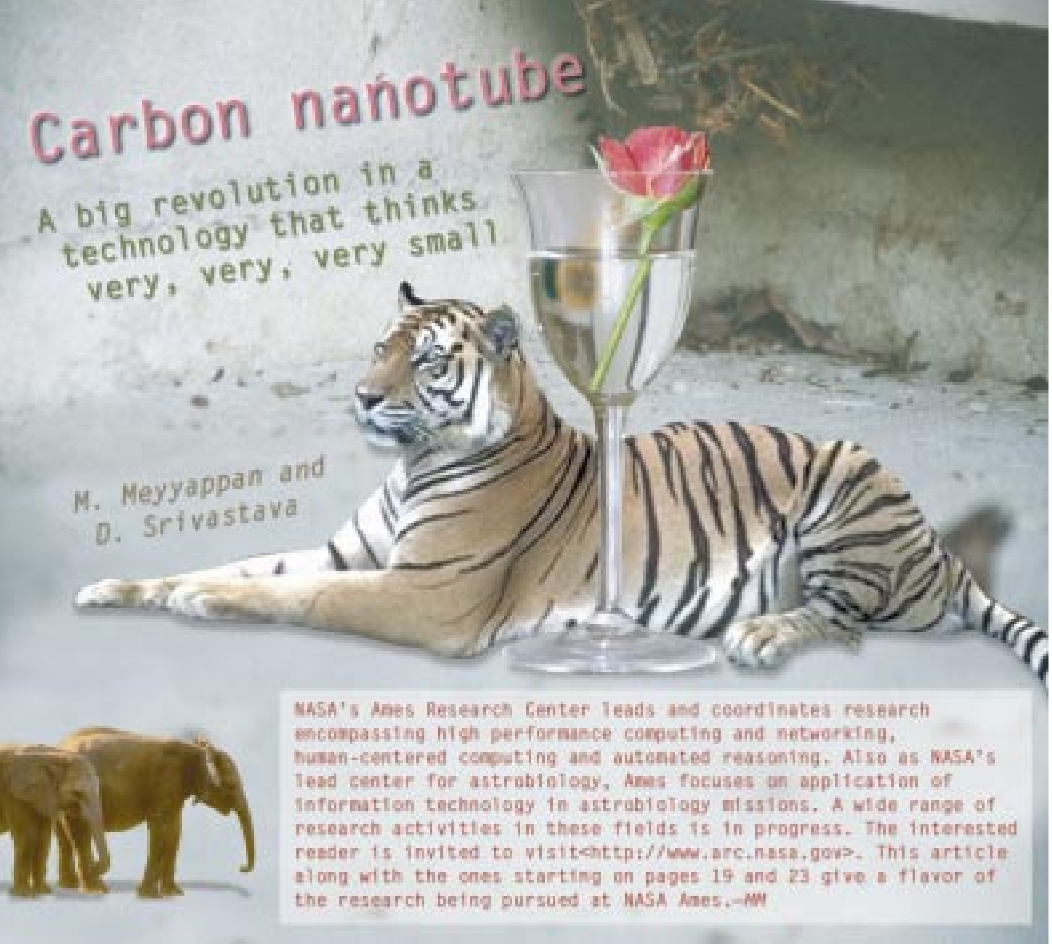

Nanotechnology relates to the creation of devices, structures and systems whose size ranges from 1 to 100 nanometers (nm). These creations also exhibit novel physical, chemical or biological properties because of their nanoscale size. To place their size in context, 1 nm is 10,000 times smaller than the thickness of one strand of human hair.

A famous lecture in 1959 by Nobel Prize winning physicist Richard Feynman was titled, "There is plenty of room at the bottom." That lecture was meant to stimulate new discoveries and capabilities at the atomic and molecular scale. However, not much happened until the 1980s when the scanning tunneling microscope and other sophisticated instruments emerged. We then started to explore the atomic scale world in a real sense.

The last decade has seen significant progress in every aspect of nanotechnology: nanoparticles and powders; nanolayers and coatings; electrical, optical and mechanical nanodevices; and nanostructured biological materials. Nanotechnology's impact is going to be felt in the next 20 to 30 years in all economic areas of science and technology: information technology, medicine and health, materials and manufacturing, aeronautics and space exploration, energy and environment, and transportation and national security. We will focus on just one of the several promising areas called Carbon Nanotubes (CNT).

What are carbon nanotubes?

A carbon nanotube is a tubular form of carbon with a diameter as small as 1 nm. The length can be from a few nanometers to several microns. (One micron is equal to 1,000 nanometers.) It is made of only carbon atoms.

To understand the CNT's structure, it helps to imagine folding a two-dimensional graphene sheet. Depending on the dimensions of the sheet and how it is folded, several variations of nanotubes can arise. Also, just like the single or the multilayer nature of graphene sheets, the resulting tubes may be a single- or a multiwall type.

