5-13-2019

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Jordan Lee
Utah State University

Brian Wood
Utah State University

Gregory Wilson
Utah State University

T.-C. Shen
Utah State University

JR Dennison
Utah State University

Recommended Citation

Jordan Lee, Brian Wood, Gregory Wilson, T.C. Shen and JR Dennison, "Influence of Vibrationally-Induced Structural Changes on Carbon Nanotube Forests Suppression of Electron Yield," Proceedings of the Applied Space Environments Conference 2019, (Los Angeles, CA, May 12-17, 2019).

Influence of Vibrationally-Induced Structural Changes on Carbon Nanotube Forests Suppression of Electron Yield

Jordan Lee (Jordan.lee@aggiemail.com), Brian Wood, Gregory Wilson, T.-C. Shen and JR Dennison

USU Materials Physics Group, Utah State University

I. Introduction

Carbon nanotube (CNT) forest coatings have been found to lower electron yield from material surfaces. The suppressed yields have been attributed to both the lower inherent yields of low-atomic number carbon and the enhanced electron recapture resulting from the morphology of the carbon layer. To explore the relative contributions of these two causes of yield suppression, tests have been made on CNT forest-coated conducting substrate samples subjected to vibrationally-induced changes of the coating structure. The extent of vibrationally-induced structural changes—due, for example, to shear-force conditions during space-vehicle transit—are of interest, as CNT have been a frequent topic of scientific curiosity and space applications due to their high tensile strength, high aspect ratio geometry, and unique electromagnetic characteristics. Their use has also been beneficial for sensor equipment, both terrestrial and space-faring, due to their extremely low photon and electron reflectivity.

II. Preperation and Experimental Setup

Three CNT forest coatings, vertically aligned CNT arrays grown on aluminum-coated Si substrates, were prepared using a wet injection chemical vapor deposition (CVD) method, with heights varying from 20-50 μm [Wood, 2015]. The 1 cm^2 area wafers were fixed to cylindrical copper slugs with an ultrahigh vacuum compliant conductive epoxy. Care was taken to ensure minimal sample contamination due to its effect on the characteristic of electron yield [Lundgreen, 2018].

Two characteristics, surface morphology and electron yield (EY), were examined. Surface morphology was investigated using surface imagery from a scanning electron microscope (SEM). Electron yield data were collected using a high-accuracy Hemispherical Grid Retarding Field Analyzer (HGRFA) in an ultrahigh vacuum environment [Hoffmann, 2012]. The electron energy range of the entire data set was between 15 eV to 30 keV.

The samples were taken to Space Dynamics Lab and submitted to vibration on a standard shaker table (Fig. 1). The unidirectional vibration profile mimicked a g-force profile seen in average rocket lift-off conditions. These forces were perpendicular to the preferred vertical alignment of the CNT forests normal to the substrate surface, providing maximum damage. Characteristic EY and SEM data were collected before and after the shaking session.

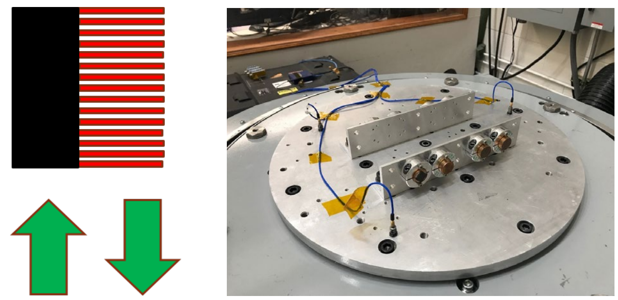

Figure 1. Representation of off-axis forces with respect to CNT forest orientation (left). Sample mounting on the shaker table (right).

III. Electron Yield and Models

Total electron yield (TEY) provides a composite view of how high-energy electrons interact with a material during electron bombardment. The yield is a ratio of emitted to incident electrons through this interaction. The relevant classifications of electrons stemming from this interaction are secondary and backscattered electrons. Backscattered electrons are produced when primary electrons interact quasi-elastically with the material, and are reflecting back out of the material without large energy loss. Secondary electrons are produced when high-energy electrons interact inelastically with the material, depositing energy into the material. This energy transferred to the material can create additional electrons with sufficient energy to overcome the work function and be emitted from the surface.

Two basic models were considered to explain yield profiles of the CNT forests (see Fig. 2). The multilayer model [Wilson, 2013; 2019a; 2019b] considers slabs of bulk carbon on a bulk substrate. A patch model considers adjacent surface regions of multiple bulk materials, in this case carbon and the Al-coated Si substrate. The pillar model combines elements of both the multilayer and patch models; the AlSi substrate again forms the lower layer while the upper layer is comprised of patches of low-density bulk carbon representing the CNT and vertical voids which act in essence as nanoscale Faraday cups to

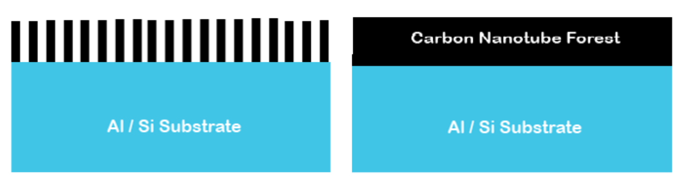

Figure 2. Idealized cross-section diagrams of the Pillar Model (left) and the multilayer model (right). Electrons would approach the sample from the top-down during electron yield testing.

