Y-Junction Carbon Nanotube Implementation of Intramolecular Electronic NAND Gate

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Abstract

In this paper we propose a method to create electronic logic circuits using single-walled semiconducting carbon nanotubes (SWCNTs). A SWCNT inverter has already been designed and experimentally tested [1]. We have designed a model for a SWCNT NAND gate using carbon nanotube Y-junctions. Any logic operation can be performed through a combination of NAND gates. However, manufacturing of this new device still remains a challenge. We suggest a fabrication method for our experimental purposes and analyze potential techniques for mass production of the SWCNT NAND gates.

1 Introduction

Single-walled carbon nanotubes (SWCNTs) are nanoscale graphite cylinders. They can be either metallic or semiconducting depending on their diameter and chirality (the angle of the circumferential vector with respect to the graphite lattice vector). Electrical properties of SWCNTs can exceed those of the best metals and semiconductors. Thus, since their discovery in the early 1990's, intense research has been conducted with the goal of developing nanotube-based molecular electronics.

The first section of this paper describes the properties and fabrication of CNTs. We explain in detail the structure and characteristics of single-walled carbon nanotubes that make them viable candidates for application in electronics. Following this, we discuss several technologies developed so far for creating the nanotubes.

So far, scientists have been able to fabricate a field-effect transistor (FET) - a three-terminal switching device - by connecting a single-walled carbon nanotube to two metal electrodes. The nanotube acts as a conductor or insulator depending on the voltage applied to the gate electrode. Both p-type and n-type FETs were created using SWCNTs. There has been steady improvement in CNTFETs' electrical characteristics since they were first fabricated in 1998. Currently, CNTFET operates at room temperature, and outperforms the most advanced silicon MOSFETs, having transconductance at least twice as high as that of MOSFETs. Furthermore, CNTFET's characteristics can be improved considerably by decreasing the contact resistance at source and drain and reducing the gate-oxide thickness. We discuss the production of CNTFETs and provide detailed comparison with silicon MOSFETS in Section 3.

The only SWCNT logic gate that has successfully fabricated to date is the inverter, or the NOT gate [2]. In this logic gate, the nanotube represents an n-type and a p-type FET connected in series and operated by a common backgate. Two complimentary transistors are obtained on the same substrate by selectively doping a single nanotube placed on top of three electrodes. We discuss the SWCNT inverter in greater detail in the section 4 (Intramolecular NOT gate). It has been experimentally tested that the SWCNT inverter has a voltage gain greater than one, which is essential for driving other gates.

We then concentrate on the developing a SWCNT NAND gate. This gate can be obtained using a single Y-shaped SWCNT with the proper arrangement of backgates and positioning of the nanotube. Currently, there are several techniques for producing SWCNT Y-junctions, we describe some of them and then concentrate on a method of fusing two nanotubes with an e-beam– the most suitable technique for our experiment. Y-junctions obtained by this method obey the Kirchoff's Current Law, and thus can be effectively used in our NAND gate arrangement for connecting transistors in parallel.

In Y-Junction CNT NAND Gate Architecture and Fabrication, we propose our design of the single-nanotube NAND gate and describe how it can be realized using currently available engineering technologies.

Finally, faster and more efficient techniques are needed for mass production of the SWCNT NAND gates. We analyze some of the technologies available today and how they can potentially be used to promote the fabrication of nanotube-based logic circuits.

In nanotube synthesis, it is impossible to obtain exclusively metallic or semiconducting tubes, because the chirality of the tubes cannot be controlled. Recent scientific research demonstrated the possibility of DNA-assisted separation of carbon nanotubes.

2 Electronic Structure and Electrical Properties of Carbon Nanotubes

The various forms of carbon nanotubes can be simply imagined as the folding of graphene sheets into perfectly closed cylinders. There are multiwalled and single walled carbon nanotubes. In this paper we look at single walled since their properties are more reliable for nanoelectronic device purposes. Also, depending upon their chirality, diameter, and electronic structure, carbon nanotubes can be metallic or semiconducting. After rolling up a graphene sheet in a certain direction one gets the resulting parameters characterizing the tube. Figure 1 illustrates how one would determine the chirality vector of a certain tube. One can then determine the diameter by simply multiplying the chiral vector by 4: $d_t = \frac{\sqrt{3}}{\pi} a_{c-c}\sqrt{m^2 + mn + n^2}$, where a_{c-c} is the distance between neighboring carbon atoms in the flat sheet. Also the chiral angle is given by $\tan^{-1}(\frac{\sqrt{3}n}{2m+n})$.

