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SECONDARY ELECTRON YIELD MEASUREMENTS OF CARBON NANOTUBE FORESTS: DEPENDENCE ON MORPHOLOGY AND SUBSTRATE

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Abstract

Total secondary and backscatter electron yield data were taken with beam energies between 15 eV and 30 keV to determine the extent of suppression of substrate yields caused by carbon nanotube (CNT) forest coatings on substrates. CNT forests are low density graphitic carbon structures of vertically oriented CNT's. Chemical vapor deposition (CVD) was used to grow multi-walled CNT forests between 20-50 µm tall on a thick silicon substrate capped with a 3 nm diffusion barrier of evaporated aluminum. CNT forests can potentially lower substrate yield due to its low-Z (atomic number) carbon composition, along with its bundled, high aspect ratio architecture. In general, lower-Z substrates are more susceptible to electron backscatter than surfaces of equal electron density such as carbon because they have a lower density of bulk electrons for the incident electrons to interact with, thereby reducing the yields. Rough surfaces, and in particular surfaces with deep high-aspect-ratio voids, can also suppress yields as electrons emitted from lower lying surfaces are recaptured by surface protrusions rather than escaping the near-surface region. Modification of yields from coatings can be modeled essentially serially, as layered materials with different yield curves contribute more at certain incident energies. However, it is shown that the suppression of the yields due to forest morphology is more significant than simple proportional contributions of components, and is related to the angular distribution of backscattered and secondary electrons as a function of energy. These two effects are expected to be most pronounced at low energies, where the incident electrons interact preferentially with the carbon at the surface.

This study measured yields from three CNT forests of varied height and density, along with yields of an annealed substrate and constituent bulk materials. At incident electron energies above ~1200 eV the substrate yields dominated those of the CNT forests, as incident electrons penetrated through the low-density low-Z CNT forests and backscattered from the higher-Z substrate. At lower energies (<1200 eV), the CNT forests substantially reduced the overall yields of the substrate, and for <500 eV CNT forest yields were <1 and well below the already low yields of bulk graphite. The yield's dependence on the height and density of the CNT forest is also discussed. By understanding these effects on electron yield, CNT growth can be tailored for specific environments to mitigate spacecraft charging.

I. Introduction

There is significant interest in reducing secondary electron emission from materials used for a variety of applications. This can be done by:

- Coating surfaces with intrinsically low-yield materials.
- Modifying the surface morphology.
- \[ \text{Yield} = \frac{\text{Number of emitted electrons}}{\text{Number of incident electrons}} \]

II. Forest Growth and Characterization

CNT forests were made in the Utah State University Nanofabrication Lab using a non-plasma enhanced chemical vapor deposition method. Substrates of n-type silicon wafer with a 3 nm layer of evaporated aluminum deposited to produce the proper in-diffusion rate. The wafer was then diced into 1 cm² pieces and loaded into a tube furnace at 700 °C. A chemical precursor of xylene with a smaller molar concentration of ferrocene was used to deposit carbon nanotubes on the substrate. The carbon nanotubes were then oxidized in air to form carbon nanotube forests.

III. Theory and Experimental Setup

Electron yield is an incident energy-dependent measure of the interactions of incident electrons with a material and characterizes the number of electrons emitted per incident electron. The total electron yield (TEY) is defined as the ratio of emitted electron flux to the incident flux, \[ \text{TEY} = \frac{\text{Emission current}}{\text{Incident current}} \]

Backscatter electron yield (BSEY) describes electrons emitted from the material which originate from the incident beam; operationally BSE are defined as electrons with emission energies >50 eV. SE yield (SEY) describes electrons which originate within the material and are excited through inelastic collisions with the incident electrons; operationally SE are defined as electrons with emission energies <50 eV. Absolute yield were measured using a fully-enclosed hemispherical grid rotating field analyzer (HGRFA) (Fig. 2), which determines absolute yield accurately (<5% absolute uncertainty), since the encapsulating design captures almost all of the emitted electrons. Concentric hemispherical grids are used to energetically discriminate the collected electrons. SEY is calculated as the difference between TEY and BSEY.

IV. Results and Conclusions

Due to the multi-component nature of the CNT forest-substrate structure, understanding of the yield is done by looking at contributions from all materials individually. The contribution made by bare Si and Al to the ASI substrate SEY is shown in Fig. 4(a). The penetration depth of Al-matches the layer thickness of 3 mm at 265 eV, below which the SEY of Al should dominate. After this energy, Si starts to rule the contribution to the yield, where ASI SEY lies ~30% above the difference of yields between bare Si and Al, with the rate attributed to secondary electrons still being generated in the thin Al layer. Fig. 3 shows that the penetration depth of graphite set to ~3% of its normal density does not reach 3000 eV, a factor of 7 higher than the 1200 eV transition energy seen. This suggests that the effect of the CNTs at low energies is about an order of magnitude larger than simple density arguments predict, perhaps due to the CNT morphology. More quantitative measurements of mass density are needed to confirm this. determine how the morphology suppresses substrate yield beyond density arguments.

Total secondary and backscatter electron yield data of a CNT forest and bulk graphite is seen in Fig. 4(b), taken with beam energies between 15 eV and 30 keV to demonstrate that CNT forests can substantially suppress substrate yields. Figure 4(c) at incident electron energies above ~1200 eV shows the substrate yields dominated those of the CNT forests, as incident electrons penetrated through the low-density low-Z CNT forests and backscattered from the higher-Z substrate. Above ~1200 eV, the yield of the forests is slightly higher than the bare substrate, which may result from lower attenuation of SE produced by BSE detected back out of the material. At lower energies (<1200 eV), the CNT forests substantially reduced the overall yields of the substrate, and for <500 eV CNT forest yields were <1 and well below the already low yields of bulk graphite. This suggests that the effect of the CNTs at low energies is about an order of magnitude larger than simple density arguments predict, perhaps due to the CNT morphology. The yield's dependence on the height and density of the CNT forest is relatively small, but is consistent with increased influence of carbon scatter as the areal density of CNTs increases.