The tube's orientation is denoted by a roll-up vector (see Fig. 1) $\mathbf{c} = n\mathbf{a} + m\mathbf{b}$. Along this vector, the graphene sheet is rolled into a tubular form. The **a** and **b** are vectors defining a unit cell in the planer graphene sheet, n and m are integers, and θ is the angle.

A variety of tubes—based on the orientations of the benzyne rings on the graphene tube—are possible. If the orientation is parallel to the tube axis, then the resulting "zigzag" tubes are semiconductors. When the orientation is perpendicular to the tube axis, the corresponding "arm chair" tubes are metallic. In between the two extremes, when (n-m)/3 is an integer, the nanotubes are semimetallic.

The two key parameters, the diameter d and the chiral angle θ, are related to (n,m) by $d = 0.078\sqrt{n^2 + nm + m^2}$, $\theta = \arctan[\sqrt{3}m/(m + 2n)]$. For example, a (10,10) nanotube is 1.35 nm in diameter whereas a (10,0) tube is 0.78 nm in diameter.

Carbon nanotubes exhibit extraordinary mechanical properties as well. For example, the Young's modulus is typically over 1 Tera Pascal. Also, the nanotube along the axis is as stiff as a diamond. The estimated tensile strength is about 200 Gpa, which is an order of magnitude higher than that of any other material.

Here we are mainly interested in carbon nanotube's electronic behavior and applications. The metallic and semiconducting nature described previously has given rise to the possibilities of metal-semiconductor or semiconductor-semiconductor junctions. These junctions may form nanoelectronic devices based entirely on single atomic species such as carbon.

Growth and processing

Sumio Iijima of NEC Corporation was the first to grow carbon nanotubes. He used a dc arc discharge in argon consisting of a set of carbon electrodes. The discharge temperature was in the range of 2000-3000 degrees C at nominal conditions of 100 Amps and 20 volts. This apparatus produced multiwall nanotubes in the soot.

Later, Nobel Laureate Richard Smalley and his group at Rice University (TX) pioneered a laser ablation technique to produce single wall CNTs. In this process, a quartz tube is heated to about 1200 degrees C in a furnace. Within the furnace, an argon flow at sub-atmospheric pressure is maintained. The tube contains a block of graphite compressed with small amounts of a transition metal catalyst. The laser is used to vaporize the graphite.

The nanotubes nucleate in the vapor

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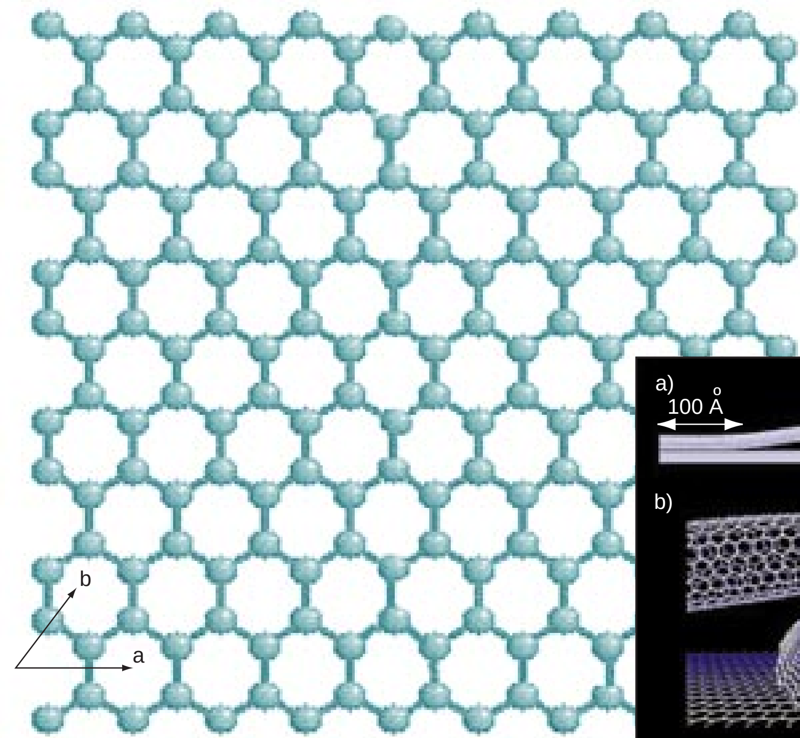
phase, coalesce, get carried away by the flowing argon and condense downstream on the cooler walls of the quartz tube. The felt-like material, when scraped off the wall, contains single wall nanotubes mixed with graphite and metal particles. Many purification methods have been developed to extract high yield samples of single- and multiwall nanotubes.