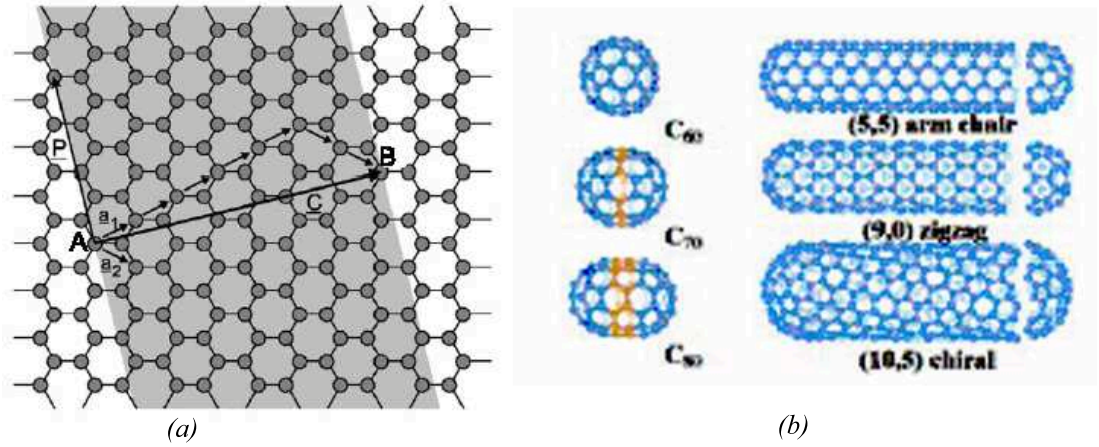

Figure 1: (a) generating chirality vector for nanotube from graphene sheet. $C = na_1 + ma_2 = (n, m)$, where a_1 and a_2 are unit vectors of the hexagonal lattice. [5] (b) Various carbon nanotubes resulting from different foldings of graphene sheets

When a number of carbon atoms are brought together to form a graphene sheet (lattice), the discrete energy levels of the free carbon atoms now broaden into energy bands in the lattice. These energy bands are formed because electrons are now free to move from one atom to another resulting in having different amounts of kinetic energy dependent upon their motion. We then get various quantum states corresponding to one free atom giving rise to one energy band. According to the Bloch theorem each state has a unique energy and plotting this energy as function of k (wave vector of the state) gives the energy

band structure. The unique hexagonal energy band structure of graphene allows for it to behave as both a metal and a semiconductor. However to realize the electronic structure and therefore electronic properties of carbon nanotubes one must apply another quantization condition, since as tubes, the electrons are now bound in the circumferential direction.

The quantization condition needed is k_c . $C = 2\pi j$, where k_c is the wavevector in the circumferential direction, C is the chirality vector of the nanotube, and j an integer. With all boundary conditions in place we can now recalculate the energy band structure for the carbon nanotube. What is most important is how the energy states interact near the Fermi energy (energy of the highest occupied electronic state at zero temperature), or some may say the Fermi surface. The Fermi surface separates unfilled and filled orbitals at absolute zero. Electrical properties of the material are then determined by the shapes of the Fermi surface and current is related to changes in the occupancy of states near the Fermi surface as well. Once again the unique hexagonal band structure of carbon nanotubes (energy as a function of k), allows them to be both metals and semiconductors, since the band structure is in between these extremes. In general for an (n, m) tube, a metallic nature will be seen if $n = m$ or when $n - m = 3i$, i being an integer, and a semiconducting nature will arise when $n - m \neq 3i$. Although n and m determine their physical behavior, the chemical bonds of the tubes are the same in all cases. It is the special electronic structure that gives a zero band gap semiconductor, meaning the top of the valence band has the same energy as the bottom of the conduction band, and this energy equals the Fermi energy for one special wavevector, the K-point of the 2-D Brillouin zone, the corner point of the hexagonal unit cell in reciprocal space for graphene. It is shown that nanotubes are metallic when an allowed wavevector in the circumferential direction passes though this K-point. Also as the diameter of the tube increases, more wavevectors are allowed in the circumferential direction, and since semiconductor band gap is inversely proportional to tube diameter, the band gap approaches zero for large diameters, becoming semiconducting (fig. 2, 3).

Realizing this general, but only introductory information into the physics of carbon nanotubes has taken researchers years of experimentation, using the help of scanning tunneling microscopes (STMs) and atomic force microscopes (AFMs), they have gathered enough information that fits solid state theories about carbon nanotubes and to come to the conclusion that their physics is suitable for nanotubes to be used as nanoelectronic devices and complex logic circuits. Further more advanced physics is still in the process of modeling and more importantly being able to extract important information about the tubes like, resistivity, voltage, and current, only a few items that will help us one day construct quantum scale logic circuits.

