**Resource Letter: Nanotubes**

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The author has selected resource material that focuses primarily on carbon nanotubes.

**I. INTRODUCTION**

A carbon nanotube(CNT) is graphite which is rolled into a seamless cylinder. Carbon nanotubes have a wide variety of properties depending on their construction which enables almost boundless different applications given that these properties could become manifest by adequate synthesis techniques.

A singular sheet of graphite which forms a single walled carbon nanotube is a hexagonal or honey comb lattice of which is classically sp2 bonded carbon with 1 double bond for every 2 single bonds. However it is possible to have sp3 bonds when another atom, like hydrogen for instance, is bonded onto the given carbon atom. If symmetry of the hexagonal lattice is broken and have 2 or 3 bonds dedicated to peripheral atoms, while only 1, or 2 dedicated to bonding the original carbon atom to the tube. Also it is possible that different atomic constituents could be substituted into the nanotube in conjunction with different peripheral bonding to widen the properties of nanotubes to a much broader scope than will be discussed further in this resource letter. Multiple graphite sheets can be wrapped into a carbon nanotube forming a multiwalled carbon nanotubes. Traditionally these multiwalled nanotubes have no interlayer covalent bonding and have Van der Waals forces holding the layers of tubes from sliding apart from each other.

Folding of nanotubes depends on the Chiral vector which delineates the line across which the folding occurs. There are 3 types of folding structure armchair, zigzag, and everything else, chiral. In zigzag construction seams form along lines that always go across the hexagonal lattice without going in parallel to any covalent bonds yet go along the long sides of a rectangle formed with shorter rectangular sides which are parallel sides of the hexagon unit cell. In armchair construction the seams form along lines that go along the bonds of the hexagonal lattice for every other lattice site in essence the diagonal to the previously described rectangle. For a precise visualization of these different geometries see the Wikipedia article on carbon nanotubes.

The electrical properties of carbon nanotubes depends on this folding. For chiral vectors (n,m) where n minus m is a multiple of 3 then these carbon nanotubes will have an electronic conductivity on the order of 10-4 Ω-cm at 300 K and are considered metallic. Some small radius single walled nanotubes exhibit the property of a superconductor below 20 K(6.7). Thus armchair nanotubes are more than 10 times more conductive than copper, while zigzag and many chiral nanotubes are semiconductors. Because of their electrical properties these semiconducting nanotubes are N-type FETs but when exposed to slight amounts of oxygen they will become P-type FETs. The right combination of the 2 will enable the production of a not gate which can be used in conjunction with other not gates to enable a CNT computer which if constructed will provide far more processing power than any equally sized silicon computer chips.

The Young’s modulus for single and multi walled carbon nanotubes is above 1000 GPa (6.5), while the tensile strength lies around 150 GPa. In comparison Steel has a Young’s modulus of 208 GPa, and a tensile strength of .4 GPa. In summary CNTs are much much stronger than steel. Not only that but because these CNTs have nanoscopic structure there is no room for dislocations of other imperfections in the lattice structure. So even under extreme stress/strain these CNTs will not sustain any plastic deformations and will return to their native state when the given stress is removed.

Carbon nanotubes are the best thermal conductor that has ever been discovered. They conduct at around 6000 W/m/K where as copper only conducts at 385 W/m/K. Also these structures will remain intact at around 3000 K within a vacuum and around 1000 K within air, an oxygen rich environment.( 6.1)

**II. JOURNALS**

2.1 *Fullerenes, nanotubes and carbon nanostructures*, Marcel Dekker, (2002-). A journal written entirely about the field of carbon nanostructures.

2.2 *Journal of Applied Polymer Science*, Wiley Periodicals. Information on synthesis of plastics, other polymers, and nanostructures.

2.3 *Journal Of Composite Materials*. Sage Journals. Information on composite materials and subsequent design, analysis, testing, performance, and certain applications

2.4 *Nanoscale Research Letters*, Springer, New York. Journal of research letters on anything that is on the scale of angstroms or nanometers.

2.5 *Sensors & Actuators: B. Chemical*, Elsevier. Interdisciplinary journal about the field of chemical sensors, actuators and microsystems.

**III. BOOKS**

3.1 2006 Complete Guide to Nanotechnology, National Nanotechnology Initiative, Nanoscale Science, Nanomaterials, Nanobots, Nanobiotech, Nanotubes, U.S. Government, (Progressive Management, April 22, 2006) The US government’s guide on everything nanotechnological.

3.2 Carbon Nanotubes (NATO Science Series II: Mathematics, Physics and Chemistry), Valentin N. Popov, Philippe Lambin, (Springer, March 30, 2006) A guide to specialists in the field of nanotech research with conventional growth techniques and uses.

3.3 Carbon Nanotubes: Science and Applications, M. Meyyappan, (CRC, July 15, 2004). Provides a comprehensive review on carbon nanotubes with an emphasis on real world growth and potential applications.

3.4 Carbon Nanotubes: Synthesis, Structure, Properties and Applications, R.E. Smalley, Mildred S. Dresselhaus, Gene Dresselhaus, Phaedon Avouris, (Springer, April 20, 2001). A comprehensive review of carbon nanotubes involving reviews of all current research on the subject.

3.5 Carbon Nanotubes and Related Structures, Peter J. F. Harris, (Cambridge University Press, January 15, 2002). A relatively short comprehensive guide to carbon nanotubes and other carbon structures like carbon nanoparticles and inorganic fullerenes.

3.6 Carbon Nanotube Electronics, Ali Javey, Jing Kong, (Springer, May, 2007).Review of carbon nanotubes with a strong emphasis on their varying electrical properties and various electrical applications.

