Pushparaj VL, Ci L, Sreekala S, Kumar A, Kesapragada S, Gall D, et al. Effects of compressive strains on electrical conductivities of a macroscale carbon nanotube block. Applied Physics Letters 2007;91:153116-18.

[3] Xu J, Fisher TS. Enhancement of thermal interface materials with carbon nanotube arrays. Intl. J. Heat and Mass Transfer 2006;49:1658-1666.
[4] Li C, Chou T-W. A structural mechanics approach for the analysis of carbon nanotubes. Intl. J. Solids Struct. 2003;40:2487-2499.
[5] Demczyk BG, Wang YM, Cumings J, Hetman M, Han W, Zettl A, Ritchie RO. Direct mechanical measurement of the tensile strength and elastic modulus of multiwalled carbon nanotubes. Mater. Sci. Eng. A. 2002;A334:173-178.
[6] Tersoff J, Ruoff RS. Structural properties of a carbon-nanotube crystal. Phys. Rev. Lett. 1994;73:676-679.
[7] Liu YJ, Chen XL. Evaluations of the effective material properties of carbon nanotube-based composites using nanoscale representative volume element. Mech. Mater. 2003;35:69-81.
[8] Goze C, Vaccarini L, Henrard L, Bernier P, Hernandez E, Rubio A. Elastic and mechanical properties of carbon nanotubes. Synth. Metals 1999;103:2500-2501.
[9] Salvetat JP, Bonard JM, Thomson NH, Kulik AJ, Forro L, Benoit W, et al. Mechanical properties of carbon nanotubes. Appl. Phys. A 1999;69:255-260.
[10] Dickrell PL, Sinnott SB, Hahn DW, Raravikar NR, Schadler LS, Ajayan PM, et al. Frictional anisotropy of oriented carbon nanotube surfaces. Tribology Letters 2005;18:59-62.
[11] Waters JF, Reister L, Jouzi M, Guduru PR, Xu JM. Buckling instabilities in multiwalled carbon nanotubes under uniaxial compression. Appl. Phys. Lettrs. 2004;85:1787-1789.
[12] Yap HW, Lakes RS, Carpick RW. Negative stiffness and enhanced damping of individual multiwalled carbon nanotubes. Phys. Rev. B 2008;77:045423-1-7.
[13] Yu MF, Lourie O, Dyer MJ, Moloni K, Kelly TF, Ruoff RS. Strength and breaking mechanism of multiwalled carbon nanotubes under tensile load. Science 2000;287:637-640.
[14] Thostenson ET, Chou T-W. Nanotube buckling in aligned multi-wall carbon nanotube-reinforced composites. Carbon 2004;42:3015-3018.
[15] Moniruzzaman M, Winey KI. Polymer nanocomposites containing carbon nanotubes. Macromolecules 2006;39:5194-5205.
[16] Gibson RF, Ayorinde O, Wen, Y. Vibrations of carbon nanotubes and their composites: A review. Comp. Sci. Tech. 2007;67:1-28.
[17] Ajayan PM, Suhr J, Koratkar N. Utilizing interfaces in carbon nanotube reinforced polymer composites for structural damping. J. Mater. Sci. 2006;41:7824-7829.
[18] Yunus EM, Spearing SM, McBride JW. Investigation of gold sputter coated vertically aligned multi-walled carbon nanotubes for RF MEMS contact surfaces. In Microelectromechanical Systems-Materials and Devices II, edited by Spearing SM, Vengallatore S, Sheppard N, Bagdahn J. Matls. Res. Soc. Proc. 2009;1139:GG05-04.
[19] Johnson RD, Bahr DF, Richards CD, Richards RF, McClain D, Green D, et al. Thermocompression bonding of vertically aligned carbon nanotube turfs to metalized substrates. Nanotechnology 2009;20:65703.
[20] Suhr J, Victor P, Ci L, Sreekala S, Zhang X., Nalamasu O, et al. Fatigue resistance of aligned carbon nanotube arrays under cyclic compression. Nature Nanotechnology 2007;2:417-421.
[21] C. Cao, A. Reiner, C. Chung, S.-H. Chang, I. Kao, R.V. Kukta, C.S. Korach, “Buckling Initiation and Displacement Dependence in Compression of Vertically Aligned Carbon Nanotube Arrays”, Carbon, 2011;49:3190.
[22] C.S. Korach, C. Cao, T. McCune, N. Machtay, R.V. Kukta, “Carbon Nanotube Array-Based Contact Sensing”, Proceedings of the 2011 STLE Annual Meeting and Exhibition, May 15-19, 2011, Atlanta, GA