Physicists rely on two major molecular physical methods to model the properties of nanotubes: ab initio and classical molecular dynamics. Ab ini-

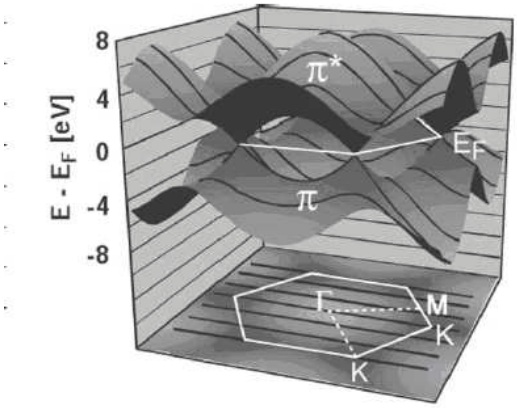

Figure 2: Electronic Band Structure of 2D graphene sheet; six K-points lying at Fermi energy are shown as well as the first Brillouin zone [5]

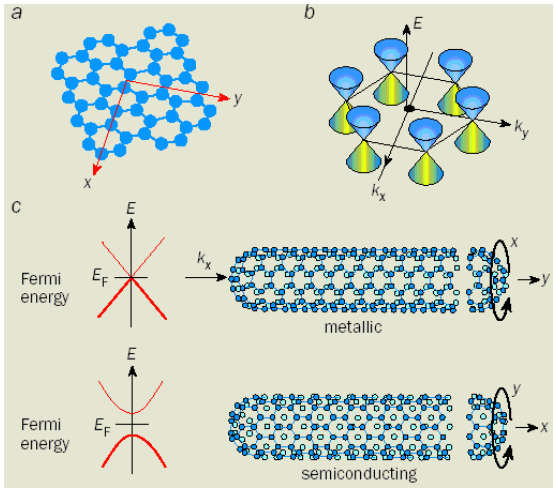

Figure 3: (a) lattice graphene (b) energy conducting states in graphene as function of wavevector k (band structure of nanotube would then be 1D slices through the 2D bandstructure) (c) graphene rolled around y axis results in metallic nature, rolled around x axis results in semiconducting nature. [6]

tio, latin for "from the beginning", is the approach in which accurate solutions to the Schrodinger equation are desired. There are not many exact solutions of course, making it a difficult process that requires the use of many different approximations that people have developed. Another more common method used is the Tight Binding Model also known as LCAO, since it is a method to analyze larger systems more accurately by taking a Linear Combination of the Atomic Orbitals in the system, giving a new basis to compute calculations. The other major molecular physical method uses Newton's second law, mass x acceleration, or Force, is equal to the minus the change in the potential gradient. It gives continuous and multiscale models. It requires the use of many different potentials. More and more methods are refined and tuned in modeling the physics of carbon nanotubes throughout the years and their accuracy is checked via the help of STMs and AFMs.

When one does actually measure the conductance of a carbon nanotube as a function of the gate voltage, distinct behaviors are seen for metallic and semiconducting tubes, as physical models predict. [7] Figure 4 shows the signature nature of metallic nanotubes having weak gate and temperature dependence, meaning that their conductance is not significantly affected by the addition of charge carriers at room temperature, unlike the conductance of semiconducting nanotubes.

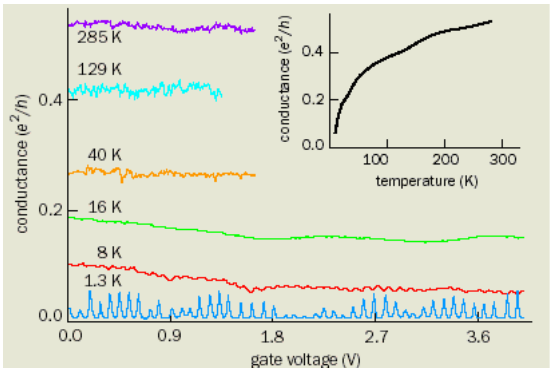

Figure 4: conductance of metallic nanotubes at six different temperatures as a function of gate voltage; average conductance slowly decreases as temperature is lowered. [6]

Most importantly what has been discovered about semiconducting carbon nanotubes, is the fact that they can work as transistors, three terminal devices. Years of experience with complex logic functions has shown that three terminal devices are better than two, since two terminal devices suffer from the fact that their output varies from device to device, and errors in output values grow through successive logic operations [5]. In a three terminal device like a transistor, the output is restored to a defined digital value at each step.

