An Introduction to Carbon Nanotubes

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Abstract

This paper will introduce many of the interesting aspects of carbon nanotubes. It will give an overview of the geometry, metallicity, physical properties, transport and applications of carbon nanotubes.

1 Introduction

Nanomaterials are a fairly new and fascinating subject in physics. The prototypical subjects to study are the carbon based materials. Carbon nanotubes are the high aspect ratio carbon based nanomaterial. Carbon nanotubes can be classified into two major groups. Single-wall carbon nanotubes (SWCNT) can be thought of as a single sheet of graphite, also known as graphene, rolled up into a cylinder. Multi-walled carbon nanotubes (MWCNT), on the other hand, can be thought of as several sheets of carbon stacked on each other that roll up together into a cylinder.

2 History

The discovery of Carbon nanotubes is somewhat contriversial. The discovery of SWCNT is pretty clear. There were two papers submitted to Nature

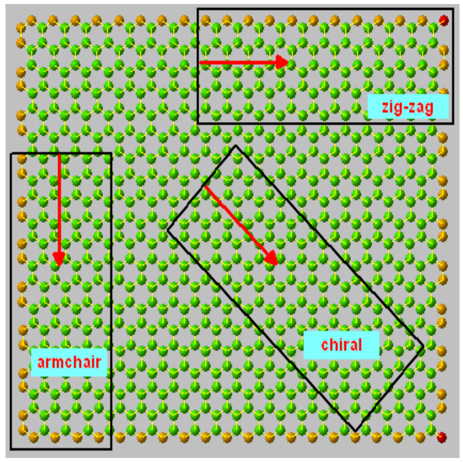

Figure 1: A roll up vector is defined by (n,m). It defines the type of Carbon nanotube and tell us something about its metallicity and chirality. Pictured is an armchair, zigzzag and chiral nanotube.

independently in 1993 by Iijima and Ichihashi and Bethune et al. from IBM. The controversy begins when considering MWCNTs. In 1991 Iijima brought MWCNTs to the attention of the scientific community at large, but in 1952 in the Jurnal of Physics and Chemistry of Russia, Radushkevich and Lukyanovich reported TEM images of hallow nanodiameter carbon fibers. The problem was that during the Cold War Western scientists would not have had this report and it was only published in Russian. It is somewhat unclear who should get the credit for discovering CNTS[1].

3 Geometry

It is important to be able to discuss the different ways carbon nanotubes can be rolled up. As one can see in see in Figure 3 you can define the way the tube rolls up by two integers (n,m) that define a chiral vector C_h that have units $\sqrt{3}a_{C-C}$, a_{C-C} being the carbon bond length 2.46 $\mathring{A}$, and a chiral angle θ which can be defined as $sin(\theta) = \frac{\sqrt{3}m}{2\sqrt{n^2+m^2+nm}}$[2]. θ is confined to be $0 \leq \theta \leq 30°$.

A zigzag carbon nanotube is one that is of the form (n,0) and a armchair nanotube is one of the from (n,n). All other carbon nanotubes are called

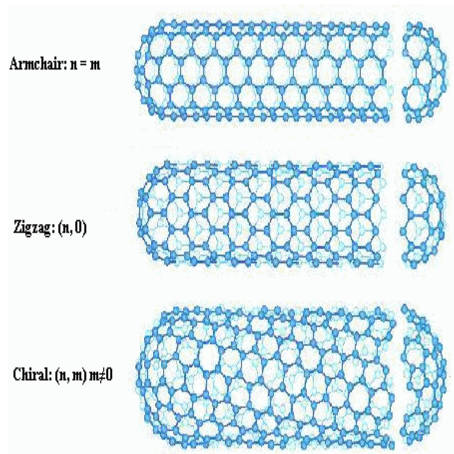

Figure 2: Carbon nanotubes of different chiral angles shown in profile. Pictured is an armchair, zigzag and chiral nanotube. Notice that the carbon sites line up differently.[3].

chiral nanotubes. You can see in Figure 3 the way in which the carbon atoms line up in profile is different depending on the chiral angle. Another important feature the chiral vector reviles is the metallicity. If n-m is divisible by 3 then the carbon nanotube is a metal otherwise it is a semiconductor[2]
.

4 Physical Properties

Carbon nanotubes have some amazing physical properties. These SWCNT can be spun together to create ropes. The elastic and shear modulus of these materials have been studied and the reports are noteworthy. The reduced elastic modulus, E_r, and shear modulus, G, where measured as a function of radius of different SWCNT ropes. The ropes were cast over a porous membrane. An AFM is then used to apply a force to the rope over one of the pores. This force and the amount the rope is displaced is measured.

A simple model would treat the ropes as noninteracting tubes but this was found to be incorrect. This assumption led to unrealistically large elastic moduli. This insinuates that there is significant shear even when bending. The carbon nanotube ropes seemed to have large $E_r \approx 1TPa$ but a much

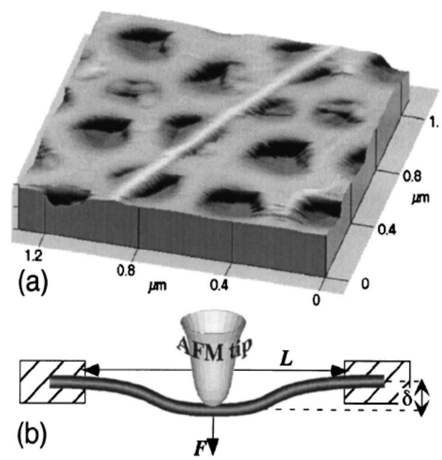

Figure 3: SWCNT rope is cast over a porous membrane and probed with AFM tip. Used to determine physical properties of CNT rope[4].

smaller than expected $G \approx 1GPa$. The elastic modulus is much larger than most conventional materials but the shear modulus is not very good[4].

