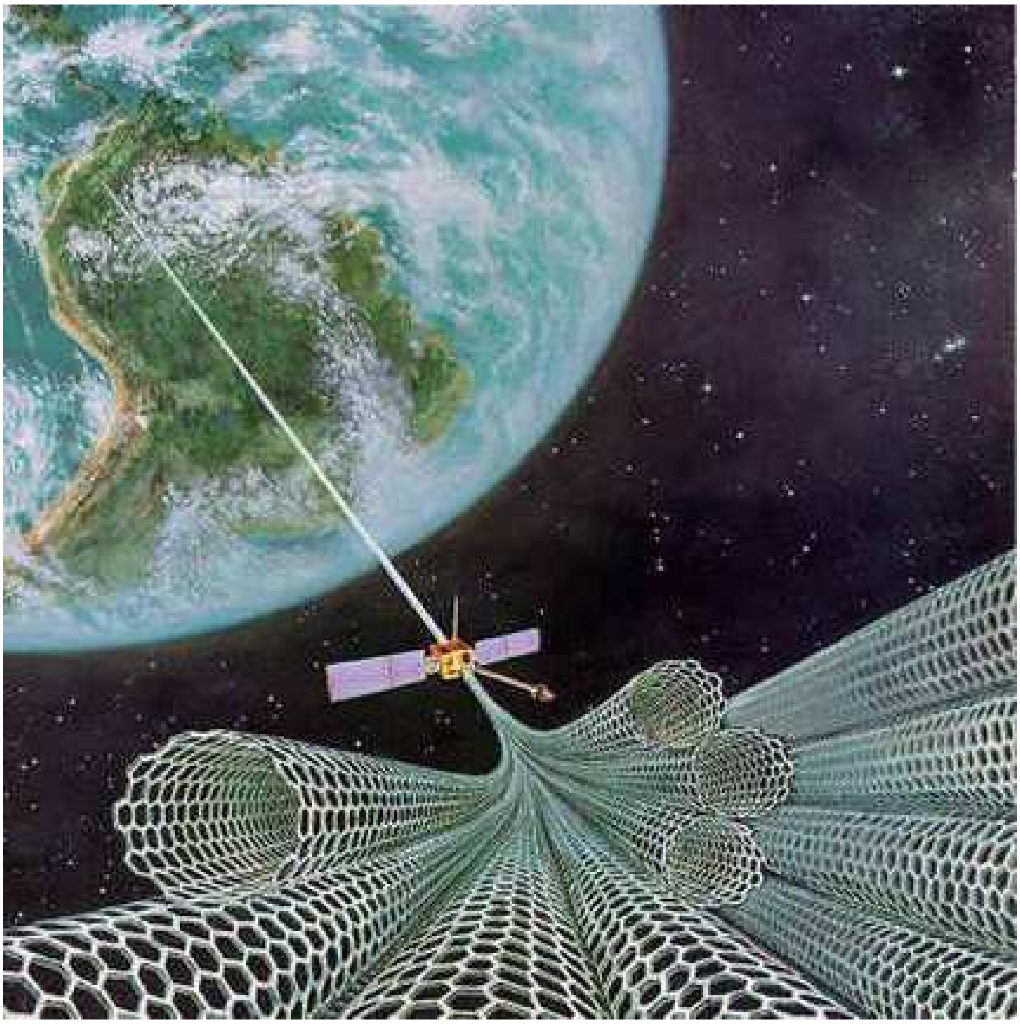
Properties and applications of carbon nanotubes

Project Work
FY 3114
By
Sanjay Kumar Karna
Physics Department, NTNU



Submitted to
Prof. Randi Holmestad
Physics Department, NTNU

Preface

Marvelous properties of carbon nanotube attracted my attention to do my project report on this topics. I am very much interested towards the properties and the applications of carbon nanotube. So I chose this topics for the project work for Functional material (FY 3114). I found numerous properties and applications of carbon nanotube in the websites. So I have studied and taken most of the references from the internet website.

I want to thanks Prof. Randi Holmestad for instructing me and providing me a lot of information about the project writing techniques.

Thanks
Sanjay Kumar Karna
Trondheim, 2007

Abstract

After the discovery of carbon nanotube in 1991 by Iijima, they have been of great interest, both from a fundamental point of view and for future applications. Most of the important features of these structures are their electronic, mechanical, optical and chemical characteristics, which open a way to future applications. These properties can even be measured on single nanotubes.

Different types of carbon nanotubes can be produced in various ways. The most common techniques used nowadays are: arc discharge, laser ablation, chemical vapour deposition and flame synthesis.

Fundamental and practical nanotube researches have shown possible applications in the fields of energy storage, molecular electronics, nanomechanic devices, and composite materials. Real applications are still under development.

This report provides an overview of current nanotube technology, with a special focus on synthesis and energy storage in nanotubes and molecular electronics. CNTs have also proven to be good field emitters and single molecule transistors. The characteristics of and the production techniques for these devices are briefly presented.

List of abbreviations

CNT	Carbon nanotube
SWCNT	Single-walled carbon nanotube
MWCNT	Multi-walled carbon nanotube
TEM	Transmission electron microscopy
AFM	Atomic force microscopy

1.0 Introduction

Nanotubes are members of the fullerene structural family, which also includes buckyballs. Whereas buckyballs are spherical in shape, a nanotube is cylindrical, with at least one end typically capped with a hemisphere of the buckyball structure. Their name is derived from their size, since the diameter of a nanotube is on the order of a few nanometers (approximately 50,000 times smaller than the width of a human hair), while they can be up to several millimeters in length. Researchers at the University of Cincinnati (UC) have developed a process to build extremely long aligned carbon nanotube arrays. They've been able to produce 18-mm-long carbon nanotubes which might be spun into nanofibers. There are two main types of nanotubes: single-walled nanotubes (SWNTs) and multi-walled nanotubes (MWNTs).

The discovery of fullerenes by Harold Kroto of Sussex University in the UK and Richard Smalley and co-workers at Rice University in the US stimulated researchers to explore carbon filaments further. Indeed, the realization that the ends of carbon nanotubes must be fullerene-like "caps" explained the fact that the diameter of a carbon nanotube could only be as small as a fullerene molecule.

The nature of the bonding of a nanotube is described by applied quantum chemistry, specifically, orbital hybridization. The chemical bonding of nanotubes are composed entirely of sp^2 bonds, similar to those of graphite. This bonding structure, which is stronger than the sp^3 bonds found in diamond, provides the molecules with their unique strength. Nanotubes naturally align themselves into "ropes" held together by Van der Waals forces. Under high pressure, nanotubes can merge together, trading some sp^2 bonds for sp^3 bonds, giving great possibility for producing strong, unlimited-length wires through high-pressure nanotube linking.

Theory suggests that carbon nanotubes have a variety of useful properties, and experiments to test these redictions are just becoming possible.

Carbon nanotubes are unique nanostructures with remarkable electronic and mechanical properties. Interest from the research community first focused on their exotic electronic properties, since nanotubes can be considered as prototypes for a one-dimensional quantum wire. As other useful properties have been discovered, particularly strength, interest has grown in potential applications. Carbon nanotubes could be used, for example, in nanometre-sized electronics or to strengthen polymer materials.

An ideal nanotube can be thought of as a hexagonal network of carbon atoms that has been rolled up to make a seamless cylinder. Just a nanometre across, the cylinder can be tens of microns long, and each end is "capped" with half of a fullerene molecule. Single-wall nanotubes can be thought of as the fundamental cylindrical structure, and these form the building blocks of both multi-wall nanotubes and the ordered arrays of single-wall nanotubes called ropes. Many theoretical studies have predicted the properties of single-wall nanotubes.

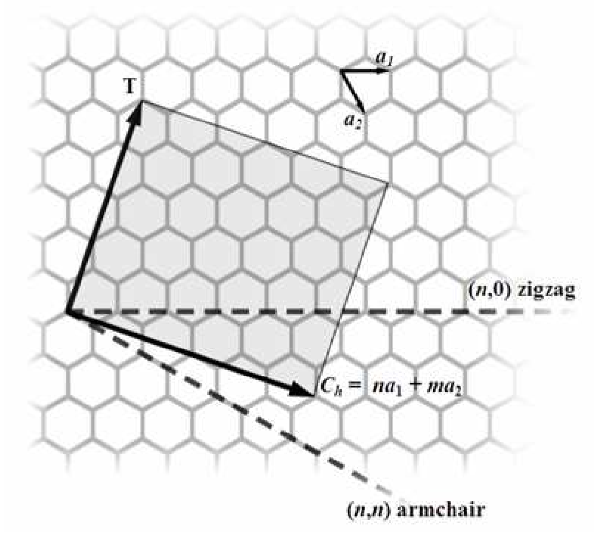


Figure 1.1 Geometry of Grephene sheet

Although Iijima's first observations were of multi-wall nanotubes, he observed single-wall carbon nanotubes less than two years later, as did Donald Bethune and colleagues at IBM Almaden in California. In 1996 the Rice group, led by Smalley, synthesized bundles of aligned single-wall carbon nanotubes for the first time. The bundles contained many nanotubes with a narrow distribution of diameters, making it possible to perform experiments relevant to one-dimensional quantum physics. Several groups have now measured some of these remarkable properties, which seem to confirm many of the theoretical predictions.