A semiconducting nanotube is made to conduct by applying a negative

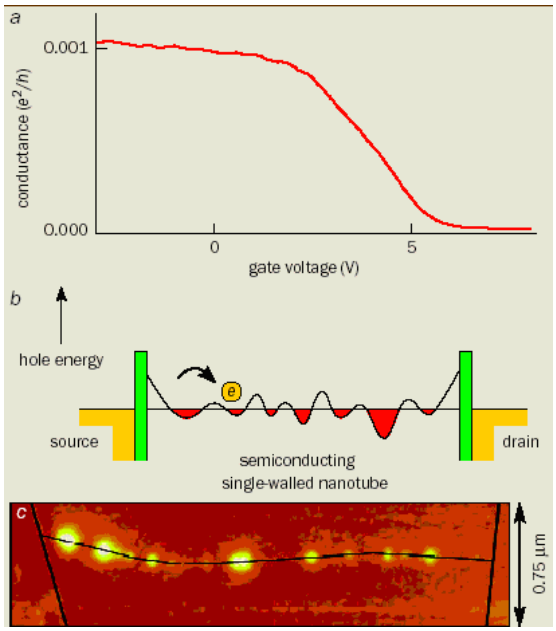

Figure 5: (a) conductance of semiconducting nanotube as function of gate voltage (b) potential profile of disorders experienced by holes due to impurities in structure of the nanotube (c) STM measuring nanotube conductance [6]

bias to the gate and conduction is stopped by applying a positive bias. Negative bias induces holes on the tube, making it conduct, while positive bias depletes holes, decreasing conductance. The physical behavior is similar to that of a p-type metal oxide silicon field effect transistor (MOSFET), the difference now being that a carbon nanotube is replacing silicon as the material hosting charge carriers. It is believed that metal electrodes and chemical species adsorbed onto the tubes make them p-type. The tube's chemical environment can change the level of doping, resulting in sometimes significant changes of the voltage necessary to turn the device "on". Tubes can also be doped to be n-type. The conduction of a semiconducting nanotube rises linearly as the gate voltage is reduced, becoming a better conductor as more holes are added from electrode to nanotube. Conductance is limited only by barriers like structural defects as holes cross the tube. Resistance of the tube will be dominated then by the greatest barrier in the nanotube. This is all true for single walled carbon nanotubes (SWCNTs), multiwalled tubes have a layer of carbon shells with differing physics that can all potentially interact. It is shown that only the outer shell of MWCNTs contributes to electrical transport, and so only small diameter MWCNTs could be used to make transistor devices [5].

Research into making arrays out of carbon nanotube field effect transistors (CNTFETs) is the next step to make complex logic circuits. The ultimate goal is to make an intramolecular logic gate as we propose out of one unified carbon

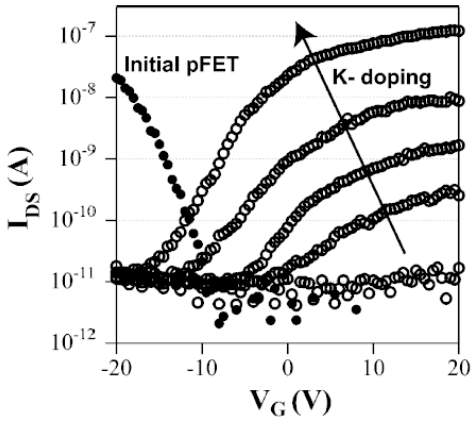

Figure 6: changing output characteristics of CNT field effect transistor being doped with potassium [5]

nanotube. However, more complex configurations of CNTs are required to create a NAND gate using one continuous nanotube. Fortunately, researchers have begun to study the physics of deformed or altered configurations of carbon nanotubes to see if they also could be used to construct logic devices, and data from STMs and AFMs seem promising.

3 Electrical Characteristics of the CNTFET

A CNT field-effect transistor consists of a single semiconducting single-walled nanotube connecting two electrodes placed on an oxide-coated, heavily doped silicon wafer. The carbon nanotube is the active channel between source and drain. The wafer is used as a back gate. Back gate voltage controls the nanotube's conductance, and thus the current between drain and source. Gold or platinum electrodes are defined using electron beam lithography (Fig. 7).

Figure 8 demonstrates that as the gate voltage increases, the source-drain current decreases rapidly. Therefore, the transport through the semiconducting SWCNT is dominated by positive carriers, and the behavior of the SWCNT FET is similar to that of a p-channel metal-oxide-semiconductor FET.

This type of CNT transistor displays high parasitic resistance ($1M\Omega$), low drive current, low transconductance, $g_m \approx 1nS$, high subthreshold slope, and no current saturation. This device requires large values of gate voltage (several volts) to turn on because of the thick gate dielectric ($\approx 100 - 200nm$).

