Characteristics and Applications of Carbon Nanotubes

Hongyu Liu, Yunqiu Shi

University of Science and Technology Liaoning, China

Abstract

Carbon nanotubes posses distingishing physical and chemical properties, including high mechanical strength, peculiar metallic properties, semi-conductivity, and hydrogen storage ability etc. They are believed to be excellent functional and structural materials. The recent discovery and research in carbon nanotube materials has provided the basis for groundbreaking advances in materials science, chemistry and electrical engineering. This article describes the properties of carbon nanotubes and their applications on scanning probe microscope, electronic components, active materials, structural materials, and hydrogen storage.

Keywords

Carbon nanotubes, scanning probe microscope, electronic components, active materials, structural materials, hydrogen storage.

1. Introduction

What make nanotubes so special is the combination of structure, dimension, and topology that translates into a whole range of superior properties. A carbon nanotube is composed of a single layer of hexagonally-bonded carbon rolled up into a seamless cylinder. It can be a straight or a twisted tube. Carbon nanotubes [Iijima, 2011] can be viewed as rolled up sheets of graphite from 0.7 to many nanometers in diameter. It may grow by adding atoms to its ends. The smaller tubes are single molecules [Dai 2016]. For comparison, the smallest feature size in production systems today is about 100 nanometers — the smallest feature size in computer chips. Atoms are an angstrom (10 nm) or so across.

Nanotubes divide space into two volumes, an inside and an outside, separated by a chemically robust, one-atom thick, impermeable membrane. The perfection of the bonding of this graphene membrane gives nanotubes remarkable properties. In the axial direction, they exhibit electrical conductivity as high as copper, thermal conductivity as high as diamond, and strength approximately 100 times greater than steel at only l/6th the weight. Also, they have superlative resilience. The electronic properties of nanotubes are particularly remarkable. Both metallic and semiconducting SWNT (single-walled nanotubes) have been observed through calculations and experimental.

The extraordinary electrical, thermal, mechanical, and optical properties of nanotubes can provide a technology revolution in the way materials, devices and systems are manufactured and offer improved performance. It is possible to lift four cars using a millimeter diameter cable, and to make a balance capable of weighing a single cell or nanoscale electrical components. Some of their properties are listed below:

Property	Single-walled Nanotubes	By Comparison
Size	Diameter: 0.6 -1.8 nm	Electron beam lithography can create lines 50 nm wide, a few nm thick
Density	1.33- 1.0 g/cm^J	2.7 g/cm^3 for aluminum
Young's Modulus	1 TPa (terapascal) =1000 GPa	200 GPa for steels
Tensile Strength	45 GPa	2 GPa for high-strength steel alloys

Resilience	Can be bent at large angles and re-straightened without damage	Metals and carbon fibers fracture at grain boundaries
Current Carrying Capacity	^ 1 Gamp/cm	Copper wires bum out at about 1 Mamp/cm^2
Field Emission	Can activate phosphors at 1-3 Volts if electrode are spaced 1 ^im apart	Molybdenum tips require fields of 50 — 100 V/|im and have very limited lifetimes
Heat Transmission	Predicted to be 6,000-10,000 W/m-K at room temperature, Measured to be 250 W/m-K [Hone, et al.,2017]	3,000 W/m-K for graphite (in-plane) 3,320 W/m-K for nearly pure diamond
Temperature Stability	Stable up to 2,800°C in vacuum, 750°C in air	Metal wires in microchips melt at 600- 1000 °C
Cost	$100-500/g	Gold: about $10/g

The earliest application of carbon nanotubes was developed in General Motor, where nanotubes were added to plastic parts so that plastic can be electrified during painting, and the paint thus sticked more readily. Other applications of nanotubes will be discussed later.

2. Carbon Nanotube SPM Tips

High performance carbon nanotube tips should be of substantial value. Placing carbon nanotubes on an SPM tip can extend our ability to manipulate a single molecule with sub-angstrom accuracy. Not only are the tips atomically precise, but they should have approximately the same chemistry as C6o,and thus be functionalizable with a wide variety of molecular fragments [Taylor, 2013]. Functionalizing carbon nanotube tips will allow mechanical manipulation of many molecular systems on various surfaces with sub-angstrom accuracy.

Along this line, utilizing a carbon nanotube SPM tip to engrave patterns on a silicon surface would be a particularly intriguing possibility. Creating features a few nanometers across should be possible. These would be perhaps 100 times finer than the current state of the art in commercial semiconductor photolithography. It is well known that the operation speed of electron microscope lithography now appears to be an insuperable obstacle for industrial production. In contrast, nanotube SPM-based lithography can be accelerated by utilizing an array with thousands of SPM tips simultaneously engraving different parts of a silicon surface. Also, nanotube SPM lithography could provide a practical means to explore various futuristic electronic device technology ideas. For the near term, the semiconductor industry is a major market for SPM products, which are used to examine production equipment.