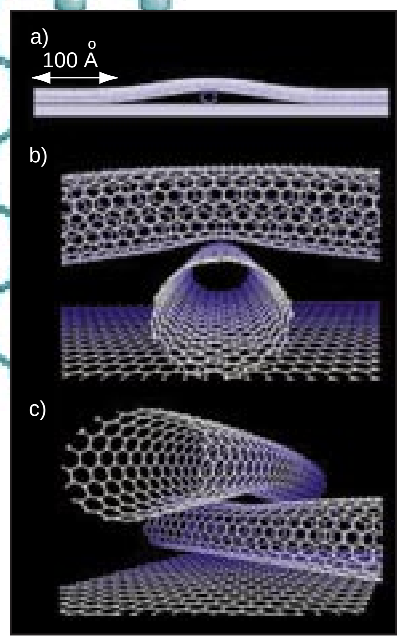


***Fig. 1** Two-dimensional sheet of graphene. A two-dimensional roll-up vector (n,m) defines the number of steps taken in each direction (a,b) in the formation of the nanotube. (Inset: carbon nanotubes courtesy of IBM)*

These approaches, in principle, can lead to components of nanoelectronics grown literally in a bottle. However, many groups have recently opted for a Chemical Vapor Deposition (CVD) approach to grow CNTs on a variety of substrates. For example, nanotubes can be grown on patterned substrates as well as on interconnects of nanometer scale separated by metallic islands. The CVD approach is amenable to further processing by well-known silicon device fabrication techniques. Regardless of the approach, however, currently there are no ways to control the diameter or the type of nanotubes.

CNT-based electronics

CMOS chips, which form the basis of the digital revolution, have gate lengths of 250 nm in production now. The Semiconductor Industry Association (SIA) roadmap projects 70 nm feature-size devices by the year 2007. Beyond that, the future of silicon-based electronics is not clear.

The laws of quantum mechanics may prevent further miniaturization of the CMOS chip below the 50 nm gate length. Manufacturing issues related to lithography, interconnects and such may also make further miniaturization difficult and uneconomical.

As mentioned earlier, CNTs can be a metallic or a semiconducting type. Recent developments at Rice University, and groups at Stanford and Berkeley (CA), have shown that the conductivity of nanotubes changes significantly with the adsorption or the functionalization of chemical reactants on the sidewalls.

For example, functionalization of nanotubes with fluorine (F) atoms on the sidewall can lower the conductivity of a metallic tube to the levels of an insulator. In addition, heteroatomic nanotubes—due to substitutional doping with boron (B) and nitrogen (N) on the sidewalls—are also possible. They can engineer the electronic band-gap varying from 0 for a pure metallic type to about 5eV for an insulator type.

All these possibilities can lead to a wide spectrum of electronic characteristics with nanoscale devices of various types. For example, two- and three-terminal nanotube heterojunctions have been proposed which form nanoscale tunnel junctions as models for switching and transistor devices (see Fig. 3). These were constructed by introducing topological defects such as pentagon (five) and heptagon (seven) member rings in, otherwise, all hexagon (six) based tubular graphene layers.

Heterojunctions based on partial chemical functionalization and/or substitutional doping may also be possible. They will require localized functionalization or doping of nanotubes in desired shapes and patterns. A mechanical deformation or kink-catalyzed chemistry of sidewalls has been recently proposed. It may be useful in decorating the nanotubes with many desired shapes and patterns on the sidewalls.

Lastly, electronic properties can also be tailored through mechanical deformations as well, i.e., axial compression/elongation, bending and twisting of the nanotubes. The remarkable combination of electronic and mechanical properties of CNTs discussed previously has the potential for revolutionary electronics devices as well as NanoElectroMechanical Systems (NEMS).

Theoretical models and high fidelity simulations have helped us to discover the potential of nanotubes in various applications. Experimental research that demonstrates these ideas has been emerging from various laboratories around the world. The strong metallic nature of armchair nanotubes has been shown to be ideal for one-dimensional molecular quantum wires for nanoscale interconnects. The nanotubes can also carry a very high current density (10^7 - 10^9 A/cm^2).

Researchers from Delft University (The Netherlands) and IBM have fabricated the first molecular size Field Effect Transistor (FET) using a carbon nanotube and have also demonstrated room temperature operation. The conductance of the transistor was modulated by more than five orders of magnitude by varying the gate voltage. These revelations are just the beginning for CNT-based molecular electronics.

Other applications

Carbon nanotube is a good field emission electron source. Because of its small radius of curvature at the tip, the CNT can readily emit electrons under a moderate electric field. Yahachi Saito's group at Mie University (Japan) has demonstrated cathode ray tube-lighting elements and vacuum fluorescent display flat panels using nanotube field emitters.