Another type of CNT-FET with improved electrical characteristics has been manufactured. During the device fabrication, the nanotube, instead of being laid down upon the source and drain electrodes, relying on weak van der

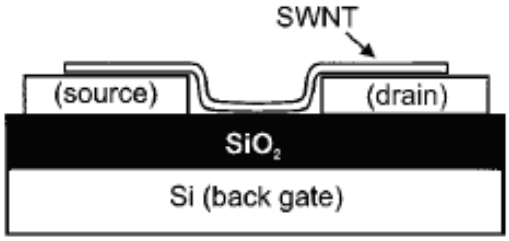

Figure 7: Schematic cross section of a SWCNT FET

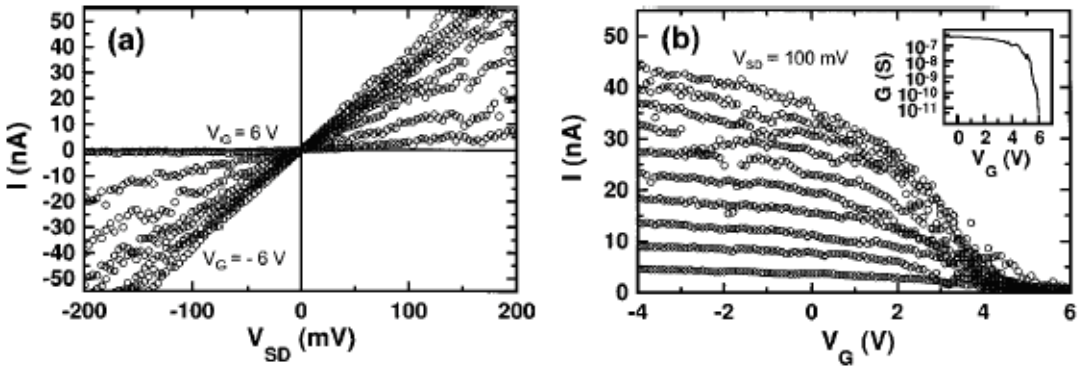

Figure 8: output and transfer characteristics for a CNT FET with 30 nm thick Au electrodes and a single-walled nanotube of 1.6 nm diameter [1]. (a) shows $I - V_{SD}$ curves measured for $V_G = -6, 0, 1, 2, 3, 4, 5, 6V$. (b) shows $I - V_G$ curves for $V_{SD} = 10 - 100mV$ in steps of $10mV$. The inset shows that the gate modulates conductance by 5 orders of magnitude.

Waals forces for contact, is deposited on the substrate, with the electrodes patterned on top of it. To improve the metal/nanotube contact, Ti and Co are used with a thermal annealing step. As a result, contact resistance is reduced from several $M\Omega$ to $30k\Omega$.

The CNT-FETs described are both p-type. N-type conduction can be achieved by doping from an alkali (electron donor) gas, or by thermal annealing in vacuum. In addition, ambipolar conduction can be achieved, in which both electron and hole transport are possible. Given that both p- and n-type CNT-FETs can be fabricated, it is possible to produce carbon nanotube CMOS logic circuits.

Device structure of CNT-FETs can be further optimized to improve their electrical characteristics. However, some of the CNT-FETs' "on current" and transconductance already exceed those of the state-of-the-art MOSFETs. The use of high dielectric constant gate insulators, and additional improvements

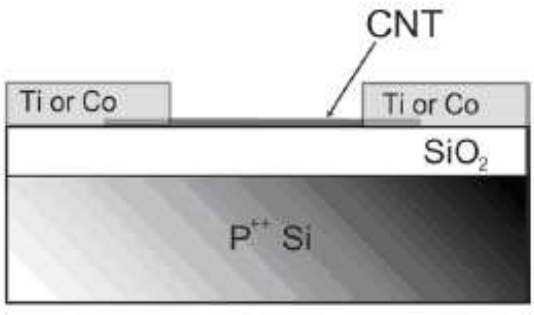

Figure 9: Schematic cross-section of the improved CNT-FET

in the metal/nanotube contact resistance at the source and drain can improve CNT-FET performance. Such improvements are possible for both p-type and n-type CNT-FETs.

4 Intramolecular NOT gate

Grown semiconducting SWCNTs were shown to exhibit p-type characteristics [3]. However in 2001 V. Derycke et al [2] reported on a method of creating n-type SWCNTs wither by vacuum annealing p-type SWCNTs, they also explored the uses of directly doping the tube with an electropositive element such as potassium as previously proposed[4]. They constructed an intramolecular inverter where one part of the nanotube acts as a p-type FET and the other part as an n-type FET by protecting the n-type FET area and doping the unprotected area. The whole device was prepared as shown in figure 10.

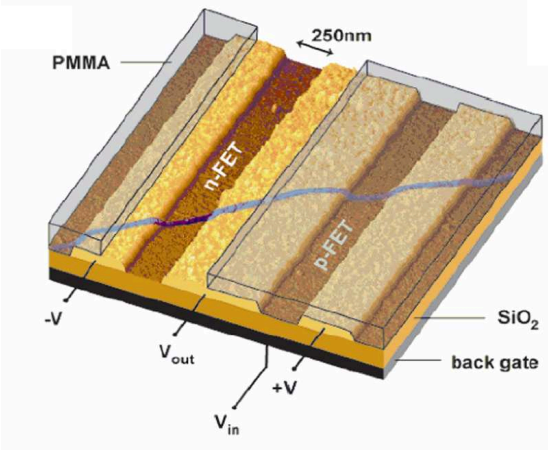

Figure 10: Intramolecular Inverter

V. Derycke et al. proceeded to test the electronic characteristics of their

device and discovered that, as expected, the device functioned as an inverter as shown in figure 11. As can be seen, the device behaved very well, having a gain of more then one and thus making it possible to drive another gate.