1.1 Fullerenes

In fact, what had been discovered was not just a single new molecule but an infinite class of new molecules: the fullerenes. Each fullerene – C_{60}, C_{70}, C_{84}, etc. – possessed the essential characteristic of being a pure carbon cage, each atom bonded to three others as in graphite. Unlike graphite, every fullerene has exactly 12 pentagonal faces with a varying number of hexagonal faces (e.g., buckyball – C_{60} – has 20).

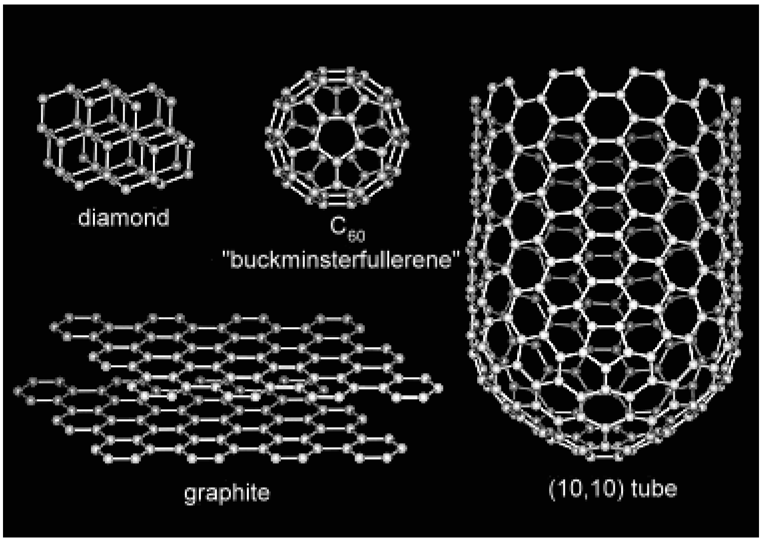


Fig. 1.2 Various forms of fullerenes

Some fullerenes, like C_{60}, were spheroidal in shape, and others, like C_{70}, were oblong like a rugby ball. Dr. Richard Smalley recognized in 1990 that, in principle, a tubular fullerene should be possible, capped at each end, for example, by the two hemispheres of C_{60}, connected by a straight segment of tube, with only hexagonal units in its structure. Millie Dresselhaus, upon hearing of this concept, dubbed these imagined objects “buckytubes.”

1.2 Carbon Nanotubes

1.21 Single wall carbon nanotube

A single wall carbon nanotube is a one-atom thick sheet of graphite (called graphene) rolled up into a seamless cylinder with diameter of the order of a nanometer. This results in a nanostructure where the length-to-diameter ratio exceeds 10,000. Such cylindrical carbon molecules have novel properties that make them potentially useful in a wide variety of applications in nanotechnology, electronics, optics and other fields of materials science. They exhibit extraordinary strength and unique electrical properties, and are efficient conductors of heat. Inorganic nanotubes have also been synthesized.

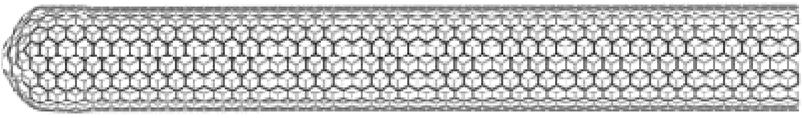


Figure 1.3 Buckytube or carbon nanotube

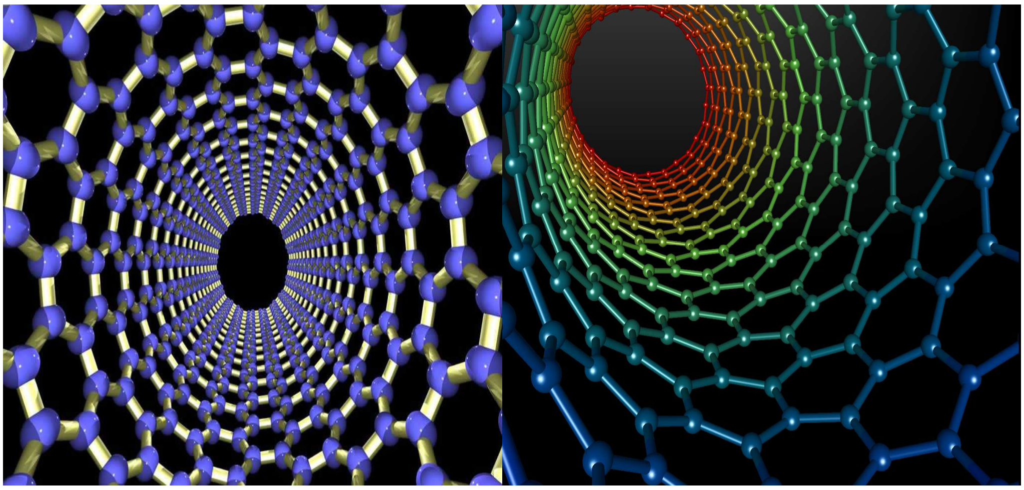


Fig. 1.4 Single walled carbon nanotube

1.22 Multiwall carbon nanotube

Multi-walled nanotubes (MWNT) consist of multiple layers of graphite rolled in on themselves to form a tube shape. There are two models which can be used to describe the structures of multi-walled nanotubes. In the *Russian Doll* model, sheets of graphite are arranged in concentric cylinders, e.g. a (0,8) single-walled nanotube (SWNT) within a larger (0,10) single-walled nanotube. In the *Parchment* model, a single sheet of graphite is rolled in around itself, resembling a scroll of parchment or a rolled up newspaper. The interlayer distance in multi-walled nanotubes is close to the distance between graphene layers in graphite, approximately 3.3 Å. The special place of double-walled Carbon Nanotubes (DWNT) must be emphasized here because they combine very similar morphology and properties as compared to SWNT, while improving significantly their resistance to chemicals. This is especially important when functionalisation is required (this means grafting of chemical functions at the surface of the nanotubes) to add new properties to the CNT. In the case of SWNT, covalent functionalisation will break some C=C double bonds, leaving "holes" in the structure on the nanotube and thus modifying both its mechanical and electrical properties. In the case of DWNT, only the outer wall is modified. DWNT synthesis on the gram-scale was first proposed in 2003 by the CCVD technique, from the selective reduction of oxides solid solutions in methane and hydrogen. Multi Walled Nanotubes (MWNT) can be considered as a collection of concentric SWNTs with different diameters. The length and diameter of these structures differ a lot from those of SWNTs and, of course, their properties are also very different.

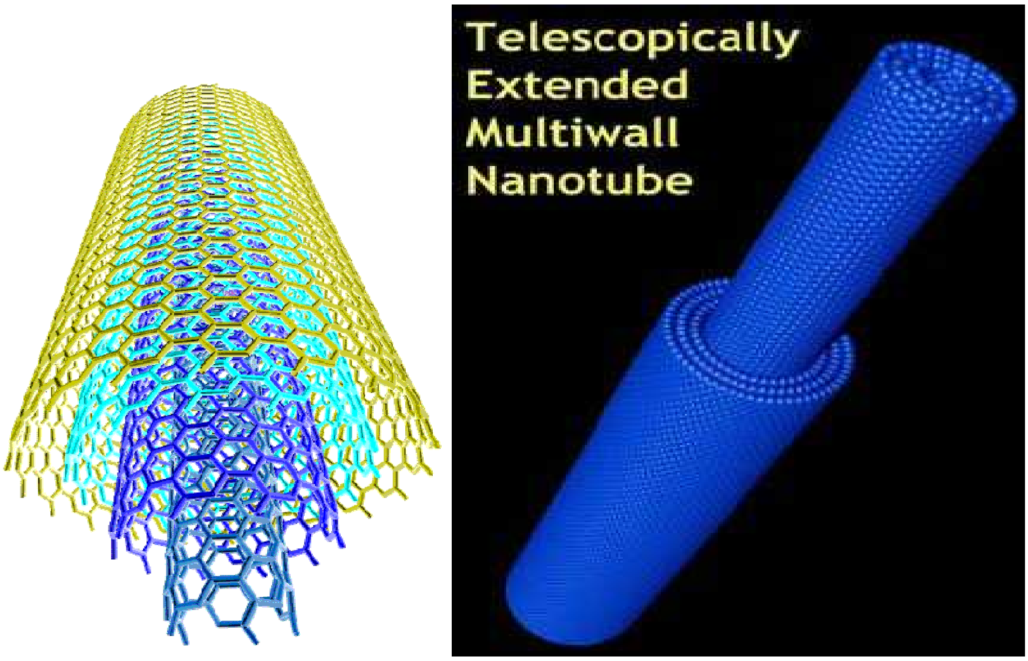


Fig. 1.5 Multiwalled carbon nanotueb

1.3 Buckytubes

In contrast, buckytubes are fullerenes, and are thus molecules: perfect, hollow molecules of pure carbon linked together in a hexagonally bonded network to form the hollow cylinder as shown in. The tube is seamless, with either open or capped ends. The diameter of single-wall carbon nanotubes is 0.7 to 2 nm (typically about 1.0 nm) – 100,000 times thinner than a human hair. Buckytube lengths are typically hundreds of times their diameters.

