Nanocarbon: Properties and Applications

Trial lecture
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Kai de Lange Kristiansen

(being available in an internet space)
Nano

- Size – $10^{-9}$ m (1 nanometer)
- Border to quantum mechanics
- Form
  → Emergent behavior
Carbon

- Melting point: ~ 3500°C
- Atomic radius: 0.077 nm
- Basis in all organic compounds
- 10 mill. carbon compounds
Allotropy and Allotropes of Carbon (Family)

http://chemistry.tutorvista.com/inorganic-chemistry/allotropes-of-carbon.html
Nanocarbon

- Fullerene
- Tubes
- Cones
- Carbon black

Properties & Application
- Electrical
- Mechanical
- Thermal
- Storage
Bonding

Graphite – sp$^2$

Diamond – sp$^3$
Nanocarbon

Shenderova et al.
Nanocarbon

1 – 5 pentagons

6 + 6 pentagons

12 pentagons
Fullerene

"The most symmetrical large molecule"

- Discovered in 1985
  - Nobel prize Chemistry 1996, Curl, Kroto, and Smalley

- C\textsubscript{60}, also 70, 76 and 84.
  - 32 facets (12 pentagons and 20 hexagons)
  - prototype

Epcot center, Paris

Architect: R. Buckminster Fuller
Fullerene

- Symmetric shape
  → lubricant
- Large surface area
  → catalyst
- High temperature (~500°C)
- High pressure
- Hollow
  → caging particles
- Ferromagnet?
  - polymerized C_{60}
  - up to 220°C
Fullerene

- Chemically stable as graphite
  - most reactive at pentagons
- Crystal by weak van der Waals force
- Superconductivity
  - $K_3C_{60}$: 19.2 K
  - $RbCs_2C_{60}$: 33 K

Nanotube

- Discovered 1991, Iijima

Roll-up vector:

\[ C_{h} = n \vec{a}_1 + m \vec{a}_2 \]
Nanotube

Electrical conductance depending on helicity

\[ C_h = n \mathbf{\tilde{a}}_1 + m \mathbf{\tilde{a}}_2 \]

\[
\text{If } \frac{2n + m}{3} = \delta, \text{ then metallic} \\
\text{else semiconductor}
\]

- **Current capacity**
  - Carbon nanotube: 1 GAmps / cm²
  - Copper wire: 1 MAmps / cm²

- **Heat transmission**
  - Comparable to pure diamond (3320 W / m·K)

- **Temperature stability**
  - Carbon nanotube: 750 °C (in air)
  - Metal wires in microchips: 600 – 1000 °C

- **Caging**
  - May change electrical properties
  
  → sensor
Nanotube

Properties

Diameter:
as low as 1 nm

Length:
typical few μm

High aspect ratio:
\[
\frac{\text{length}}{\text{diameter}} > 1000
\]

→ quasi 1D solid

SWCNT – 1.9 nm

Nanotubes

Carbon nanotubes are the strongest ever known material.

- **Young Modulus** (stiffness):
  - Carbon nanotubes: 1250 GPa
  - Carbon fibers: 425 GPa (max.)
  - High strength steel: 200 GPa

- **Tensile strength** (breaking strength)
  - Carbon nanotubes: 11-63 GPa
  - Carbon fibers: 3.5-6 GPa
  - High strength steel: ~2 GPa

- **Elongation to failure**: ~20-30%

- **Density**:
  - Carbon nanotube (SW): 1.33 – 1.40 gram / cm³
  - Aluminium: 2.7 gram / cm³
Carbon nanotubes are very flexible

http://www.ipt.arc.nasa.gov/gallery.html

Nanoscience Research Group
University of North Carolina (USA)
http://www.physics.unc.edu/~rsuper/research/
Cones

- Discovered 1994 (closed form) Ge & Sattler
  1997 (open form) Ebbesen et al.

- Closed: same shape as HIV capsid
- Possible scale-up production (open form)
- Storage?
  → Hydrogen

Scale bar: 200 nm

19.2°  38.9°  60.0°  84.6°  112.9°

Carbon black

Large industry
- mill. tons each year

• Tires, black pigments, plastics, dry-cell batteries, UV-protection etc.

• Size: 10 – 400 nm
Writing

Carbon – graphite

$C_{60}$: 1000x better resolution than ink (Xerox)
CNT / polymer composite

- Transparent electrical conductor
  - Thickness: 50 – 150 nm
  - High flexibility

Transistor

- Vacuum tubes
  - Nobel prize 1906, Thomson.

- Semiconductor, Si-based
  - Nobel prize 1956, Shockley, Bardeen, and Brattain.
  - 2000, Kilby.

IBM, 1952.
Transistor

- **SWCNT**
  - 2.6 GHz, T = 4 K
  - Logical gates

Bachtold, Dekker *et al.*

Antenna

- Dipole
  ~ 3/4 m

Radio wave:
\[
 f = \frac{c}{\lambda} = \frac{3 \cdot 10^8 \text{m}}{3 \text{m}} \approx 100 \text{ MHz}
\]

- Nanotube

Optical wave:
\[
 \lambda \sim \frac{L}{2} \sim 500 \text{ nm}
\]

Flat screen displays

Plasma TV
Flat screen displays

- Field emission

Atomic Force Microscopy

Application
Atomic force microscopy

- Tube or cone
- Chemical probe

Wong, Lieber et al.
Yarn

Yarn

MWCNT

- Operational: $-196^\circ C < T < 450^\circ C$
- Electrical conducting
- Toughness comparable to Kevlar
- No rapture in knot

Hydrogen storage

\[ 2 \text{H}_2(\text{g}) + \text{O}_2(\text{g}) \rightarrow 2 \text{H}_2\text{O} (\text{l}) + \text{energy} \]

Application

- \( \text{Mg}_2\text{NiH}_2 \)
  - 3.16 wt%
- \( \text{LaNi}_5\text{H}_6 \)
  - 1.37 wt%
- \( \text{H}_2 \) (liquid)
- \( \text{H}_2 \) (200 bar)

Hydrogen storage

- **Aim**: 5 - 7 wt% $H_2$

- **SWCNT**
  - Dillon *et al.* (1997): 8 wt% (questionable)
  - Tarasov *et al.* (2003): 2.4 wt% reversible, 25 bar $H_2$, -150°C.

- **Cones**
  - Mealand & Skjeltorp, (2001)
    US Patent 6,290,753

Eldrid Svåsand, IFE Kjeller
Warnings

- Environment and health
- No scale-up production of fullerenes and tubes
- No scale-up design, yet.
Summary

• Carbon comprises a number of allotropes
• Each has characteristic/novel properties
• Fabricating nanocarbon uses a number of approaches, each with special equipment
• Applications of nanocarbon include electronics, structural materials, and energy
• We are still at the beginning of a relatively long journey into nanocarbon engineering
References

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