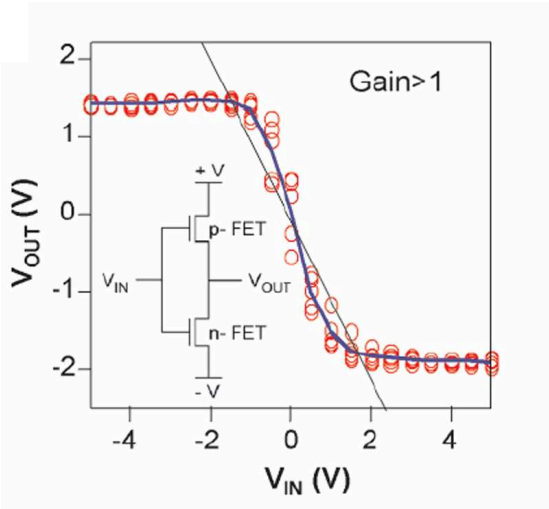

Figure 11: Intramolecular inverter measurements

Encouraged by the results obtained in [2] we set out to develop a NAND gate in order to create a complete basis allowing the implementation of any arbitrary boolean function using only intramolecular gates. However, if we are to develop the NAND gate with one continuous piece of carbon nanotube, the mechanical structure of the CNT must be modified. In the following section, we introduce the Y-branch CNT.

5 SWCNT Multiterminal Junctions

5.1 Fabrication of Y-junction Carbon Nanotube

Numerous research groups around the world have invested a significant amount of time on fabricating CNTs. Some published methods include arc discharge [12], laser vaporization [13], catalytic decomposition of hydrocarbons [14], and thermal decomposition of fullerene [15, 16, 17].

Two types of catalytic decomposition of hydrocarbon methods are presented. First, B. C. Satishkumar, et al [18] proposed using pyrolysis, a form of incineration that chemically decomposes organic materials by heat in the absence of oxygen. The scheme is shown in figure 12.

This method gives a 70% yield, an impressive number for industrial purposes. However, this method only fabricates multi-walled Y-junctions (fig. 13). Single-walled Y-junctions are of interest to us due to their fast, ballistic, and

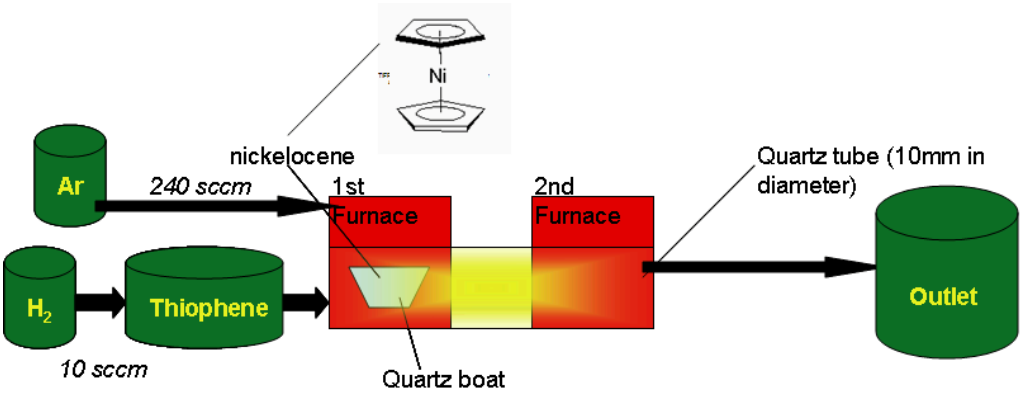

Figure 12: the scheme of pyrolysis method of fabrication Y-junction carbon-nanotubes

more reliable transport properties. Some post-modifications [23] may be applied to peel away the extra graphite layers, such as laser vaporization [24] or arc-plasma [25], but this will hinder the possibility of mass production due to various dimensions of nanotubes.