2.0 History[2]

A 2006 editorial written by Marc Monthioux and Vladimir Kuznetsov in the journal *Carbon* has described the interesting and often misstated origin of the carbon nanotube. A large percentage of academic and popular literature attributes the discovery of hollow, nanometer sized tubes composed of graphitic carbon to Sumio Iijima of NEC in 1991.

In 1952 Radushkevich and Lukyanovich published clear images of 50 nanometer diameter tubes made of carbon in the Soviet *Journal of Physical Chemistry*. This discovery was largely unnoticed, the article was published in the Russian language, and Western scientists' access to Soviet press was limited during the Cold War. It is likely that carbon nanotubes were produced before this date, but the invention of the transmission electron microscope allowed the direct visualization of these structures.

Carbon nanotubes have been produced and observed under a variety of conditions prior to 1991. A paper by Oberlin, Endo, and Koyama published in 1976 clearly showed hollow carbon fibres with nanometer-scale diameters using a vapour-growth technique. Additionally, the authors show a TEM image of a nanotube consisting of a single wall of graphene. Later, Endo has referred to this image as a single-walled nanotube.

In 1981 a group of Soviet scientists published the results of chemical and structural characterization of carbon nanoparticles produced by a thermocatalytical disproportionation of carbon monoxide. Using TEM images and XRD patterns, the authors suggested that their “Carbon multi-layer tubular crystals” were formed by rolling graphene layers into cylinders. Additionally, they speculated that during rolling graphene layers into a cylinder, many different arrangements of graphene hexagonal nets are possible. They suggested two possibilities of such arrangements: circular arrangement (armchair nanotube) and a spiral, helical arrangement (chiral tube).

In 1987, Howard G. Tennent of Hyperion Catalysis was issued a U.S. patent for the production of "cylindrical discrete carbon fibrils" with a "constant diameter between about 3.5 and about 70 nanometers…, length 10^2 times the diameter, and an outer region of multiple essentially continuous layers of ordered carbon atoms and a distinct inner core…."

Iijima's discovery of carbon nanotubes in the insoluble material of arc-burned graphite rods created the buzz that is now associated with carbon nanotubes. Nanotube research accelerated greatly following the independent discoveries by Bethune at IBM and Iijima at NEC of *single-walled* carbon nanotubes and methods to specifically produce them by adding transition-metal catalysts to the carbon in an arc discharge. The arc discharge technique was well-known to produce the famed Buckminster fullerene on a preparative scale,[12] and these results appeared to extend the run of accidental discoveries relating to fullerenes. The original observation of fullerenes in mass spectrometry was not anticipated, and the first mass-production technique by Krätschmer and Huffman was used for several years before realising that it produced fullerenes.

The discovery of nanotubes remains a contentious issue, especially because several scientists involved in the research could be likely candidates for the Nobel Prize. Many believe that Iijima's report in 1991 is of particular importance because it brought carbon nanotubes into the awareness of the scientific community as a whole.

3.0 Synthesis[1]

3.1 Introduction

In this section, different techniques for nanotube synthesis and their current status are briefly explained. First, the growth mechanism is explained, as it is almost general for all techniques. However, typical conditions are stated at the sections of all the different techniques. The largest interest is in the newest methods for each technique and the possibilities of scaling up. Carbon nanotubes are generally produced by three main techniques, arc discharge, laser ablation and chemical vapour deposition. Though scientists are researching more economic ways to produce these structures. In arc discharge, a vapour is created by an arc discharge between two carbon electrodes with or without catalyst. Nanotubes self-assemble from the resulting carbon vapour. In the laser ablation technique, a high-power laser beam impinges on a volume of carbon –containing feedstock gas (methane or carbon monoxide). At the moment, laser ablation produces a small amount of clean nanotubes, whereas arc discharge methods generally produce large quantities of impure material. In general, chemical vapour deposition (CVD) results in MWNTs or poor quality SWNTs. The SWNTs produced with CVD have a large diameter range, which can be poorly controlled. But on the other hand, this method is very easy to scale up, what favours commercial production.

3.2 Growth mechanism

The way in which nanotubes are formed is not exactly known. The growth mechanism is still a subject of controversy, and more than one mechanism might be operative during the formation of CNTs. One of the mechanisms consists out of three steps. First a precursor to the formation of nanotubes and fullerenes, C_2, is formed on the surface of the metal catalyst particle. From this metastable carbide particle, a rodlike carbon is formed rapidly. Secondly there is a slow graphitisation of its wall. This mechanism is based on in-situ TEM observations.

The exact atmospheric conditions depend on the technique used, later on, these will be explained for each technique as they are specific for a technique. The actual growth of the nanotube seems to be the same for all techniques mentioned.

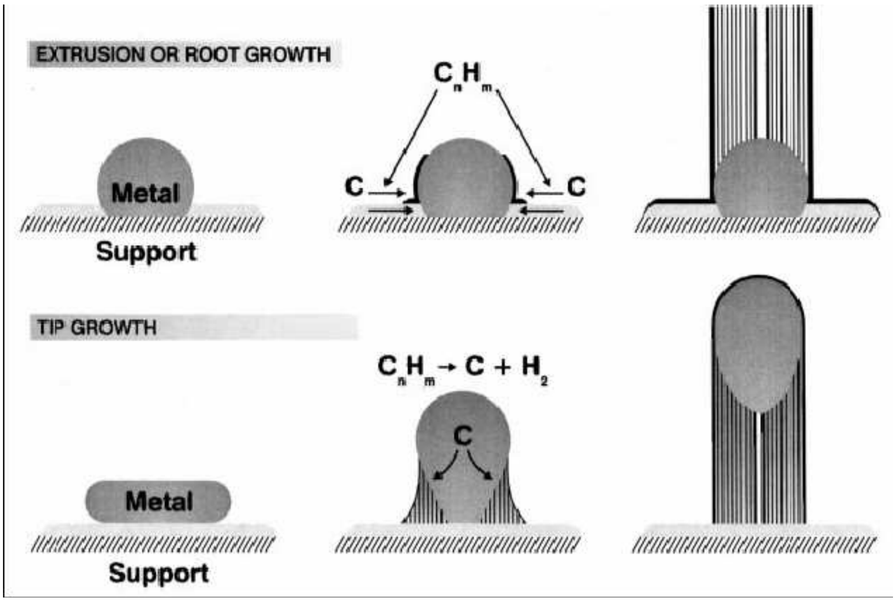


Figure 2.1: Visualisation of a possible carbon nanotube growth mechanism.

There are several theories on the exact growth mechanism for nanotubes. One theory13 postulates that metal catalyst particles are floating or are supported on graphite or another substrate. It presumes that the catalyst particles are spherical or pear-shaped, in which case the deposition will take place on only one half of the surface (this is the lower curvature side for the pear shaped particles). The carbon diffuses along the concentration gradient and precipitates on the opposite half, around and below the bisecting diameter. However, it does not precipitate from the apex of the hemisphere, which accounts for the hollow core that is characteristic of these filaments. For supported metals, filaments can form either by ‘extrusion (also known as base growth)’ in which the nanotube grows upwards from the metal particles that remain attached to the substrate, or the particles detach and move at the head of the growing nanotube, labelled ‘tip-growth’. Depending on the size of the catalyst particles, SWNT or MWNT are grown. In arc discharge, if no catalyst is present in the graphite, MWNT will be grown on the C2-particles that are formed in the plasma.

3.3 Arc discharge

The carbon arc discharge method, initially used for producing C60 fullerenes, is the most common and perhaps easiest way to produce carbon nanotubes as it is rather simple to undertake. However, it is a technique that produces a mixture of components and requires separating nanotubes from the soot and the catalytic metals present in the crude product.

This method creates nanotubes through arc-vaporisation of two carbon rods placed end to end, separated by approximately 1mm, in an enclosure that is usually filled with inert gas (helium, argon) at low pressure (between 50 and 700 mbar). Recent investigations have shown that it is also possible to create nanotubes with the arc method in liquid nitrogen14. A direct current of 50 to 100 A driven by approximately 20 V creates a high temperature discharge between the two electrodes. The discharge vaporises one of the carbon rods and forms a small rod shaped deposit on the other rod. Producing nanotubes in high yield depends on the uniformity of the plasma arc and the temperature of the deposit form on the carbon electrode15.

Insight in the growth mechanism is increasing and measurements have shown that different diameter distributions have been found depending on the mixture of helium and argon. These mixtures have different diffusions coefficients and thermal conductivities. These properties affect the speed with which the carbon and catalyst molecules diffuse and cool., affecting nanotube diameter in the arc process. This implies that single-layer tubules nucleate and grow on metal particles in different sizes depending on the quenching rate in the plasma and it suggests that temperature and carbon and metal catalyst densities affect the diameter distribution of nanotubes15.

