ECET499 Guest Lecture

Carbon Nanotubes: Synthesis and Applications

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Overview

• Nanotechnology
• CNT Synthesis
• CNT Applications
• My Perspective
Nanotechnology

- Study of materials and phenomena at nanoscale
- National Nanotechnology Initiative (NNI)
  - Launched in 2001 to coordinate research activities
- Birck Nanotechnology Center
  - $58 million facility opened in 2005
  - 187,000 ft$^2$ of space, 25,000 ft$^2$ cleanroom
  - Over 45 faculty members and 145 students
Nanotechnology
Nanotechnology

Top 15 institutions by the Number of Active NSE Awards in FY 2009

Purdue: 100
GA Tech: 90
U of Michigan: 83
Northwestern: 82
U of Minn: 74
U of Texas: 72
Penn State: 70
Arizona State: 69
U of Florida: 66
Cornell: 64
U of Wisconsin: 62
UC Berkeley: 61
U of Washington: 60
MIT: 59

Nanotechnology

• Carbon nanotubes (CNTs)

Carbon Nanotubes (CNTs)

• Timeline


Carbon Nanotubes (CNTs)

• Timeline


2001  Integration of CNTs for logic circuits  P. Avouris et al., Science 292, 706 (2001)


Recommended review book: Carbon Nanotubes: Synthesis, Structure, Properties, and Applications
by M. S. Dresselhaus, G. Dresselhaus, and P. Avouris
Carbon Nanotubes (CNTs)

• Structure
  – Formed from the hexagonal graphene carbon structure
  – Can form single-wall (SWNT) or multi-wall (MWNT) structures
  – Ends (tips) can be open or closed (capped)
  – High aspect ratio (length = ~1000 x diameter)
Carbon Nanotubes (CNTs)

• Properties
  – Mechanical: Young’s modulus ~1 TPa (5X steel) (Treacy et al. 1996)
  – Electrical: Metallic or semiconductor behavior, depending on wall structure of SWNTs, and high conductivity
  – Thermal: Room-temperature thermal conductivity ~3000 W/mK (8X copper) - similar to diamond
  – Chemical: high storage capacity
Overview

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CNT Synthesis

• Heterogeneous catalysis
  – Carbon atoms: gas to solid
  – Catalyst precursor metal deposition
    • E-beam evaporation at $7 \times 10^{-7}$ Torr
    • 20nm Cr underlayer used for adhesion and prevention of catalyst poisoning
    • Varying Ni catalyst thicknesses: 5nm, 10nm, 20nm
CNT Synthesis

- Fe/dendrimer catalyst (wet chemistry based)

Fe\(^{3+}\)/G4-NH\(_2\) composite

Fe\(_2\)O\(_3\) nanoparticles

AFM images of Fe\(_2\)O\(_3\) nanoparticles

MPCVD System

H₂ – 1000cm³/min
CH₄ - 10cm³/min

DC bias:
0 – 600 V; 0 – 1.7 A

Stage temperature control with heating up to 1000°C
CNT Synthesis

• Growth process
  – Samples placed on molybdenum puck
  – Chamber evacuated to 0.7 Torr for 5 min.
  – Supplied with $H_2$ at 50 sccm and 10 Torr
  – Susceptor temperature set to 700°C
  – Plasma ignited at 500W for 2 min.
  – Supplied with $CH_4$ at 10 sccm introduced for 10 min.
CNT Synthesis
CNT Synthesis

Fe, Ni, Co
CNT Synthesis

250°C, 0V
900°C, 0V

250°C, 0V

900°C, 0V

250°C, 0V

900°C, 0V
Effects of Inlet Gas Composition on MWCNT Diameter

Effects of Catalyst Layer Thickness on MWCNT Diameter

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CNT Applications

• Biosensor material
  – Enzymatic biosensors: immobilization of enzyme on CNTs
  – Glucose / glucose oxidase
    • Electrons formed and collected $\rightarrow$ amperometric

Schematic diagram of the glucose/glucose oxidase reaction (adapted from Sotiropoulou and Chaniotakis, 2003).
CNT Applications

- Integration of CNT sample with PDMS cell
Protein Adsorption on CNTs

Protein Adsorption on CNTs

0V -100V -200V -300V

250 °C  550 °C  700 °C  900 °C
Characterization: SEMs

- Estimation of CNT surface area
Characterization: Raman Spectroscopy

Intensity of the G-band relative to the D-band ($I_G/I_D$) calculated to assess quality of CNTs (Amama et al., 2007, Eklund et al., 1995)

D-band peak at around 1300 cm$^{-1}$ (amorphous carbon)

G-band peak at around 1600 cm$^{-1}$ (well graphitized structure)
Current per CNT Area vs Raman

Protein Adsorption on CNTs
Protein Adsorption on CNTs

• Demonstration of successful protein adsorption
• Nanostructure found to profoundly affect degree of protein adsorption
  – SEM/TEM/Raman
  – Cyclic voltammetry

⇒ More defect sites and higher levels of amorphous carbon lead to better protein adsorption (higher negative bias voltage, lower calcination temperatures)

⇒ Large CNT area, large number of defect sites per CNT area is best
CNT Applications

- Vapor chambers
  - Phase change phenomena
  - Wicking of working fluid
  - Micrometer sized mesh

CNT Applications

• Why CNTs?
  – Good thermal interface characteristics
  – High inherent thermal conductivity
  – Wicking capability
    • Thinning out of liquid layer for improved evaporation

Vapor Chamber Wicks

• Integration of copper mesh with Cu-Mo-Cu substrate
• Catalyst metal deposition
• Growth of CNTs in MPCVD

Vapor Chamber Wicks

Vapor Chamber Wicks
Vapor Chamber Wicks

- Thermal performance

Vapor Chamber Wicks

- Thermal performance
  - Effective in dissipating upwards of 500 W/cm² at low levels of superheat without any observed dryout or CHF
  - Positive bias, nominal thickness of Cu coating strongly influence level of superheat and wick thermal resistance

→ denser growth of CNTs, thicker Cu coating leading to better performance
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My Perspective

• Mechanical engineering
  – Ph.D., Purdue University, 2008
  – M.S., KAIST, 2002
  – B.S., Korea University, 2000

• Engineering devices using CNTs
  – Performance is driven by structure
  – Ability to control structure

Growth Parameters  CNT Structure  Function
My Perspective

• Challenges
  – Mass production
  – Characterization of properties
  – Increased control over geometry
  – Optimization of growth parameters
  – Integration with engineering devices
Thank you!!

Questions ?

Comments !