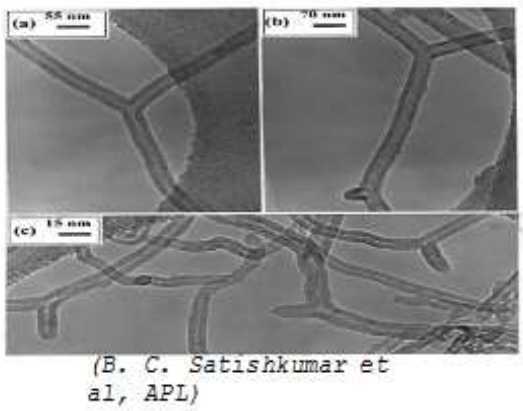

Figure 13: TEM image of a Y-junction carbon nanotube

The second method is proposed by Jingming Xu, et al at Brown University [19]. Using a technique similar to pyrolysis, Xu et al, use a nanochannel alumina (NCA) template to fabricate the Y-junction nanotubes. The advantage of this method is that there is more control over the length and diameter of the tube. Once again, this method produces only multi-walled nanotubes (fig. 14). Unfortunately, no efficient method for growing single-walled Y-branch nanotubes is known.

A third method different from the catalytic decomposition processes is based on the thermal decomposition of fullerene in the presence of transition metals, such as Ti, Cr, Fe, Co, or Ni. The detailed proportionality could be found in

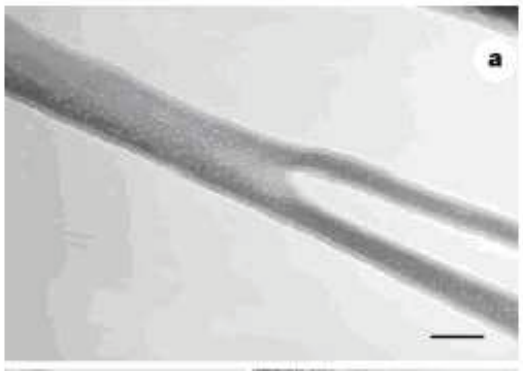

Figure 14: Y-junction tube (scale bar, $50nm$) with stem $90nm$ and branches $50nm$ in diameter.

[17]. The major advantage of this method is that only low amounts of byproducts are produced. Also, this fabrication method uses a mechanical constraint. Here, the tube grows because of an inherent effect of the structure. These details could be found in [20, 21, 22].

Single-walled Y-junctions can also be formed by forcing two single-walled nanotubes together. Researchers at the Max-Planck Insitut have dispersed single-walled nanotubes in ethanol and deposited them onto holey carbon grids for observation and processing with a transmission electron microscope (TEM). At 800 degrees Celsius, an e-beam was generated by the TEM and positioned onto touching nanotubes, irradiating them at the desired junction point. Terrones et al, claim to have successfully fabricated single-walled Y and T-junctions along with some four-terminal types (X-junctions) using this method and using tight-binding molecular dynamics simulations. However, some of the irradiated junctions were defective in their atomic arrangement, having seven or eight ? instead of the usual six ? carbon atoms in the ring where atoms are shared between nanotubes. Another drawbrack is that this process takes on the order of minutes to perform, making it an inefficient method for mass-production purposes. However, this process is sufficient for our proposed methods [26]

As mentioned previously, there has not been an efficient technique to produce single-walled Y-junction carbon nanotubes. Even though some post-modification method might work, it cannot prevent the possible and significant defects. In order to massively produce Y-junction nanotubes, more research must be invested in fabricating single-walled Y-junctions. Also, two main problems will exist after the fabrication setup. One, how would researchers separate metallic Y-junctions from semiconducting ones? And two, how do we position the Y-junction onto our device? Both questions will be discussed in more detail in section 7.

5.2 Electronic Structure and Electrical Properties

The physics for our proposed model of using a Y-branched single wall carbon nanotube to form an intramolecular NAND gate has not been studied by many but the data they have obtained gives enough results to see it as a very plausible construction. Y junction nanotubes can be formed from chemical vapor deposition, welding two crossed nanotubes with an electron beam at high temperature, or using irradiation techniques on an touching tubes to form a Y tube. Researchers are slowly developing physical models to analyze the resulting properties from this structural deformation.

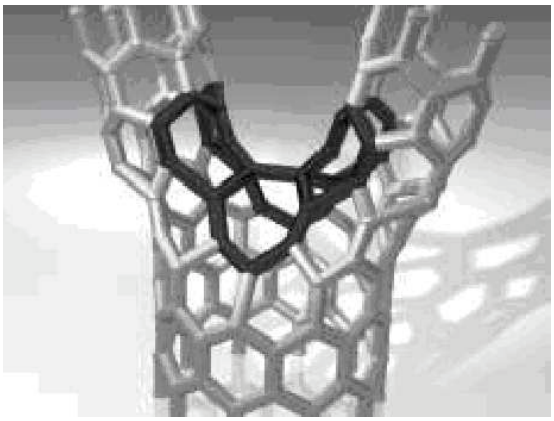

Figure 15: Y branch nanotube; topological defect of carbon nanotube [8]