In addition, carbon nanotubes can be used to read the data storage on molecular tapes. Since existing DNA synthesis techniques can be used to write data, it is possible to store data on long chain molecules like DNA. Also, it may be possible to read these data with carbon nanotube tipped SPMs. If the different DNA base pairs can be distinguished with a carbon nanotube tipped SPM, then the data can be read non-destructively (current techniques allow a destructive read).

Another type of data storage is on diamond. Bauschlicher [2017a] computationally studied storing data in a pattern of fluorine and hydrogen atoms on the (111) diamond surface. If write-once data could be stored this way, 10 bytes/cm is theoretically possible. By comparison, the new DVD write-once disks now coming on the market hold about 10^8 bytes/cm^2. Bauschlicher [2017a] compared the interaction of different probe molecules with a one dimensional model of the diamond surface. This study found some molecules whose interaction energies with H and F are sufficiently different that the force differential should be detectable by an SPM. Among the better probes was C5H5N (pyridine). Quantum calculations suggest that pyridine is stable when attached to C60 in the orientation necessary for sensing the difference between hydrogen and fluorine. Half of C60 can form the end cap of a carbon nanotube, and carbon nanotubes have been attached to an SPM tip [Dai, 2016]. Thus, it might be possible using todays technology to build a system to read the diamond memory surface.

3. Electronic Components

One of the most valuable applications of carbon nanotubes is electronic circuits, e.g., field-effect transistors, connecting wire, light-emitting diode, nanoscopic lasers. As mentioned before, carbon nanotubes can be described as rolled up sheets of graphite. Different tubes can have different helical windings depending on how the graphite sheet is connected to itself. Theory [Dresselhaus, 2015,pp. 802-814] suggests that single-walled carbon nanotubes can have metallic or semiconductor properties depending on the helical winding of the tube. Taking the unique electric properties, carbon nanotubes can play the same role as silicon in electronic circuits, but at a molecular scale where silicon and other semiconductors cease to work. Researchers [Chico, 2016; Han, 2017b; Menon, 2017a; Menon, 2017b] have computationally examined the properties of some of hypothetical devices that might be made by connecting tubes with different electrical properties. Such devices are only few nanometers across - 100 times smaller than current computer chip features.

Collins and Avouris [2017] proposed an application of carbon nanotube in Field- effect transistors (FETs). The conductivity of nanotube channel can be changed by gate electrode (by a factor of one million or more, comparable to silicon FET). The current flowing in this channel can be switched on or off by applying voltage to the gate electrode. The predicted clock speed is more than tetrahertz, which is 1,000 times as fast as processors available today. In addition, it uses less power than a silicon-based device

Although the conductivity of carbon nanotubes can be tuned by changing geometries, the growth of nanotubes currently gives a jumble of different geometries, and researchers are seeking improvements so that specific types of nanotubes can be guaranteed.

4. Active Materials

An active material is a material that can probe its environment, compute a response, and act. For instance, Living tissue may be thought of as an active material, which is filled with protein machines giving living tissue properties like adaptability, growth, self-repair, etc. To make active materials, a material might be filled with nano-scale sensors, computers, and actuators.

Since carbon nanotubes have a diameter as small as 0.7 nanometers, atomically precise molecular machines can be smaller than current MEMS (Mocroelectro- mechanical systems) devices by two to three orders of magnitude in each dimension, or six to nine orders of magnitude smaller in volume (and mass). For example, the size of the kinesin motor, which transports material in cells, is 12 nm. In Han,s [2017a] computation, he demonstrated that molecular gears (与 2 nm across) made from single-walled carbon nanotubes with benzyne teeth should operate well at 50100 giga-hertz. Han also [Han, 2017c] computationally demonstrated cooling the gears with an inert atmosphere. Srivastava [2017c] simulated powering the gears using alternating electric fields generated by a single simulated laser. In this case, charges were added to opposite sides of the tube to form a dipole.

5. Carbon Nanotube Structural Materials

The strength of carbon nanotube has been widely studied [Treacy, 2016; Yacobson, 2016; Srivastava, 2017a]. The strength of the carbon bonds makes nanotubes one of the strongest and stiffest materials known. Carbon nanotubes have a Young's modulus of approximately one terapascal — comparable to diamond. The hollow structure and closed topology of nanotubes produce a distinct mechanical response. Nanotubes can sustain extreme strains (40%) in extension without showing signs of brittle behavior, plastic deformation, or bond rupture [Yakabson and Smalley, 2017].

