15-398 Introduction to Nanotechnology

Carbon Nanotubes

Seth Copen Goldstein
seth@cs.cmu.edu
CMU

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Basics

- CNTs come in two basic flavors
  - Single walled
  - Multi-walled

- CNTs are basically rolled up Graphite

http://www.photon.t.u-tokyo.ac.jp/~maruyama/agallery/agallery.html

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Some Arrangments of Carbon

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Types of SWNT

Armchair (n,n)

Zig-zag (n,0)

Chiral (n,m)

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A Graphene Sheet

http://ipn2.epfl.ch/CHBU/NTbasics1.htm

An Armchair nanotube (10,10)

http://www.photon.t.u-tokyo.ac.jp/~maruyama/agallery/agallery.html

A chiral nanotube (10,5)

Geometries

- Length: can be > 1μm
- Diameter:
  - down to 1nm (SWNT)
  - Upto 50nm (MWNT)
- Tubes formed from h
- Ends from pentagons (1/2 a fullerene)
- Open and closed
- Branching possible

The Wondrous World of Carbon Nanotubes

http://ipn2.epfl.ch/CHBU/NTbasics1.htm

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Calculating Diameter of SWNT

SWNT structure can be
1. (n,m) Armchair
2. (n,m) Zigzag
3. (n,m) Chiral

Where (n,m) are found with:

$$R = na_1 + ma_2$$

The diameter is found with:

$$d = (n^2 + m^2 + nm)^{1/2} 0.0783\text{nm}$$

FIGURE 1. (a) Schematic honeycomb structure of a graphene sheet. Single-walled carbon nanotubes can be formed by folding the sheet along lattice vectors. The two basis vectors a_1 and a_2 are shown. Folding of the (8,8), (8,0), and (10,−2) vectors lead to armchair (b), zigzag (c), and chiral (d) tubes, respectively.

Dai, H. Acc. Chem. Res. **2002**, 35, 1035-1044.

Basic Properties

- Chemical
- Conductors and semiconductors
- Stiff
- Flexible
- Thermal conduction

Manufacturing

- Many methods (covered last time)
  - Ball milling
  - Laser ablation
  - Plasma arc
  - Etc.
- Result is a mess
- Purification necessary

Purification: Why

- Soot has many contaminants:
  - Catalyst particles
  - Carbon clusters
  - Smaller fullerenes: C_{60} / C_{70}
- Even the NTs are mixed
  - Conducting, semiconductin
  - SNT and MWNT
  - Diameters, lengths

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Purification: How

- Removal of catalyst:
  - Acidic treatment (+ sonication)
  - Thermal oxidation
  - Magnetic separation (Fe)
- Removal of small fullerenes
  - Micro filtration
  - Extraction with CS_2
- Removal of other carbonaceous impurities
  - Thermal oxidation
  - Selective functionalisation of nanotubes
  - Annealing
- Main issues
  - Not to damage or modify the CNTs
  - Economics

Conductance

- Conducting or semiconducting?
  - (n-m)/3 = 0 mod 3 -> conducting
  - Otherwise -> semiconducting
- Method of conduction?
  - Not the same as bulk metal
  - Ballistic (Fermi-liquid)
- Current Densities
  - 10^9A/cm^2! 1000x better than copper!
  - What does this mean when diam = 2nm?

Mechanical Properties

- Young's modulos in GigaPascals!

J.-P. Salvetat et al., Adv. Mater. 11, 161 (99).

Some Applications

- Electronic Nanotechnology
- Field-Effect Displays
- Composites
- Sensors
- Energy Storag
- Supercapacito
- AFM tips
- ...

The Wondrous World of Carbon Nanotubes

Single nanotubes

- Pull-out and release of **MWNT** – Van der Waals force
- World's smallest balance

Weighing a 22 fg particle
Science 283, 1513(1999)
Applying hf voltage got frequency for resonance

Hydrogen Storage

- Can CNTs can be used to store hydrogen?
- Why?
  - Zero emissions
- Why not?
  - Compare Energy density
    3 MJ/l (5000 psi H_2) vs. 32 MJ/l (gasoline)
- Use: Fuel container (e.g., fuel cell) to replace use of hydrocarbons (e.g., oil)
- DOE minimum: 6.5% of Weight

Two Basic Methods

- Gas phase (physisorption)
  - Van der walls bonds
  - Room Temperature
  - Higher %wt (between 0-14?)
- Electrochemical ads
  - Electrically dissassc
  - H_2 adsorbs into C

Field-effect displays

- Generates large fields
  - Large aspect ratio
  - Large current densities
- Use as electron source in Flat-panel

Samsung display 1999

Schematic structure of nanotube flat panel display. (Choi et al.)

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CNTs for interconnect

- High current densities
- Low resistance (6.2K ohm)
- Ballistic behavior
- However,
  - Inductance
  - Contact resistance
  - assembly

Measuring the resistance

- Note quantization of conductance

Bachtold

MWNT resistance

Frank et al., Science 280, 1744 (1998)

SWCN Crosspoint Memory

- On - off state controlled by nanotube contact
- Hysteresis in both states
  - Off - Elastic restoring force
  - On - van der Waals attractive force
- Crosstalk and addressing are still problems

C. Lieber, et al., *Science* 2000, *289*, 94.

Nanotube transistor

S.J. Tans et al., Nature 393, 49 (1998).

Carbon Nanotube FETs

IBM Nanoletters

Using CNTs in circuits

Fig. 4. Demonstration of one-, two-, and three-transistor logic circuits with carbon nanotube FETs. (A) Output voltage as a function of the input voltage of a nanotube inverter. (Inset) Schematic of the electronic circuit. The resistance is 100 megaohms. (B) Output voltage of a nanotubes NOR for the four possible input states (1,1), (1,0), (0,1), and (0,0). A voltage of 0 V represents a logical 0 and a voltage of −1.5 V represents a logical 1. The resistance is 50 megaohms. (C) Output voltage of a flip-flop memory cell (SRAM) composed of two nanotube FETs. The output logical stays at 0 or 1 after the switch to the input has been opened. The two resistances are 100 megaohms and 2 gigaohms. (D) Output voltage as a function of time for a nanotube ring oscillator. The three resistances are 100 megaohms, 100 megaohms, and 2 gigaohms.

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ig. 1. Device layout. (A) Height image of a ingle-nanotube transistor, acquired with an tomic force microscope. (B) Schematic side iew of the device. A semiconducting nanotube s contacted by two Au electrodes. An Al wire, overed by a few-nanometers-thick oxide layer, s used as a gate. (C) Height-mode atomic force nicroscope image of two nanotube transistors onnected by a Au interconnect wire. The arows indicate the position of the transistors. our alignment markers can also be seen.

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CNT Sensors

J. Kong et al., Science 287, 622 (2000).

Next Time

- Lets pop up a level
  - Nanocomputing
- Paper will be posted on the web

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