3.3.1 Synthesis of SWNT

If SWNTs are preferable, the anode has to be doped with metal catalyst, such as Fe, Co, Ni, Y or Mo. A lot of elements and mixtures of elements have been tested by various authors16 and it is noted that the results vary a lot, even though they use the same elements. This is not surprising as experimental conditions differ. The quantity and quality of the nanotubes obtained depend on various parameters such as the metal concentration, inert gas pressure, kind of gas, the current and system geometry. Usually the diameter is in the range of 1.2 to 1.4 nm. A couple of ways to improve the process of arc discharge are stated below.

a) Inert gas

The most common problems with SWNT synthesis are that the product contains a lot of metal catalyst, SWNTs have defects and purification is hard to perform. On the other hand, an advantage is that the diameter can slightly be controlled by changing thermal transfer and diffusion, and hence condensation of atomic carbon and metals between the plasma and the vicinity of the cathode can control nanotube diameter in the arc process. This was shown in an experiment in which different mixtures of inert gases were used17.

It appeared that argon, with a lower thermal conductivity and diffusion coefficient, gave SWNTs with a smaller diameter of approximately 1.2 nm. A linear fit of the average nanotube diameter showed a 0.2 nm diameter decrease per 10 % increase in argon helium ratio, when nickel/yttrium was used (C/Ni/Y was 94.8:4.2:1) as catalyst.

b) Optical plasma control

A second way of control is plasma control by changing the anode to cathode distance (ACD). The ACD is adjusted in order to obtain strong visible vortices around the cathode. This enhances anode vaporisation, which improves nanotubes formation. Combined with controlling the argon-helium mixture, one can simultaneously control the macroscopic and microscopic parameters of the nanotubes formed18.

With a nickel and yttrium catalyst (C/Ni/Y is 94.8:4.2:1) the optimum nanotube yield was found at a pressure of 660 mbar for pure helium and 100 mbar for pure argon. The nanotube diameter ranges from 1.27 to 1.37 nanometre.

b) Catalyst

Knowing that chemical vapour deposition (CVD) could give SWNTs with a diameter of 0.6–1.2 nm, researchers tried the same catalyst as used in CVD on arc discharge. Not all of the catalysts used appeared to result in nanotubes for both methods. But there seemed to be a correlation of diameter of SWNTs synthesised by CVD and arc discharge

As a result, the diameter can be controllably lowered to a range of 0.6-1.2 nm with arc-discharge. Using a mixture of Co and Mo in high concentrations as catalyst resulted in this result. These diameters are considerably smaller than 1.2-1.4 nm16, which is the usual size gained from arcdischarge.

c) Improvement of oxidation resistance

There is also progress in developing methods to improve the oxidation resistance of the SWNTs, which is a consequence of the defects present in nanotubes. A strong oxidation resistance is needed for the nanotubes if they have to be used for applications such as field emission displays. Recent research has indicated that a modified arc-discharge method using a bowl-like cathode, decreases the defects and gives cleaner nanotubes, and thus improves the oxidation resistance.

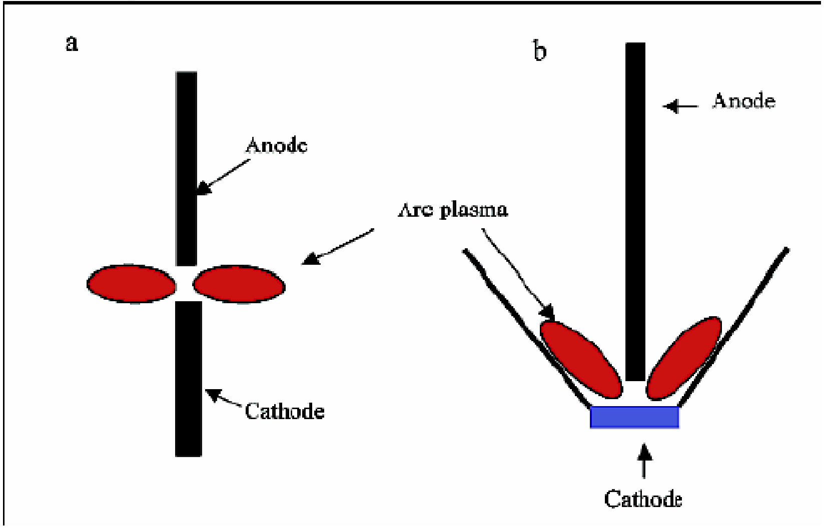


Figure 3.3: Schematic drawings of the electrode set-ups for (a) the conventional and (b) the new arc discharge electrodes

The Raman spectrum of the newly synthesised nanotubes shows that the nanotubes formed are cleaner and less defective compared with those synthesised by conventional methods. The anode rod contained Ni and Y catalyst (C /Ni/Y is 94.8:4.2:1). No information is given about the diameter size.

3.4 Laser ablation

In 1995, Smalley's group25 at Rice University reported the synthesis of carbon nanotubes by laser vaporisation. The laser vaporisation apparatus used by Smalley's group is shown in. A pulsed 26, or continuous laser is used to vaporise a graphite target in an oven at 1200 °C. The main difference between continuous and pulsed laser, is that the pulsed laser demands a much higher light intensity (100 kW/cm2 compared with 12 kW/cm2). The oven is filled with helium or argon gas in order to keep the pressure at 500 Torr. A very hot vapour plume forms, then expands and cools rapidly. As the vaporised species cool, small carbon molecules and atoms quickly condense to form larger clusters, possibly including fullerenes. The catalysts also begin to condense, but more slowly at first, and attach to carbon clusters and prevent their closing into cage structures.30 Catalysts may even open cage structures when they attach to them. From these initial clusters, tubular molecules grow into single-wall carbon nanotubes until the catalyst particles become too large, or until conditions have cooled sufficiently that carbon no longer can diffuse through or over the surface of the catalyst particles. It is also possible that the particles become that much coated with a carbon layer that they cannot absorb more and the nanotube stops growing. The SWNTs formed in this case are bundled together by van der Waals forces.

There are some striking, but not exact similarities, in the comparison of the spectral emission of excited species in laser ablation of a composite graphite target with that of laser-irradiated C60 vapour. This suggests that fullerenes are also produced by laser ablation of catalyst-filled graphite, as is the case when no catalysts are included in the target. However, subsequent laser pulses excite fullerenes to emit C2 that adsorbs on catalyst particles and feeds SWNT growth. However, there is insufficient evidence to conclude this with certainty.

Laser ablation is almost similar to arc discharge, since the optimum background gas and catalyst mix is the same as in the arc discharge process. This might be due to very similar reaction conditions needed, and the reactions probably occur with the same mechanism.

3.5 Chemical vapour deposition

Chemical vapour deposition (CVD) synthesis is achieved by putting a carbon source in the gas phase and using an energy source, such as a plasma or a resistively heated coil, to transfer energy to a gaseous carbon molecule. Commonly used gaseous carbon sources include methane, carbon monoxide and acetylene. The energy source is used to "crack" the molecule into reactive atomic carbon. Then, the carbon diffuses towards the substrate, which is heated and coated with a catalyst (usually a first row transition metal such as Ni, Fe or Co) where it will bind. Carbon nanotubes will be formed if the proper parameters are maintained. Excellent alignment31, as well as positional control on nanometre scale32, can be achieved by using CVD. Control over the diameter, as well as the growth rate of the nanotubes can also be maintained. The appropriate metal catalyst can preferentially grow single rather than multi-walled nanotubes.

CVD carbon nanotube synthesis is essentially a two-step process consisting of a catalyst preparation step followed by the actual synthesis of the nanotube. The catalyst is generally prepared by sputtering a transition metal onto a substrate and then using either chemical etching or thermal annealing to induce catalyst particle nucleation. Thermal annealing results in cluster formation on the substrate, from which the nanotubes will grow. The temperatures for the synthesis of nanotubes by CVD are generally within the 650–900 oC range. Typical yields for CVD are approximately 30%.

These are the basic principles of the CVD process. In the last decennia, different techniques for the carbon nanotubes synthesis with CVD have been developed, such as plasma enhanced CVD, thermal chemical CVD, alcohol catalytic CVD, vapour phase growth, aero gel-supported CVD and laserassisted CVD.

3.6 Flame synthesis

This method is based on the controlled flame enviorenment, that produces the temperature, forms the carbon atoms from the inexpensive hydrocarbon fuels and forms small aerosol metal catalyst islands. SWNTs are grown on these metal islands in the same manner as in laser ablation and arc discharge.