5 Transport

The electrical transport properties of carbon nanotubes are also very interesting. First one could consider the metallic tubes. It has been reported that a large number of sturcturally similar armchair carbon nanotubes, all of which much be metallic because $n - m = 0$, could be produced. The individual SWCNTs then had their transport properties measrued using a four point probe. It was interesting to note that the conductance seemed to have a strong peak that decreased with temperature. This is a strange behavior that implies that the conduction took place in a single molecular orbital. This molecular orbital would then have to stratch the length of the rope, $140nm$, and shows that the electrons are not stronly localized even though the SWCNTs are strongly one dimensional.

Another interesting application for carbon nanotubes is in the production of molecular field-effect transistors. As one can see from figure citegate the MWNT or SWNT is laid across the usual transistor substrate. With the SWCNT transistors the source-drain current drastically decreases with

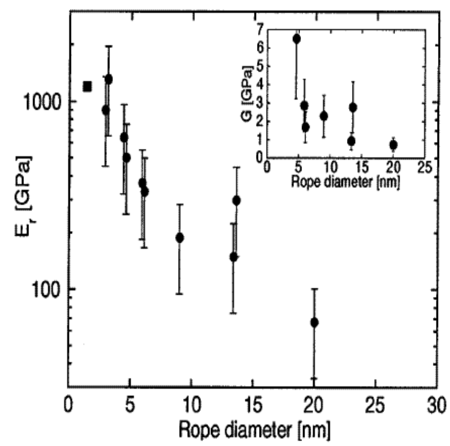

Figure 4: Reduced elastic modulus and shear modulus as a function of rope radius[4].

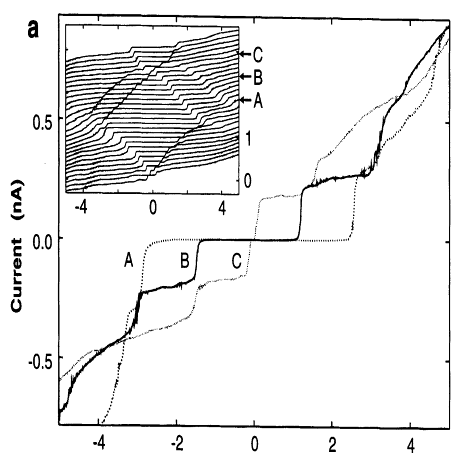

Figure 5: Strongly temperature dependent conductance peak consistant with single molecular orbital transport. Shows that the CNT does not have contineous density of states and therefore conduction is done by nonlocalized electrons in single molecular orbital[5].

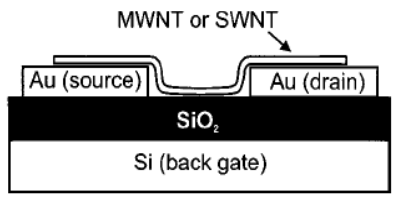

Figure 6: Make up of molecular transistor using CNT to transport current[6].

increasing gate-voltage showing that the device works as a field-effect transistor and that the carriers are holes.

Also as you can see from Figure [?] the conductance of the transistor changes about 5 orders of magnitued over the measured gate voltages.

Next MWNT devices were measured. This was less successful but it did show some promise when the MWCNT collapesed as can be seen in Figure [?]. Clearly nanotubes can be used to make field effect transistors[?].

6 seperation

One challenge to using carbon nanotubes in industrial applications is the production of a single species of nanotubes. An interesting way to do this is to use the difference in density between the species to seperate them. Using ultracentrifugation Arnold et.al were able to seperate SWCNTs such that more than 97% of the SWCNTs are within 0.02nm of each other in diameter. Diameter correlates to chiral angle so this technique should allow one to isolate a specific species of SWCNTs[7].

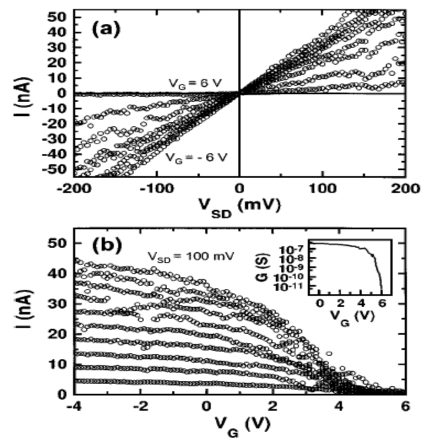

Figure 7: This figure shows the increase in current with gate voltage and the drastic change in conductance with gate voltage. Proves CNT transistor could be produced and used in principle[6].

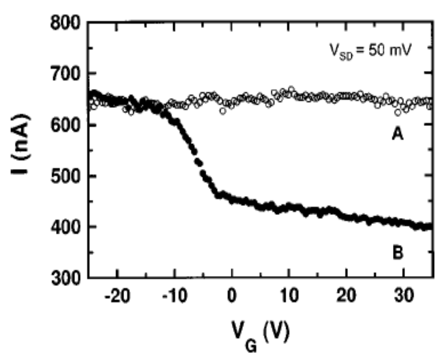

Figure 8: This figure shows the behavior of a MWCNT transistor. Clearly it is not as nice as the SWCNT and does not even have transistor like behavior for large tube diameters[6].

7 Conclusion

It is clear form this that CNT research has many interesting applications. The transport properties have a lot of promise in molecular electronics and transister technology. Also CNTs have amazing physical properties and may actually be the best materials for strong and light composits. Further research will hopefully bring about new technologies.

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