3.7 Understanding Carbon Nanotubes: From Basics to Applications, A. Loiseau, (Springer Verlag GmbH, January 30, 2007) Foundations of Carbon nanotubes with a focus on interdisciplinary applications and specific issues involved with their characterization.

**IV. GENERAL REVIEW ARTICLES**

“Biomolecular nanotechnology”, M. Köhler, Reviews in molecular biotechnology, a section of Journal of biotechnology, v. 82, no. 1 (Nov. 2001) A general review article on nanotechnology as it relates to biosensors.

"Carbon nanotubes", T.W. Ebbesen, Annual Review of Materials Science, vol.24, P235 (1994). General review on nanotubes and subsequent applications.

“Chemical sensors based on nanostructured materials”, X J Huang, Y K Choi, Sensors & Actuators: B. Chemical, vol. 122, no. 2, pp. 659-671, “(26 Mar. 2007). Comprehensive review of nanotubes, nanorods, nanobelts, and nanowires chemical sensors.

“General theory of nano-technology”, K. Yoshihara, Japanese Materials Science and Technology, Vol. 39, no. 5, pp. 169-173. (Oct. 2002). A very brief description of various research in all nanotechnology fields with potential applications for a variety of newly discovered structures including nanotubes, microsprings, and nanodrills.

"Nanotubes from carbon", P.M. Ajayan, Chemical Reviews, vol. 99, P1787 (1999). Another general review on nanotubes and subsequent applications.

**V. SELECTED REVIEW ARTICLES**

5.1 “Directed assembly of highly-organized carbon nanotube architectures”, Pulickel M Ajayan, Ramanath Ganapathiraman, Anyuan Cao, US7189430, 2007. Method for aligning carbon nanotubes to serve as a template to direct growth of carbon nanotubes to tailor desired properties.

5.2 “Field Emission Properties of Carbon Nanotube/Conducting Polymer Composite Thin Film”, Eiji Itoh, Kino Zairyo, Vol. 27, no. 2, pp. 33-39, (Feb. 2007). Discourse on the properties of oxidized carbon nanotubes to be used as field effect transistors.

5.3 “Multiwall-carbon-nanotube-reinforced poly(ethylene terephthalate) nanocomposites by melt compounding”, Jun Young Kim, Hawe Soo Park, Seong Hun Kim, Journal of Applied Polymer Science, Vol. 103, no. 3, pp. 1450-1457, (5 Feb. 2007). Description of strength enhancing properties of carbon nanotubes when melted into plastics.

5.4 “POLYMER-CARBON NANOTUBE COMPOSITE FOR USE AS A SENSOR”, UNIVERSITY OF DAYTON, WO2007033189. Sensor of perpendicularly aligned carbon nanotubes from a polymer composite with 2 electrodes attached to measure a change in conductivity of the composite.

5.5 “Production of Single Walled Carbon Nanotubes In a Reduced Gravity Environment”, Van Cise, Edward A., 1999 Project Final Report, 02 June 1999

<http://data.engin.umich.edu/umseds/kc135/nanotubes/report/FinalReport.htm>

A research producing carbon nanotubes in a reduced gravity environment.

5.6 “Torsional Buckling of Multi-walled Carbon Nanotubes Subjected to Torsional Loads”, X Y Wang, X Wang, Journal Of Reinforced Plastics and Composites, vol. 26, no. 5, pp. 479-494, (Mar. 2007). Investigation in torsional buckling based on the number of interspatial layers and derivation of a single buckling equation when the innermost radius is above a certain value.

**VI. WEB RESOURCES**

6.1 *Carbon nanotube*, Wikipedia, <http://en.wikipedia.org/wiki/Carbon_nanotubes>. Basic overview of carbon nanotubes including basics of folding structure, thermal, mechanical, electronic properties and history. Provides good set of references.

6.2 *The Nanotube Site*, <http://www.pa.msu.edu/cmp/csc/nanotube.html>. An extensive collection of links on carbon nanotubes with include webpages with basic properties of carbon nanotubes and a timeline documenting major advances.

6.3 LeRoy, Brian, PhD, et al. *Carbon Nanotube Electrical Properties,* Delft University of Technology. <http://www.tudelft.nl/live/pagina.jsp?id=e0dd62ef-4af2-459e-aaca-e29a693211ea&lang=en>. Highlights research done at TU Delft on the measurement of electrical properties of nanotubes by connecting them between two leads. Includes citations to the research articles on this topic published by researchers at TU Delft.

6.4 Alex Zettl, *Nanotubes: Superhard, Superstrong, Super Useful* http://www.lbl.gov/Science-Articles/Research-Review/Magazine/2001/Fall/features/02Nanotubes.html . Superficial description of research involving nanotube oxidation to produce field effect transistors and other mechanical contrivances.

6.5 *Basic Properties of Carbon Nanotubes*, <http://www.applied-nanotech.com/cntproperties.htm>. Basic diagrams and specs on the properties of carbon nanotubes.

6.6 *Breakthrough Publications in Carbon Nanotubes,* [http://cobweb.ecn.purdue.edu/~mdasilva/timeline.shtml](http://cobweb.ecn.purdue.edu/%7Emdasilva/timeline.shtml). Carbon nanotubes historical timeline.

6.7 Carbon Nanotubes – Electrical, Thermal, Mechanical and Other Useful Properties of Carbon Nanotubes by Cheap Tubes, <http://www.azonano.com/Details.asp?ArticleID=1564>. Information on electrical conductivity, strength, and FET carbon nanotubes transistors.