4.0 Properties

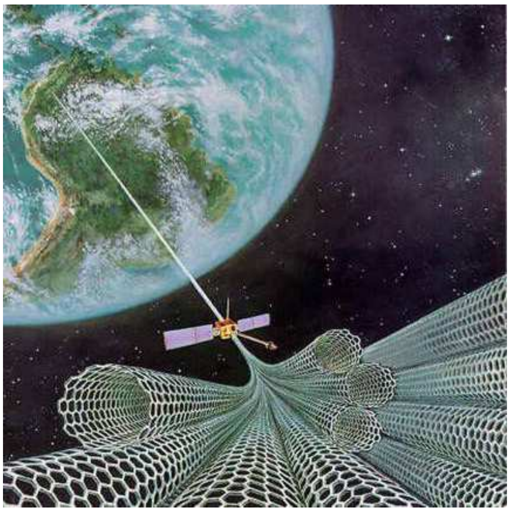
4.1 General properties [4]

Table: 4.1 General properties of cabon nanotubes

Parameter	Value
Average Diameter of SWNT's	1.2-1.4 nm
Distance from opposite Carbon Atoms (Line 1)	2.83 Å
Analogous Carbon Atom Separation (Line 2)	2.456 Å
Parallel Carbon Bond Separation (Line 3)	2.45 Å
Carbon Bond Length (Line 4)	1.42 Å
C-C Tight Bonding Overlap Energy	~ 2.5 eV
Group Symmetry (10, 10)	C5V
Lattice: Bundles of Ropes of Nanotubes: Triangular Lattice(2D)	
Lattice Constant	17 Å
Lattice Parameter:	
(10, 10) Armchair	16.78 Å
(17, 0) Zigzag	16.52 Å
(12, 6) Chiral	16.52Å
Density:	
(10, 10) Armchair	1.33 g/cm3
(17, 0) Zigzag	1.34 g/cm3
(12, 6) Chiral	1.40 g/cm3
Interlayer Spacing:	
(n, n) Armchair	3.38 Å
(n, 0) Zigzag	3.41 Å
(2n, n) Chira	l3.39 Å

Optical Properties	
Fundamental Gap:	
For (n, m); n-m is divisible by 3 [Metallic]	0 eV
For (n, m); n-m is not divisible by 3 [Semi-Conducting]	~0.5 eV
Electrical Transport	
Conductance Quantization	n x (12.9 kW)-1
Resistivity	10-4 W·cm
Maximum Current Density	1013 A/m2
Thermal Transport	
Thermal Conductivity(Room Temperature)	~ 2000 W/m•K
Phonon Mean Free Path	~ 100 nm
Relaxation Time	~ 10-11 s
Elastic Behavior	
Young's Modulus (SWNT)	~ 1 TPa
Young's Modulus (MWNT)	1.28 TPa
Maximum Tensile Strength	~30 GPa

4.2 Mechanical[4]



The carbon nanotubes are expected to have high stiffness and axial strength as a result of the carbon–carbon sp2 bonding. The practical application of the nanotubes requires the study of the elastic response, the inelastic behavior and buckling, yield strength and fracture. Efforts have been applied to the experimental and theoretical, investigation of these properties.

Carbon nanotubes are one of the strongest and stiffest materials known, in terms of tensile strength and elastic modulus respectively. This strength results from the covalent sp^2 bonds formed between the individual carbon atoms. In 2000, a multi-walled carbon nanotube was tested to have a tensile strength of 63 GPa.[22] In comparison, high-carbon steel has a tensile strength of approximately 1.2 GPa. CNTs have very high elastic moduli, on the order of 1 TPa.[23] Since carbon nanotubes have a low density for a solid of 1.3-1.4 g/cm^3,[16] its specific strength of up to 48,462 kN·m/kg is the best of known materials, compared to high-carbon steel's 154 kN·m/kg.

Under excessive tensile strain, the tubes will undergo plastic deformation, which means the deformation is permanent. This deformation begins at strains of approximately 5%[24] and can increase the maximum strain the tube undergoes before fracture by releasing strain energy.

CNTs are not nearly as strong under compression. Because of their hollow structure and high aspect ratio, they tend to undergo buckling when placed under compressive, torsional or bending stress.

Table: 4.2 Young's modulus, tensile strength and density of carbon nanotubes compared with some other materials

Material	**Young’s modulus GPa**	**Tenisle strength GPa**	**Density (g/cm^3)**
Single wall nanotube	1050	150	
Multi wall nanotube	1200	150	2.6
Stee	l208	0.4	7.8
Epoxy	3.5	0.005	1.25
Wood	16	0.008	0.6

4.3 Electrical [8]

Because of the symmetry and unique electronic structure of graphene, the structure of a nanotube strongly affects its electrical properties. For a given (*n*,*m*) nanotube, if *n* - *m* is a multiple of 3, then the nanotube is metallic, otherwise the nanotube is a semiconductor. Thus all armchair (*n*=*m*) nanotubes are metallic, and nanotubes (5,0), (6,4), (9,1), etc. are semiconducting. In theory, metallic nanotubes can have an electrical current density more than 1,000 times greater than metals such as silver and copper.

Carbon nanotubes have some distinct electrical properties. One of the important properties of carbon nanotube is that it can exhibit the characteristics of a metal or a semiconductor [6]. Specially, the energy gap is determined by the rolling direction of nanotube.

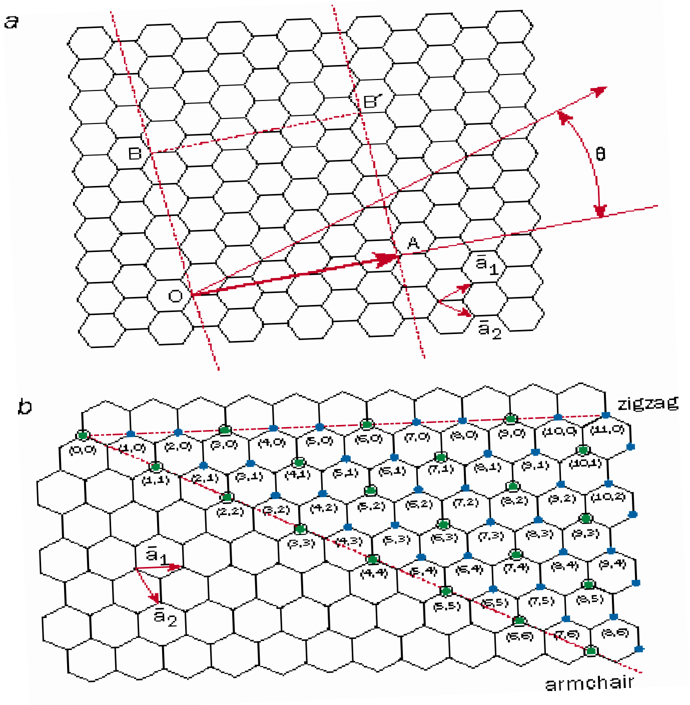


Fig. 4.3 Conducting property of CNT depends on geometry of graphite sheet

In Figure 5.1, Ch is Mamada vector connecting two crystallographical equivalent sites, and and are the unit vectors of the unit cell. Ch= n+, wherenand are integers. The nanotube is formed by connecting A and A’ point. There is a simple rule to determine if the nanotube acts as a metal or a semiconductor: if (n+)/3 = integer, nanotube acts as a metal otherwise it acts as a semiconductor. Due to the miniscule size of the nanotube, the electrical conductivity is measured by the four point probe method to determine the sheet resistance. The four point probe method measures the resistivity of any semiconductor material. At the same time, nanotubes have been studied to make switches and transistors, which would be much smaller than the silicon chips currently used. The wires made by nanotubes are capable of currents that are 100 times greater than metal wires, making nanotubes useful in the production of flat panels.

4.4 Thermal[8]

All nanotubes are expected to be very good thermal conductors along the tube, exhibiting a property known as "ballistic conduction," but good insulators laterally to the tube axis. It is predicted that carbon nanotubes will be able to transmit up to 6000 watts per meter per kelvin at room temperature; compare this to copper, a metal well-known for its good thermal conductivity, which only transmits 385 W/m/K. The temperature stability of carbon nanotubes is estimated to be up to 2800 degrees Celsius in vacuum and about 750 degrees Celsius in air.

4.5 Optical[5]

Fluorescence occurs when a substance absorbs one wavelength of light and emits a different wavelength in response. The Rice experiments, conducted by Smalley's group and the photophysics research team of chemist R. Bruce Weisman, found that nanotubes absorbed and gave off light in the near-infrared spectrum, which could prove useful in biomedical and nanoelectronics applications.

4.6 Magnetic[6]

Physicists have shown that carbon nanotubes can become magnetized when they are placed in contact with a magnetic material. Michael Coey of Trinity College in Dublin and colleagues believe the mechanism relies on the transfer of spin – carried by electrons – from the magnetic substrate to the nanotube.

It is widely believed that graphite and other forms of carbon can have ferromagnetic properties, but the effects are so weak that physicists are not sure if the magnetism is due to tiny amounts of iron-rich impurities, or if it is an intrinsic property of the carbon. In 2002 Coey’s group measured the magnetic properties of a meteorite sample and found that only two-thirds of the magnetization could be accounted for by magnetic minerals present in the sample. The rest, they argued, must come from the carbon. In particular, they proposed that ferromagnetic nanocrystals in the sample induced a magnetic moment in the carbon via proximity effects.

The basic electrical properties of semiconducting carbon nanotubes change when they are placed inside a magnetic field. The phenomenon is unique among known materials, and it could cause semiconducting nanotubes to transform into metals in even stronger magnetic fields.

Scientists found that the "band gap" of semiconducting nanotubes shrank steadily in the presence of a strong magnetic force, said lead researcher Junichiro Kono, an assistant professor of electrical and computer engineering at Rice University. The research, which involved a multidisciplinary team of electrical engineers, chemists and physicists, helps confirm quantum mechanical theories offered more than four decades ago, and it sheds new light on the unique electrical properties of carbon nanotubes, tiny cylinders of carbon that measure just one-billionth of a meter in diameter.

