da Vinci's notebook

*da Vinci's Notebook,* vol. 3 (2011)

# Single Walled Carbon Nanotubes as Quantum Wires

Matt Smyth
First-Year Student (B.Sc. Nanoscience)
College of Physical and Engineering Science, University of Guelph, CANADA

Quantum wires, or nanowires, are single strands of molecules that are electrically conductive under the influence of quantum effects. Carbon nanotubes have proven to make excellent quantum wires due to their high conductivity, small mass and size as well as being extremely strong. These carbon nanotubes are made up of rolled up sheets of graphene, having diameters as small as 1 nanometer (Dekker, 1999). The electrical properties of the carbon nanotubes can vary, with some showing metallic properties and others acting as semiconductors (Biercuk, Ilani, Marcus, & McEuen, 2008). The conductive properties of the nanotubes are determined most intimately by the diameter and the chirality of the tube (Dekker, 1999). This paper will look at these physical and electrical properties of carbon nanotubes and why they are excellent specimens of quantum wires.

The first nanotubes were discovered in 1991 by Japanese scientist Sumio Iijima, using an evaporation method. In this method of synthesis, an electric current is directed through two graphite electrodes in a helium atmosphere. The graphite evaporates and the nanotubes form on the surface of the cathode (Harris, 2010). The first nanotubes were multiple layers thick and were closed at both ends. In 1993, nanotubes with only a single wall layer were synthesized, and their valuable unique properties were discovered soon after (Harris, 2010). Besides the evaporation method, carbon nanotubes can be “grown” via decomposition of organic gas over a metal-covered substrate. The metal, usually iron or nickle, acts as a catalyst in the reaction (Dekker, 1999). A third method of carbon nanotube production is using a laser to vaporize the graphite (Harris, 2010). Each method has different costs and product yields and all are used as a universal method has not yet been discovered.

Graphene itself is a sheet of carbon atoms in a hexagonal formation and is only one atom thick (Dumé, 2010). The strength and orientation of the carbon bonds makes graphene (nanotubes) one of the strongest fibers known to man. Its stiffness has been measured to be about five times that of steel and its tensile strength fifty times stronger than steel (Harris, 2010). This strength, in such a lightweight material, has a number of very useful applications. There are three basic ways in which the graphene sheet will roll into a nanotube. Two ways are symmetrical in that the tubes roll either parallel or perpendicular to one side of the hexagonal shapes. These types of nanotubes are referred to as “zig zag” and “armchair” arrangements (Harris, 2010). In the third rolling arrangement, the most common of the three is the chiral arrangement. In this case, the tube is rolled on an angle, relative to the hexagonal shapes formed by the carbon bonds. The specific ways in which the tubes are rolled can be classed as a vector, which is related to the diameter and circumference of the tube (Harris, 2010).

Apart from their unique physical and mechanical properties, carbon nanotubes have electrical properties that make them excellent quantum wires. The quantized nature of carbon nanotubes affects the band structure of the tubes, made up of multiple one dimensional sub-bands (Tans et al., 1997). Band structure refers to the quantized bands or spaces moving along the surface of the material that the electrons are able or not able to pass through. One of the most surprising and unique characteristics of the nanotubes is that their electrons are distributed along the length of the tube. In a single row of atoms, the smallest defect in the chain can alter the electronic properties, causing the electrons to localize. In the carbon nanotubes, any defect can be shared over the whole circumference of the tube (Dekker, 1999). A carbon nanotube's separate sub-bands make this possible by allowing multiple paths and energies for the electrons to travel along. It is similar to having a two-lane highway where each lane is used for or allows a slightly different speed or energy level. In this way, carbon nanotubes have the benefits of one dimensional sub-bands, as well as a delocalized electron arrangement, allowing for better conductivity. Nanotubes can be divided into three classes based on their electronic properties, and the magnitude of their band-gap. Semiconducting and small-band gap nanotubes have band-gaps that cause resistance to electrons moving along the one dimensional sub-bands. These gaps, or holes are generally due to any twists or strain on the structure. Metallic tubes, being very rare are the most conductive due to little or no band-gaps (Biercuk et al*.*, 2008). Combined with multiple one dimensional sub-bands that carry current, the small or

*da Vinci's Notebook* (ISSN 1923-5720) is sponsored by the
College of Physical and Engineering Science, University of Guelph, Canada.

even absent band-gaps in metallic nanotubes gives way to conductivity higher than copper (Harris, 2010).

Since these unique properties of nanotubes were first discovered, there has been huge interest in the research and development of quantum wires. Although we have discovered multiple ways to synthesize nanotubes, scientists are still learning how to manipulate them in ways that will be useful. Carbon nanotubes are already being used in applications like flat panel displays, scanning probe microscopes and sensing devices (Harris, 2010). There are many other future applications of nanotubes that are currently in research and development. Nanotubes are lightweight and very strong making them ideal for reinforcing and building vehicles and aircraft. This same property may prove useful in energy producing machinery such as windmills. The light weight of the nanotubes allows for longer windmill arms, decreasing energy input and increasing energy output. Perhaps carbon nanotubes' most prominent future application however is in the electronics industry. Nanotube quantum wires acting as transistors and wires will allow for the progression and dominance of small scale electronics (Duan, Huang, Cui, Wang, & Lieber*,* 2001).

Recently, a new process for synthesizing quantum wires has been discovered involving "writing" the wires onto a sheet of graphene oxide. Graphene oxide is an insulator, however when heated, returns to its conductive state as graphene. Using this idea, Paul Sheehan and colleagues have been able to "write" graphene wires onto the graphene oxide using a hot AFM tip (as cited in Dumé, 2010). This allows current to flow through the narrow lines of graphene while the remainder of the sheet, the graphene oxide, remains an insulator. This process has been called thermochemical nanolithography (Dumé, 2010).

Nanotubes have been found to be excellent specimens of quantum wires. Their exceptional physical and electronic properties make them a key area of research and development in nanoscience due to their numerous applications. Nanotubes are becoming *more* efficiently and cost effectively made, broadening their range on the consumer and industrial market. Nanotubes have made their way into commercial and consumer products, however, have not completely boomed yet because the cost of making them is still very high (Harris, 2010). As we continue to find ways of manipulating and controlling the amazing properties of nanotubes and graphene, quantum wires will become more popular in the electronics industry.

## References

Biercuk, M. J., Ilani, S., Marcus, C. M., & McEuen, P. L. (2008). Electrical transport in single-wall carbon nanotubes. *Topics in Applied Physics, 111*, 455-493. doi: 10.1007/978-3-540-72865-8_15

Dekker, C. (1999). Carbon nanotubes as molecular quantum wires*, Physics Today, 52*(5), 22-28. doi: 10.1063/1.882658

Duan, X., Huang, Y., Cui, Y., Wang, J., & Lieber, C. M. (2001). Indium phosphide nanowires as building blocks for nanoscale electronic and optoelectronic devices. *Nature, 409*, 66-69. doi:10.1038/35051047

Dumé, B. (2010). AFM tip "writes" graphene nanowires. Retrieved from http://nanotechweb.org/cws/article/tech/42892

Harris, P. (2010). *Carbon nanotube science and technology*. Retrieved from http://www.personal.reading.ac.uk/~scsharip/tubes.htm

Tans, S. J., Devoret, M. H., Dai, H., Thess, A., Smalley, R. E., Geerligs, L. J., & Dekker, C. (1997). Individual single-wall carbon nanotubes as quantum wires. *Nature, 386*, 474-477. doi: 10.1038/386474a0