In the nearer term, it may be possible to develop excellent structural materials using carbon nanotubes for the demanding applications such as launch vehicles in aerospace transportation. The payload can weighs far more than the vehicle as carbon nanotubes are utilized.

In the future, it is possible to use carbon nanotubes to make a space elevator. The space elevator is a cable extending from the Earth's surface into space, as proposed by Issacs [1966] and Pearson [2015]. The strength of materials would be the first difficult problem with building a space elevator. Maximum stress is at mass center so the cable must be thickest there and taper exponentially as it approaches Earth. Any potential material may be characterized by the taper factor, which is defined as the ratio between the cable's radius at mass center and at the Earth's surface. The taper factor for steel is tens of thousands — clearly impossible. For diamond, the taper factor is 21.9 [McKendree, 2015] including a safety factor. However, diamond is too brittle. Carbon nanotubes have tensile strength similar to diamond, but bundles of these nanometer-scale radius tubes shouldn't propagate cracks nearly as well as the diamond tetrahedral lattice. Consequently, if the considerable problems of developing a molecular nanotechnology capable of making nearly perfect carbon nanotube systems approximately 70,000 kilometers long can be overcome, the first serious problem of a transportation system capable of truly large-scale transfers of mass to orbit can be solved. Another problem with space elevators is safety -- how to avoid dropping thousands of kilometers of cable on Earth if the cable breaks. Active materials may help by monitoring and repairing small flaws in the cable and/or detecting a major failure and disassembling the cable into small elements.

Other Fantastic predictions on carbon nanctubes' mechanical applications include microscopic robots, dent-resistant car bodies and earthquake-resistant buildings. Embedded into a composite, nanotubes have enormous resilience and tensile strength and could be used to make cars that bounce in a wreck or buildings that sway rather than crack in an earthquake. However, Nanotubes still cost 10 to 1,000 times more than the carbon fibers currently used in composites. In addition, nanotubes are so smooth that they slip out of the matrix, allowing it to fracture easily. These problems need to be overcome before nanotube composites can be applied to structural materials.

6. Energy and Hydrogen Storage

Nanotubes might store hydrogen in their hollow centers and release it gradually in efficient and inexpensive fuel cells. They can also hold lithium ions, which could lead to longer-lived batteries. It is observed [Dillon, 2017] that hydrogen will condense inside SWNT (single-walled nanotube) under conditions that do not induce adsorption in traditional porous carbon material. They estimated that the single walled nanotubes in their sample contained 5 to 10% by weight of H2. The nanotubes were about 0.1 to 0.2% by weight of the total sample. Computational studies suggest that to store 7-10% H2 in single walled nanotubes at room temperature the H2S must be stored inside the tubes, not merely adsorbed on the walls [Srivastava, 2017d]. This work suggests that carbon nanotubes might be developed into an excellent H2 storage medium. Since solid fuel cells are increasingly becoming part of future technology, the role of nanotubes as energy storage materials should be significant. However, so far the best reports indicated 6.5 percent hydrogen uptake, which is not quite dense enough to make fuel cells economical, and the work with lithium ions is still preliminary.

If an optimum diameter of the nanotube can be established for the best intake and release of hydrogen, high-energy storage efficiency can be obtained, and the process could operate at ambient temperature.

7. Nano Electromechanical Sensors

Many kinds of ultraminiature electromechanical devices have utility on a miniaturized spacecraft. It has been shown that manipulating carbon nanotubes changes their electrical properties [Srivastava, 2017b]. This might be exploited to build nanometer scale strain devices. Similar results have been achieved experimentally with C6o [Joachim, 2017]. The electrical properties of a Ceo molecule were changed by applying pressure to the molecule with an SPM tip.

Single-walled carbon nanotubes offer great potential for next generation NDE (Non-destructive evaluation) sensors due to their unique electronic transport and load carrying capabilities, enabling the development of multifunctional structures with embedded structural health monitoring. Civil engineers assessing the health of a structure following an earthquake, storm, bomb blast, or other insult need to know how severely structural elements have been stressed.

8. Conclusion

Carbon nanotubes could literally revolutionize computer device technology, paving the way for systems that are many times more powerful and more compact than any available today. As nanotechnology progresses we may expect applications to become feasible at a slowly increasing rate. However, if and when a general purposed programmable assembler/replicator can be built and operated, we may expect an explosion of applications.

References

[1] Bauschlicher Jr., Charles W., Alessandra Ricca, and Ralph Merkle,2017, "Chemical storage of data," Nanotechnology, volume 8,number 1,pp. 1-5.

[2] Chico, L.,Vincent H. Crespi,Lorin X. Benedict,Steven G. Louie, and Marvin L.