4.7 Field emission properties of carbon nanotubes[5]

Buckytubes are the best known field emitters of any material. This is understandable, given their high electrical conductivity, and the unbeatable sharpness of their tip (the sharper the tip, the more concentrated will be an electric field, leading to field emission; this is the same reason lightening rods are sharp). The sharpness of the tip also means that they emit at especially low voltage, an important fact for building electrical devices that utilize this feature. Buckytubes can carry an astonishingly high current density, possibly as high as 1013 A/cm^2. Furthermore, the current is extremely stable [B.Q. Wei, et al. Appl. Phys. Lett. 79 1172 (2001)].

An immediate application of this behaviour receiving considerable interest is in field-emission flat-panel displays. Instead of a single electron gun, as in a traditional cathode ray tube display, here there is a separate electron gun (or many) for each pixel in the display. The high current density, low turn-on and operating voltage, and steady, long-lived behaviour make buckytubes attract field emitters to enable this application.

Other applications utilising the field-emission characteristics of buckytubes include: general cold-cathode lighting sources, lightning arrestors, and electron microscope sources.

4.8 Electron in carbon nanotube[5]

The unique electronic properties of carbon nanotubes are due to the quantum confinement of electrons normal to the nanotube axis. In the radial direction, electrons are confined by the monolayer thickness of the graphene sheet. Around the circumference of the nanotube, periodic boundary conditions come into play. For example, if a zigzag or armchair nanotube has 10 hexagons around its circumference, the 11th hexagonal will coincide with the first. Going around the cylinder once introduces a phase difference of 2π.

Because of this quantum confinement, electrons can only propagate along the nanotube axis, and so their wavevectors point in this direction. The resulting number of one-dimensional conduction and valence bands effectively depends on the standing waves that are set up around the circumference of the nanotube. These simple ideas can be used to calculate the dispersion relations of the one-dimensional bands, which link wavevector to energy, from the well known dispersion relation in a graphene sheet.

5.0 Applications[5]

Carbon nanotubes are one of the most promising materials for the electronics, computer and aerospace industries. There are numerous properties of carbon nanotubes that make them attractive for applications in neurobiology: small size, flexibility, strength, inertness, electrical conductivity and ease of modification with biological compounds.

Carbon nanotubes and their derivatives can be used as substrates/scaffolds for neural cell growth. The chemical properties of carbon nanotubes can be systematically varied by attaching different functional groups; manipulation of the charge carried by functionalized carbon nanotubes can be used to control the outgrowth and branching pattern of neuronal processes. The ease with which carbon nanotubes can be patterned makes them attractive for studying the organization of neural networks and the electrical conductivity of nanotubes can provide a mechanism to monitor or stimulate neurons through the substrate itself. However, it is important to recognize that carbon nanotubes themselves can affect neuronal function, most likely by interaction with ion channels.

The use of carbon nanotubes in neurobiology is a promising application that has the potential to develop new methods and techniques to advance the study of neuroscience.

Carbon nanotubes are a relatively novel material which have extreme parameters due to their very high aspect ratio (allowing high tensile strength, electrical and thermal conductivities). Whilst the NanoSight instruments do not currently allow for information about the morphology of the nanoparticles to be extracted, a sphere-equivalent size does allow differentiation between nanotubes of different sizes.

5.1 The space elevator comes closer to reality[5]

Stronger than steel

Both U.S. and Japanese firms, among others, are ramping up production of carbon nanotubes, with tons of this now exotic matter soon to be available. "That quantity of material is going to be around well before five years time. It's not going to take long," he said.

Given the far stronger-than-steel ribbon of carbon nanotubes, a space elevator could be up within a decade. "There's no real serious stumbling block to this," Edwards explained.

"The making of carbon nanotubes is moving very quick," said Hayam Benaroya, a professor in the Department of Mechanical and Aerospace Engineering at Rutgers in Piscataway, New Jersey. "We're moving from the scientific stage of just developing them to actual commercial entities producing them in ton-like quantities," he said.

"Perhaps within our lifetimes we might actually see real designs of skyhooks and space tethers, these kinds of things. They may be feasible at reasonable cost," Benaroya said.

Reel world high-wire act

Getting the first space elevator off the ground, factually, would use two space shuttle flights. Twenty tons of cable and reel would be kicked up to geosynchronous altitude by an upper stage motor. The cable is then snaked to Earth and attached to an ocean-based anchor station, situated within the equatorial Pacific. That platform would be similar to the structure used for the Sea Launch expendable rocket program.

Once secure, a platform-based free-electron laser system is used to beam energy to photocell-laden "climbers". These are automated devices that ride the initial ribbon skyward. Each climber adds more and more ribbon to the first, thereby increasing the cable's overall strength. Some two-and-a-half years later, and using nearly 300 climbers, a first space elevator capable of supporting over 20-tons (20,000-kilograms) is ready for service.

Using a laser beam to boost the climbers into space is doable, said Harold Bennett, president of Bennett Optical Research, Inc. of Ridgecrest, California. "If you do it right, you can take out 96 percent of the effect of the atmosphere on the laser beam through adaptive optics," he said. The strength of the pulsed laser beam is less than the intensity of the Sun, so birds, airplanes, or human eyes wouldn't be affected, he said.

Building the impossible

The elevator to space concept does entail aggressive research work. As example, Edwards said he is looking into the environmental impacts stemming from elevator operations. Being studied too is impact of lightning, wind and clouds on an Earth-to-space cable system. Space elevators for use on other worlds, like Mars and the Moon are receiving attention as well.

One thing to keep in mind. Building the impossible is done here on Earth routinely, Edwards said.

Take for instance the $13.5 billion Millennium Tower envisioned for Hong Kong Harbor. This incredible skyscraper would be 170 stories tall. Elevator traffic within its walls is estimated at 100,000 people per day.

Edwards also points to the Gibraltar Bridge project. It would span the Straits of Gibraltar, linking Spain and Morocco at a projected cost of $20 billion. The bridge would use towers, twice as high as the world's tallest skyscraper. Roughly 1,000,000 miles (1,600,000 kilometers) of wire cables would be utilized in the project.

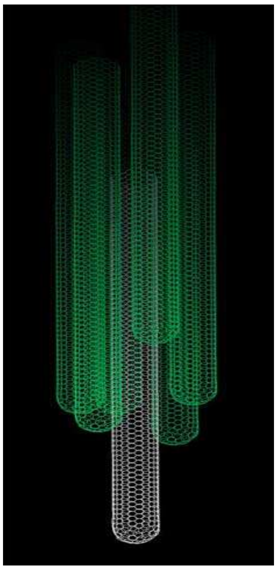


Fig. 5.1 High strength CNT that is very useful for space elevator

5.2 Supercapacitor[8]

A supercapacitor or ultracapacitor is an electrochemical capacitor that has an unusually high energy density when compared to common capacitors. They are of particular interest in automotive applications for electric (including hybrid electric) vehicles and as supplementary storage for battery electric vehicles.

Supercapacitors that can deliver a strong surge of electrical power could be manufactured from carbon nanotubes using a technique developed by researchers at UC Davis. Supercapacitors are electrical storage devices that can deliver a huge amount of energy in a short time. Hybrid-electric and fuel-cell powered vehicles need such a surge of energy to start, more than can be provided by regular batteries. Supercapacitors are also needed in a wide range of electronic and engineering applications, wherever a large, rapid pulse of energy is required.

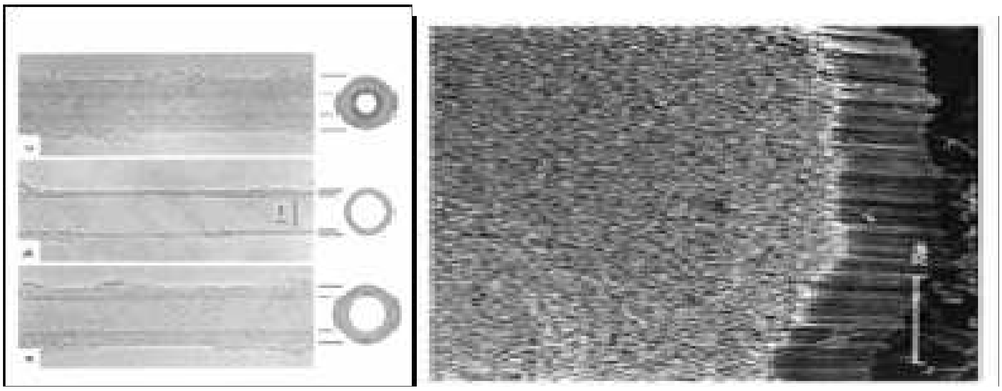
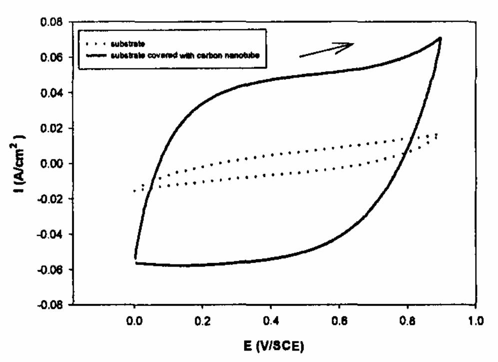


Fig.5.2: (Left) TEM Micrographs of multi wall coaxial nanotubes with various inner and outer diameters, di and do, and numbers of cylindrical shells N reported by Ilijima in 1991: (A) N = 5, do = 6.7nm; (B) N = 2, do = 5.5nm; and (C) N = 7, di = 2.3nm, do = 6.5nm. (Right) SEM micrograph of a film of vertically aligned CNTs with estimated density of 107tubes/mm2.