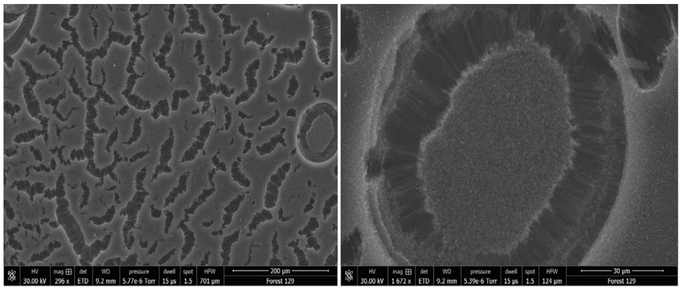

Figure 3. (a) Linear fissure damage sites seen at the edges of the shaken wafers. (b) Rarer circular damage sites.

capture scattered electrons. The morphology of the CNT forests on the surface of the substrate provided a mechanism to recapture secondary and backscattered electrons that would otherwise be emitted from the surface [Wood, 2019].

IV. Results

Both EY and SEM provided insight into the effects of damage caused to the CNT forests by the shaking.

A. *Scanning Electron Microsope (microscale)*

The SEM imagery provided evidence of vibration-induced changes on the edges of the CNT forest wafers. After shaking, two types of damage were classified on the microscale. One change appeared as linear fissures [see Fig. 3(a)], which accounted for a majority of the damage observed. Circular plateaus with an exposed base were also seen in lesser quantities [see Fig. 3(b)]. Both of these damaged regions were only found near the sample edges; they were not found in central regions of the sample where EY measurements were made and the CNY forests still appeared uniform and un-modified on a microscopic scale.

B. *Electron Yield (nanoscale)*

Total (TEY), secondary (SEY) and backscatter (BSEY) electron yield curves, taken for beam energies between 15 eV and 5 keV, do provide qualitative evidence of possible nanoscale vibration-induced structural changes occurring in the center of the CNT samples. CNT forest sample SEY and BSEY for energies below ~500 eV are still found to be lower than constituent emissions from either bulk graphitic carbon or Al-Si substrate SEY; this confirms that CNT forest morphology-induced suppression is still occurring in shaken samples. However, shaken samples have reduced SEY suppression below ~1 keV; they also exhibit more pronounced double peak structures in SEY and BSEY curves, with the second peaks near 200 eV corresponding to bulk carbon peaks. These observed differences suggest there is reduced structurally-induced yield suppression, perhaps as a result of a decrease in preferred vertical alignment of the CNT forest structure on the nanoscale. At the lower energy range where these differences were observed, the electron penetration depth is in the nanoscale regime [Wilson, 2012].

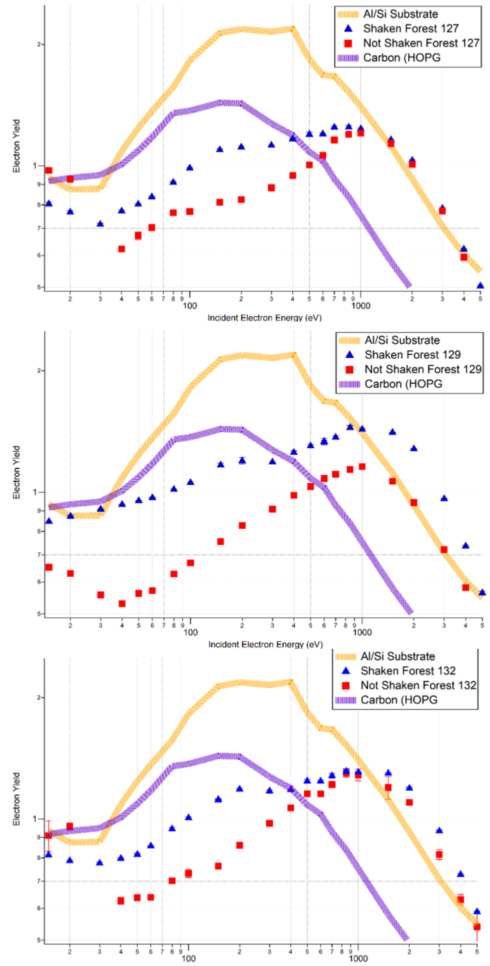

Figure 4. Secondary electron yield curves for three forest samples and for bulk materials (HOPG and AlSi substrate) comprising the samples. Red markers denote pre-shaken SEY data and blue markers denote post-shaken data.

Models considered within this study were able to provide qualitative, but not quantitate, explanations for yields of unshaken CNT forest samples [Wood, 2019]. Likewise, the models provide a qualitative explanation of the effects of shaking the CNT forest samples, suggesting that the vibrations partially reduced the preferred vertical alignment of the CNT on a nanoscale without causing any microscopic changes in the CNT such as breaking CNT or altering the CNT density. Quantitative extensions to the pillar model, incorporating both energy and angular descriptions of secondary and backscattered electrons are in progress and may able to provide a more quantitative assessment of the observed energy-dependent changes in SEY due to vibration-induced modifications.

Further tests of the influence of structural integrity of CNT forests are being explored. A more drastic mechanical compression of the CNT structure should cause increased density of the carbon layer and eliminate any residual vertical alignment; thus, yields at lower energies would be expected to be similar to bulk graphitic carbon layers on substrates tested in other studies [Wilson, 2019a; 2019b]. The secondary electron suppression effects will also be explored with additional measurements of taller CNT forest samples (from 150 µm to 500 µm) of similar density and vertical alignment to test the hypothesis that morphological suppression could be extended to higher energies >3 keV; this could produce a CNT-coated substrate with uniform low SEY <0.5 over a very wide energy range.

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