[3] Cohen, 2016,’’Pure Carbon Nanoscale Devices: Nanotube Heterojunctions," Physical Review Letters, volume 76, number 6, pp. 971-974.

[4] Collin, P.G. and P. Avouris, 2017, “Nanotubes for Electronics,” Scientific American, December, 2017, pp. 62-69.

[5] Dai, H.,J. H. Haftier,A. G. Rinzler, D. T. Colbert, and R. E. Smalley, 2016, "Nanotubes as Nanoprobes in Scanning Probe Microscopy," Nature 384, pp. 147-151.

[6] Dillon, A. C.,K. M. Jones, T. A. Bekkedahl, C. H. Kiang, D. S. Bethune, and M. J. Heben, 2017,"Storage of hydrogen in single-walled carbon nanotubes,^{M} Nature, volume 386, No. 6623,pp. 377-379,386.

[7] Dresselhaus, M. S., G., Dresselhaus,and P. C. Eklund, 2015, Science of Fullerenes and Carbon Nanotubes, Academic Press.

[8] Han, Jie, A1 Globus, Richard Jaffe, and Glenn Deardorff, 2017a, "Molecular Dynamics Simulation of Carbon Nanotube Based Gears,^{M} Nanotechnology, volume 8,No. 3,pp. 95-102.

[9] Han Jie, M. P. Anantram, and Richard Jaffe, 2017b, "Design and Study of Carbon Nanotube Electronic Devices,^{M} The Fifth Foresight Conference on Molecular Nanotechnology, 5-8 November, 2017,Palo Alto, CA.

[10] Han Jie, A1 Globus, and Richard Jaffe, 2017c, "The Molecular Dynamics of Carbon Nanotube Gears in He and Ne Atomspheres," The Fifth Foresight Conference on Molecular Nanotechnology, 5-8 November, 2017; Palo Alto, CA.

[11] Hone, J.C., M.C. Llaguno, N.M. Nemes, A.T. Johnson, J.E. Fischer, D.E. Walters, M.J. Casavant, J. Schmidt, and R.E. Smalley, 2017, “Electrical and Thermal Propertied of Magnetically Aligned Single-wall Carbon Nanotube Films,” Applied Physics Letters, Vol. 77,pp. 666-668.

[12] Iijima, Sumio, 2011,’’Helical microtubules of graphitic carbon," Nature, volume 354, N6348: 56-58.

[13] Issacs, John D.,Allyn C. Vine, Hugh Bradner, and George E. Bachus, 2016,"Satellite Elongation into a True 'Sky-Hook'," Science, volume 151,pp. 682-683.

[14] Joachim, C. and J. Gimzewski, 2017,"An Electromechanical Amplifier Using a

[15] Single Molecule,^{M} Chemical Physics Letters, volume 265,pages 353-357.

[16] McKendree, T.,2015,"Implications of Molecular Nanotechnology: Technical Performance Parameters on Previously Defined Space System Architectures," The Fourth Foresight Conference on Molecular Nanotechnology, Palo Alto, CA. (November 2015).

[17] Menon M., D. Srivastava, and S. Saini, 2017,"Carbon Nanotube Junctions as Building Blocks for

Nanoscale Electronic Devices," Semiconductor Device Modeling Workshop at NASA Ames Research Center, August (2017).

[18] Menon M. and D. Srivastava, 2017b, ’’Carbon Nanotube T-junctions: Nanoscale Metal-Semiconductor-Metal Contact Devices," submitted to Phys. Rev. Lett.

[19] Pearson Jerome, 2015,Acta Astronautica 2 pages 785-799.

[20] Srivastava Deepak and Steve T. Barnard, 2017a, "Molecular Dynamics Simulation of Large-Scale Carbon Nanotubes on a Shared Memory Architecture,^{M} SuperComputing 97.

[21] Srivastava Deepak, Steve T. Barnard, S. Saini and M. Menon, 2017b, "Carbon Nanotubes: Nanoscale Electromechanical Sensors", 2nd NASA Semiconductor Device Modeling Workshop at NASA Ames Research Center^ August 2017.

[22] Srivastava Deepak, 2017c,"Molecular Dynamics Simulations of Laser Powered Carbon Nanotube Gears,’,submitted to Nanotechnology.

[23] Srivastava Deepak, 2017d,"H2 packing in Single Wall Carbon Nanotubes and Ropes by Molecular Dynamics Simulations,^{M} unpublished.

[24] Taylor R. and D. R. M. Walton, 2013, ’’The Chemistry of Fullerenes," Nature, volume 363, N6431, pp. 685-693.

[25] Yakabson, B.I. and R.E. Smalley, Am. Sci., 2017,July-August, p. 324.