A matrix of vertically aligned carbon nanotube (CNT) has been investigated as a DLC electrode (see Fig.5.2 right). Our analysis shows that this configuration can provide a combination of high power density (more than four orders of magnitude greater than fuel cells) and energy density (comparable to Li-Ion batteries). The significant enhancement in the achievable DLC power density derives from the high conductivity obtainable with CNTs, which in the limit of a few microns in length present ballistic conduction. The energy density improvement of a “nanotube enhanced electrode” is due to the higher effective surface area obtainable with a structure based on vertically aligned nanotubes over activated carbon.

The electrochemical properties of these nanotube electrodes were studied by cyclic voltammetry in 1.0M H_2SO_4 aqueous solution. The typical cyclic voltammograms (CVs) are shown in Fig.6.3, 6.4, 6.5 and 6.6. These CVs are featureless voltammograms and no Faradic peaks can be observed between 0 to 0.9 V (vs. SCE). This result has also been observed for the singlewalled carbon nanotubes.

Rectangular-shaped cyclic voltammograms over a wide range of scan rates is the ultimate goal in electrochemical double-layer capacitors. This behavior is very important for practical applications.



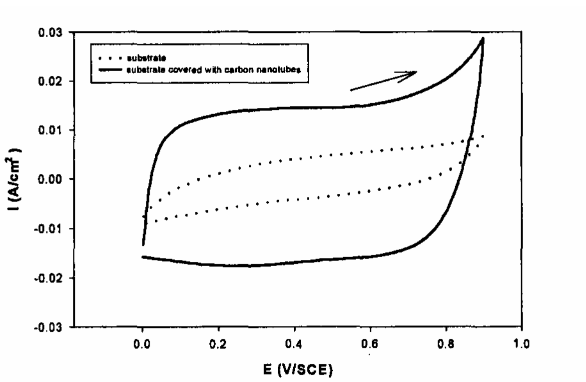
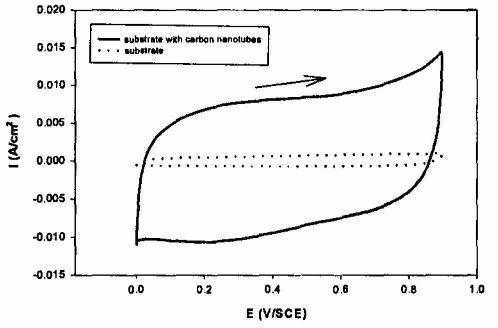


Figure 5.3 Cyclic voltammogram of sample1, in 1.0M H2SO4 aqueous solution. Sample 1: carbon nanotubes were grown directly on the graphite sheet substrate covered with activated carbon. Scan rate: 100mV/s.

Figure 5.4 Cyclic voltammogram of sample 1, in 1.0M H2SO4 aqueous solution. Sample 1: carbon nanotubes were grown directly on the graphite sheet substrate covered with activated carbon. Scan rate: 25mV/s.



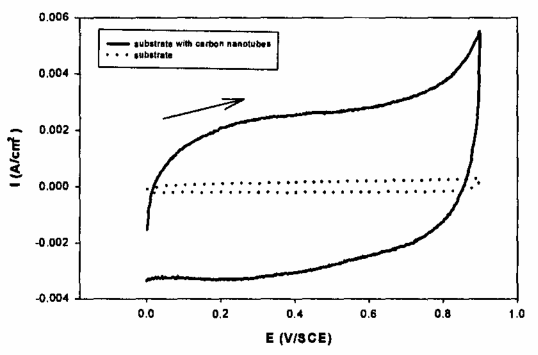


Figure 5.5 Cyclic voltammogram of sample 2, in 1.0M H2SO4 aqueous solution. Sample 2: carbon nanotubes were grown directly on the graphite sheet. Scan rate: 100mV/s

Figure 5.6 Cyclic voltammogram of sample 2, in 1.0M H2SO4 aqueous solution. Sample 2: carbon nanotubes were grown directly on the graphite sheet. Scan rate: 25mV/s

In Fig.5.3, 5.4, 5.5 and 5.6, These carbon nanotube electrodes can retain the rectangular shape of CVs up to a high scan rate (100mV/s). This means the charge and discharge processes are very fast at the interface between the nanotube electrode and electrolyte solution. The featureless CVs and high speeds of charge and discharge suggest a possible application of this kind of multi-walled carbon nanotubes to supercapacitor. The material is stable on cycling and no significant difference can be seen after continuous cycles over 30 cycles.

The results in Fig.5.3, 5.4, 5.5 and 5.6, show that the electrochemical capacitance of the electrode increases obviously when carbon nanotubes are grown on the substrates. The mass of carbon nanotubes grown on the substrate is obtained from the difference of total weight of the electrode before and after the growth of carbon nanotubes. The capacitance is calculated from the CV curves, with $C = \int idt/\Delta V$, where i is the current. The increases of the effective capacitance per unit weight of carbon nanotubes can be calculated, for example, at the scan rate of 25mV/s, are 98.6 F/g and 140 F/g for sample 1 and sample 2, respectively.

5.3 Hydrogen Storage[1]

Another property of carbon nanotubes is their ability to quickly adsorb high densities of hydrogen at room temperature and atmospheric pressure. The research group at the National Renewable Energy Laboratory already confirms that SWNTs are capable of storing hydrogen at densities of more than 63kg/m^3. Researchers have found that the interaction of hydrogen and SWNT is between the Van der Waals force of the SWMT and the chemical bonds of the hydrogen molecule (as opposed to being due to hydrogen dissociation).

Hydrogen is the cleanest, sustainable and renewable energy carrier, and a hydrogen energy system is expected to progressively replace the existing fossil fuels in the future, the latter are being depleted very fast and causes severe environmental problems. In particular, one potential use of hydrogen lies in powering zero-emission vehicles via a proton exchange membrane fuel cell to reduce atmosphere pollution. To achieve this goal feasible onboard hydrogen storage systems have to be developed. The recent discovery of the high and reversible hydrogen storage capacity of carbon nanotubes makes such a system very promising. In this overview, theoretical predictions and experimental results on the hydrogen uptake of carbon nanotubes and nanofibers are summarized, and we point out that, in order to accelerate the development of carbon nanotubes and nanofibers as a practical hydrogen storage medium in fuel cell-driven vehicles, many efforts have to be made to reproduce and verify the results both theoretically and experimentally, and to investigate their volumetric capacity, cycling characteristics and release behavior.

Due to its high surface area and abundant pore volume, porous carbon is considered as good adsorbent. For conventional porous carbon, the hydrogen uptake is pro-portional to its surface area and pore volume.

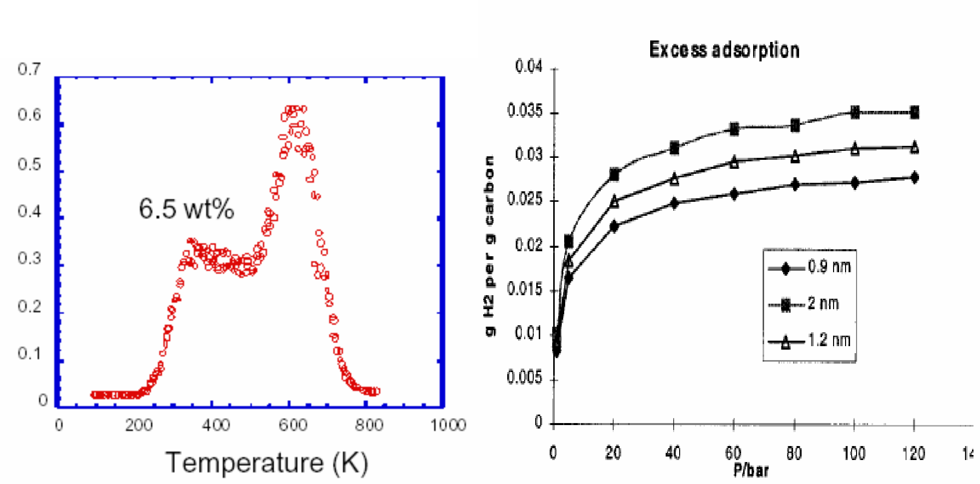


Figure 5.7 Temperature and pressure-dependent behavior of hydrogen storage

Due to its high surface area and abundant pore volume, porous carbon is considered as good adsorbent. For conventional porous carbon, the hydrogen uptake is pro-portional to its surface area and pore volume.

5.4 Memory device[5]

Because of its ability to store information as a single electronic charge, nanotubes have the potential to be used in the design of memory devices. A single electron is discrete, and thus needs less energy in order to change the state of the memory. Such a design would also take advantage of the high mobility of SWMT, which is ten times greater than that of silicon.

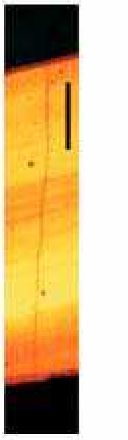


Figure 5.89 Nanotube single-electron memory cell. The dark blocks at the top and the bottom are the source and drain and the vertical dark line is nanotube.

