Characterization of Electron Yield Suppression with Carbon Nanotube Forest Grown on Silicon Substrates

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Characterization of Electron Yield Suppression with Carbon Nanotube Forests Grown on Silicon Substrates

Brian Wood, Jordan Lee, Justin Christensen, Greg Wilson, JR Dennison, T.C. Shen
Utah State University

Total Reflectance

Wavelength (µm)

PyroMark 1200
Z306
NBAL-D502

CNT (60-70 µm)
Low Density 0.5% Ferrocene

High Density 0.2% Ferrocene

Xylene: \( C_6H_4(C_5H_3)_2 \)

Ferrocene: \( Fe(C_5H_5)_2 \)

\( R(E_0) \)

26 μm
Electron Emission and Acquisition Overview

**Secondary Electron Yield**

\[
\delta = \frac{Q_{Secondary}}{Q_{Incident}}
\]

Schematic of the Hemispherical Grid and the Biasing during data collection
Between 100-10,000 eV, SEY of AlSi substrate ~ 18% higher than bare Si

Multilayer Effects

CNT Forest NOT a direct combination of substrate yield and carbon yield
CNT Morphology vs Bulk Material

Mass Density

HOPG $\sim 2.2 \ \text{g/cm}^3$  
CNTF’s $\sim 0.07 \ \text{g/cm}^3$

\begin{itemize}
  \item $\sigma_{\text{CNT}} < \sigma_{\text{HOPG}}$ for $E \leq 500 \ \text{eV}$
  \item $\sigma_{\text{CNT}}$ starts to converge with AISi Substrate higher energies
  \item Density not the only factor dictating penetration depth
\end{itemize}
Comparison of Secondary Yield Results

- CNT yield suppression viable up to 1 keV
- Yield of forests actually higher than substrate above 1 keV

<table>
<thead>
<tr>
<th>TABLE I CNT FOREST CHARACTERISTICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>AISi 127</td>
</tr>
<tr>
<td>AISi 129</td>
</tr>
<tr>
<td>AISi 132</td>
</tr>
</tbody>
</table>
Conclusions

• Carbon nanotube forests lowered secondary yield of substrate up to 1 keV incident energy

• Explanation of sample’s yield cannot be explained serially

• Forest height main factor in reducing yield

Acknowledgments

➢ T.C. Shen and Nano Device Lab
➢ Utah State Microscopy Core Facility
➢ Utah State Material Physics Group
• CNT forests have lowest BSEY, especially in the lower energy range

• CNT BSEY has similar shape as substrate

• CNT BSEY starts to match HOPG in higher energies
Data Acquisition

\[ \sigma = \frac{Q_{\text{Secondary}} + Q_{\text{backscatter}}}{Q_{\text{Incident}}} = \frac{\int \left( I_{\text{coll}} + I_{\text{grid}} + I_{\text{stage}} \right) / \Gamma_{\text{HGRFA}} \, dt}{\int \left[ \left( I_{\text{coll}} + I_{\text{grid}} + I_{\text{stage}} \right) / \Gamma_{\text{HGRFA}} + I_{\text{sample}} \right] \, dt} \]
Energy Spectra Results

- AlSi 127 and AlSi 132 almost identical secondary peak
- Taller forest has greatest secondary electron suppression ability
- AlSi 129 backscatter peak ~27% less than substrate, consistent with backscatter yield results
- Backscatter peak absent for AlSi 127 and AlSi 132 due to large secondary peak

<table>
<thead>
<tr>
<th></th>
<th>Sample</th>
<th>Height (µm)</th>
<th>Ferrocene (%)</th>
<th>Surface Coverage</th>
<th>Surface Density (µg/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlSi 127</td>
<td>24-27</td>
<td>0.5</td>
<td>0.90</td>
<td>1.50</td>
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<tr>
<td>AlSi 129</td>
<td>42-51</td>
<td>0.5</td>
<td>0.91</td>
<td>2.80</td>
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<tr>
<td>AlSi 132</td>
<td>27-32</td>
<td>0.2</td>
<td>0.82</td>
<td>1.60</td>
<td></td>
</tr>
</tbody>
</table>
HOPG Yield

\[ E_{1} = 45 \text{ eV} \quad E_{2} = 500 \text{ eV} \]

\[ E_{\text{max}} = 200 \text{ eV} \quad \text{Max Yield} = 1.34 \]

AlSi 129 Electron Yield

\[ E_{1} = 550 \text{ eV} \quad E_{2} = 1400 \text{ eV} \]

\[ E_{\text{max}} = 1000 \text{ eV} \quad \text{Max Yield} = 1.06 \]
Density

HOPG ~ 2.2 $g/cm^3$

CNTF’s ~ 0.2 $g/cm^3$

Graphite Roughly x10 Denser than Carbon Nanotubes

Graphite Roughly x10-100 Denser than Carbon Nanotubes
Electron Emission Overview Cont’d

Total Electron Yield
Secondary Electron Yield
Backscatter Electron Yield

\[ \sigma = \frac{Q_{\text{Secondary}} + Q_{\text{backscatter}}}{Q_{\text{Incident}}} \]
\[ \delta = \frac{Q_{\text{Secondary}}}{Q_{\text{Incident}}} \]
\[ \eta = \frac{Q_{\text{backscatter}}}{Q_{\text{Incident}}} \]

Energy Spectrum of Emitted Electrons

Total Yield Results of Gold

Crossover Energies

Energy Spectrum of Emitted Electrons

Crossover Energies

\( E_1 \quad E_{\text{max}} \quad E_2 \)
CNT Morphology vs Bulk Material

HOPG

21 nm

3 μm

Carbon Nanotube Forest
\[ \sigma = \frac{Q_{\text{Secondary}} + Q_{\text{backscatter}}}{Q_{\text{Total}}} = \frac{\int I_{\text{out}} dt}{\int I_{\text{in}} dt} = \frac{\int \frac{I_{\text{coll}} + I_{\text{grid}} + I_{\text{stage}}}{\Gamma_{\text{HGRFA}}} \, dt}{\int \left[ \frac{I_{\text{coll}} + I_{\text{grid}} + I_{\text{stage}}}{\Gamma_{\text{HGRFA}}} + I_{\text{sample}} \right] dt} \]
Stopping Power and Penetration Depth

\[- \frac{dE}{dz} = \frac{A}{E^{n-1}}\]

Secondary Electron Generation

\[n(E_0) = \frac{1}{\varepsilon_m} \frac{dE}{dz}\]

Production Energy \(\uparrow\)

Emission Probability

\[P(z) = \beta \cdot \alpha \cdot e^{-\frac{z}{\lambda}}\]

Mean Free Path

Escape Probability \(\uparrow\uparrow\)

Geometrical Factor
Total Yield Results

- CNT has lower total yield right till 700 and 1000 eV for HOPG and M55J respectively.
- Again, similar shape with HOPG but $E_{max}$ happening at a larger energy.
Sample

Interaction Volume

Backscattered Electron

Primary Electron Beam

Secondary Electron

Backscattered Electron Beam

Sample

Interaction Volume

Primary Electron Beam

Secondary Electron