The carbon nanotube has also been successfully used as a tip in Scanning Probe Microscopy (SPM). An SPM-based nanolithography is capable of producing nanometer scale patterns on silicon. The nanometer size and the robust nature of the CNT tips also can be exploited in developing the next generation profilometers to map the patterns on wafers in integrated circuit manufacturing. The future for carbon nanotubes appears to be very bright with applications in nanoelectronics, sensors, instrumentation, NEMS and high strength composites.

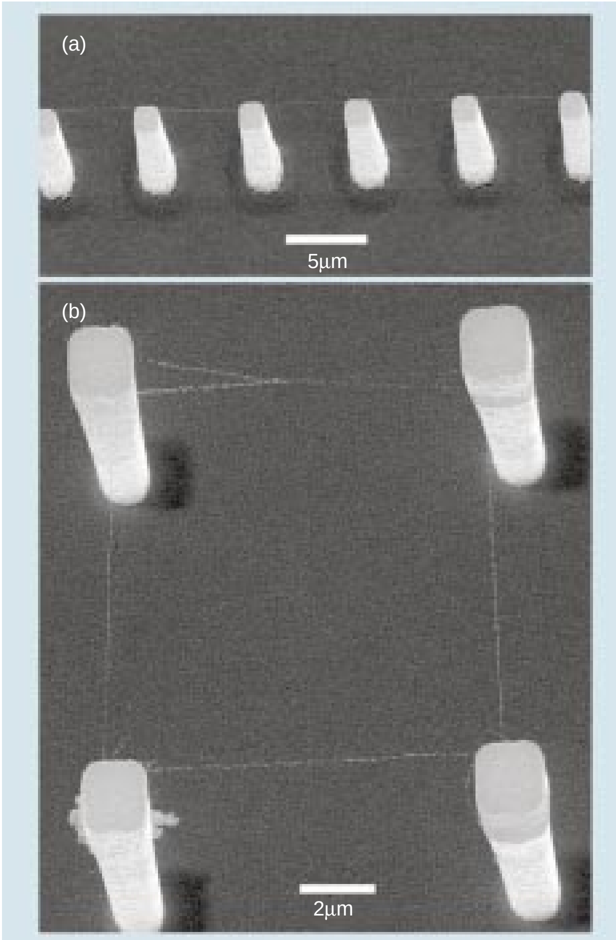


Fig. 2 Carbon nanotube "suspended bridge" between two contacts grown by chemical vapor deposition (courtesy: A. Cassell and H. Dai)

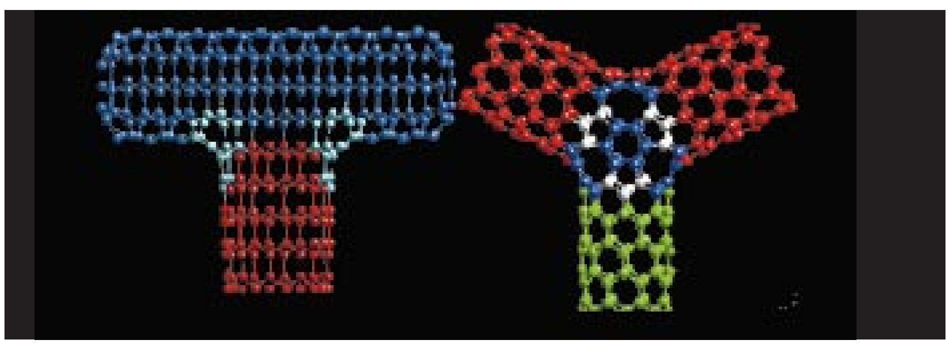


Fig. 3 Carbon nanotube metal-semiconductor-metal T junction and carbon nanotube Y junction

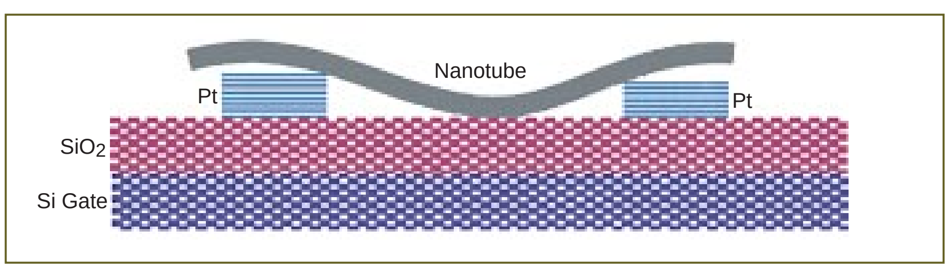


Fig. 4 Carbon nanotube molecular field effect transistor

Read more about it

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Deepak Srivastava's primary research interests are in simulation-based prototyping of nanoscale materials for nanoelectronics, mechanical and sensing device applications. He has authored or co-authored about 40 papers including more than a dozen on carbon nanotubes and nanotechnology. He was the 1997 co-winner of Feynman Prize (Theory) in molecular nanotechnology awarded by the Foresight Institute.