5.5 Carbon nanotube in Atomic force microscopy[2] [9]

The carbon atoms of a single (graphene) sheet of graphite form a planar honeycomb lattice, in which each atom is connected via a strong chemical bond to three neighboring atoms. Because of these strong bonds, the basal-plane elastic modulus of graphite is one of the largest of any known material. For this reason, CNTs are expected to be the ultimate high-strength fibers. SWNTs are stiffer than steel, and are very resistant to damage from physical forces. Pressing on the tip of a nanotube will cause it to bend, but without damage to the tip. When the force is removed, the tip returns to its original state. This property makes CNTs very useful as probe tips for very high-resolution scanning probe microscopy.

Quantifying these effects has been rather difficult, and an exact numerical value has not been agreed upon. Using an atomic force microscope (AFM), the unanchored ends of a freestanding nanotube can be pushed out of their equilibrium position and the force required to push the nanotube can be measured. The current Young’s modulus value of SWNTs is about 1 TeraPascal, but this value has been disputed, and a value as high as 1.8 Tpa has been reported. Other values significantly higher than that have also been reported. The differences probably arise through different experimental measurement techniques. Others have shown theoretically that the Young’s modulus depends on the size and chirality of the SWNTs, ranging from 1.22 Tpa to 1.26 Tpa. They have calculated a value of 1.09 Tpa for a generic nanotube. However, when working with different MWNTs, others have noted that the modulus measurements of MWNTs using AFM techniques do not strongly depend on the diameter. Instead, they argue that the modulus of the MWNTs correlates to the amount of disorder in the nanotube walls. Not surprisingly, when MWNTs break, the outermost layers break first.

[2]The mechanical properties of SiC nanorods and MWNTs were measured by use of atomic force microscopy (AFM). The MWNTs were pinned at one end to molybdenum disulfide surfaces by depositing pads of silicon oxide through a shallow mask (Fig. 33). In this method, the AFM tip can be moved perpendicular to the tube and record the lateral force arising from the elastic displacement of the beam by the tip. Large displacements can lead to buckling, plastic deformation or fracture of the nanotube and thereby determine its strength.

For small displacements the nanotube can be deformed without damage. In the latter regime, the bending force was measured versus displacement along the unpinned length. These data are used in the equation of the deflected nanotubes considering them as hollow homogeneous cylindrical cantilevers. The integration of this equation yields the applied force in terms of the Young’s modulus and the displacement of the nanotube. The estimated Young’s modulus was 1.26 TPa. It was found that nanotube buckle elastically at large deflection angles of _108 for length of 1 mm. The bending strength is defined as the force per unit area at the buckling point because the stiffness drops substantially at this point. The average bending strength was 14:2 _ 8:0 GPa, substantially smaller than for SiC nanorods. The toughness refers to the elastic energy stored by the material before failure. The estimate for a 30 nm diameter nanotube was 100 keV, which is an order of magnitude larger than the strain energy storage in SiC nanorods. Therefore, the ability of nanotubes to elastically sustain loads at large deflection angles enables them to store or absorb considerable energy used AFM tips to apply tensile load to MWNTs and measured breaking strength of MWNTs between 11 and 63 GPa and Young’s modulus between 270 and 950 GPa.

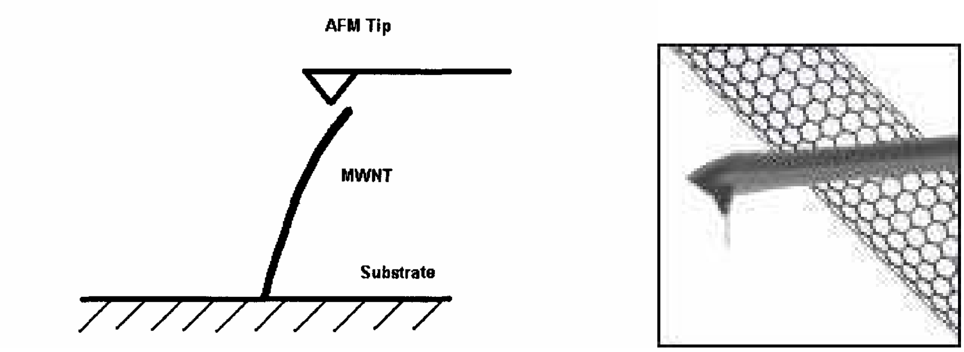


Fig. 5.9. Schematic representation of the MWNT bending with an AFM tip

5.6 Molecular Electronics[2]

The idea of building electronic circuits out of the essential building blocks of materials - molecules - has seen a revival the past five years, and is a key component of nanotechnology. In any electronic circuit, but particularly as dimensions shrink to the nanoscale, the interconnections between switches and other active devices become increasingly important. Their geometry, electrical conductivity, and ability to be precisely derived, make CNTs the ideal candidates for the connections in molecular electronics. In addition, they have been demonstrated as switches themselves.

5.7 Thermal Materials[9]

The record-setting anisotropic thermal conductivity of CNTs is enabling many applications where heat needs to move from one place to another. Such an application is found in electronics, particularly advanced computing, where uncooled chips now routinely reach over 100°C.
The technology for creating aligned structures and ribbons of CNTs [D.Walters, et al., Chem. Phys. Lett. 338, 14 (2001)] is a step toward realizing incredibly efficient heat conduits. In addition, composites with CNTs have been shown to dramatically increase their bulk thermal conductivity, even at very small loadings.

5.8 Biomedical[9]

The exploration of CNTs in biomedical applications is just underway, but has significant potential. Since a large part of the human body consists of carbon, it is generally though of as a very biocompatible material. Cells have been shown to grow on CNTs, so they appear to have no toxic effect. The cells also do not adhere to the CNTs, potentially giving rise to applications such as coatings for prosthetics, as well as anti-fouling coatings for ships.
The ability to functionalize (chemically modify) the sidewalls of CNTs also leads to biomedical applications such as vascular stents, and neuron growth and regeneration. It has also been shown that a single strand of DNA can be bonded to a nanotube, which can then be successfully inserted into a cell.

5.9 Air and water filtration[9]

Many researchers and corporations have already developed CNT based air and water filtration devices. It has been reported that these filters can not only block the smallest particles but also kill most bacteria. This is another area where CNTs have already been commercialized and products are on the market now.

5.9.1 Other applications[9]

The special nature of carbon combines with the molecular perfection of single-wall CNTs to endow them with exceptional material properties, such as very high electrical and thermal conductivity, strength, stiffness, and toughness. No other element in the periodic table bonds to itself in an extended network with the strength of the carbon-carbon bond. The delocalized pi-electron donated by each atom is free to move about the entire structure, rather than remain with its donor atom, giving rise to the first known molecule with metallic-type electrical conductivity. Furthermore, the high-frequency carbon-carbon bond vibrations provide an intrinsic thermal conductivity higher than even diamond.

In most materials, however, the actual observed material properties - strength, electrical conductivity, etc. are degraded very substantially by the occurrence of defects in their structure. For example, high-strength steel typically fails at only about 1% of its theoretical breaking strength. CNTs, however, achieve values very close to their theoretical limits because of their molecular perfection of structure.

This aspect is part of the unique story of CNTs. CNTs are an example of true nanotechnology: they are only about a nanometer in diameter, but are molecules that can be manipulated chemically and physically in very useful ways. They open an incredible range of applications in materials science, electronics, chemical processing, energy management, and many other fields.

Carbon nanotubes have prompted intense research in a wide variety of disciplines ranging from biology to physics. A complete enumeration of all possible applications

There is a wealth of other potential applications for CNTs, such as solar collection; nanoporous filters; catalyst supports; and coatings of all sorts. There are almost certainly many unanticipated applications for this remarkable material that will come to light in the years ahead, and which may prove to be the most important and valuable ones of all. Many researchers are looking into conductive and or water proof paper made with CNTs. CNTs have also been shown to absorb Infrared light and may have applications in the I/R Optics Industry.

6.0 Conclusions

This carbon modification is intermediate in its structure between the graphite and fullerenes. However, many properties of carbon nanotubes have nothing common with neither graphite nor fullerenes. It permits the consideration and study of nanotubes as an original substance, having the unique physical and chemical characteristics.

The investigations of carbon nanotubes are of substantial basic and applied interest. The basic interest to this object is caused firstly by its unusual structure and physical and chemical properties varied over a wide range, depending on their chirality. Many of these properties serve up till now as a subject of intense investigations directed to the determination of new interesting peculiarities in behaviour of nanotubes in one specified situation or another. There are still waiting for their solution the problems relating to the statement of the growth mechanism for carbon nanotubes in various experimental conditions, to the nature of their magnetic properties, to the degree of electron localization in pure and intercalated nanotubes, etc. The problem of applied usage of nanotubes is closely adjacent to the problem of studying their basic properties. The solution to the former in its turn depends on the nanotube production price exceeding notably at the moment that for gold, which apparently excludes a possibility of large scale application of this material.

Nevertheless such properties of nanotubes as extra tiny size, good conductivity, high emission characteristics, good chemical stability in the presence of considerable porosity and ability to join various chemical radicals permit us to hope for effective applications of nanotubes in such fields as measuring engineering, electronics and nanotechnologies, chemical technologies etc. In the case of successful solution to these problems we shall witness to one more impressive example of the effective influence of basic research on the scientific and technological development.

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