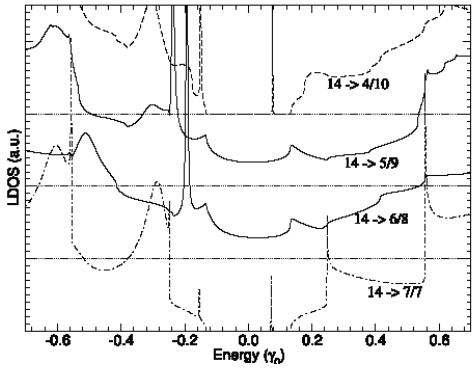

Figure 16: local density of states near Ef = 0 for both symmetric and asymmetric Y branches. [8]

The general trend in most papers is to start with quantum conductivity calculations for SWCNT Y junctions using the general Landauer expression for conductance in a 1D system, $G = (2e^2/h)\ .\ \sum_i^N T_i$, where $2e^2/h$ is the quantum

of conductance, and T_i is the transmission of a contributing sub-band (conduction channel), produced from confinement of electrons along the circumference of the CNT. The transmission function can be obtained using Green's function formalism, and the Hamiltonian of the system can be obtained by tight binding formulations. Using the formalism of Landauer and Buttiker, the current passing through the Y branch can now be calculated. The general current equation looks like this:

$$I_i = \frac{e^2}{h} \int_{-\infty}^{\infty} dE \left\{ [1 - T_{ii}E] f(E - \mu_i) - \sum_{j \neq i} T_{ij}(E) f(E - \mu_j) \right\}$$

There are different atomic orbitals and approximations used by different researchers but general results show that symmetric Y branches display rectifying behavior while asymmetric branches can serve as typical interconnects; both types of Y branches follow Kirchoff's current rules [9]. The rectifying nature of the symmetric Y-branches will destroy the function of our NAND gate; hence, non-rectifying,asymmetric Y branches are used for the intramolecular NAND gate. Figure 17 and 18 show current through a symmetric and then asymmetric Y branch.

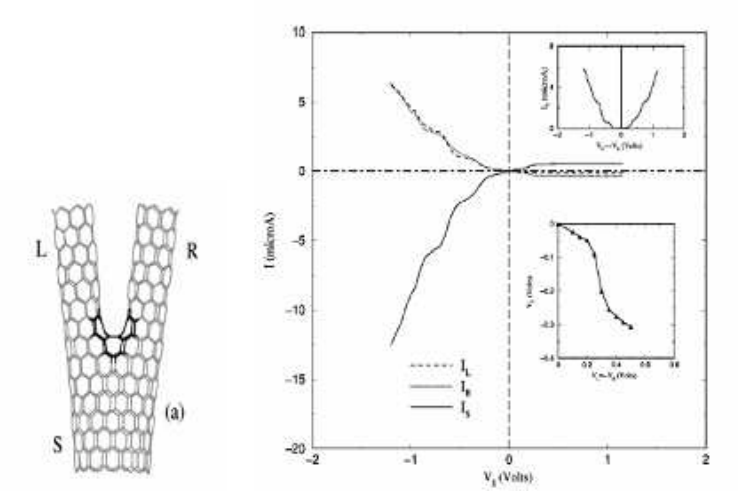

Figure 17: (left) symmetric Y branch (right) graph of current through stem, I_s, and branches I_L and I_G; current is positive flowing towards junction and negative otherwise. This figure shows rectifying behavior. [9]

Y-junction nanotubes are promising structures for logic gate designs. Designs with four Y-junctions have already been experimentally tested by Palm et al, [10]. Figure 19 and 20 show proposed device architecture and resulting data.

From research so far, the idea of using a single walled Y branch carbon nanotube as part of an intramolecular NAND gate seems like a very feasible idea.

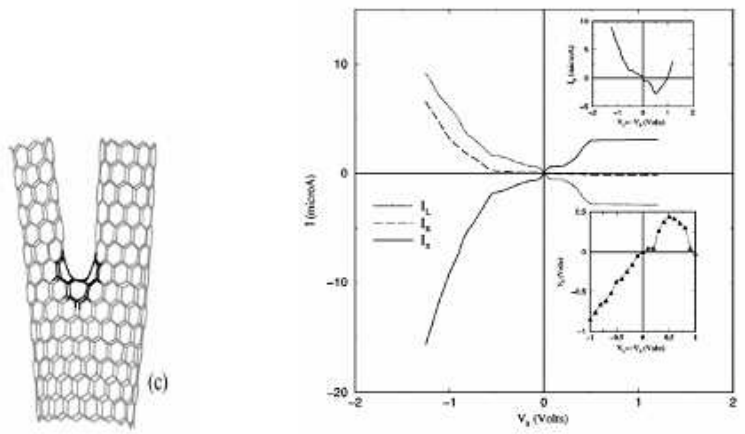

Figure 18: (left) asymmetric Y branch (right) graph of current through branch showing typical interconnect behavior, no rectification. [9]

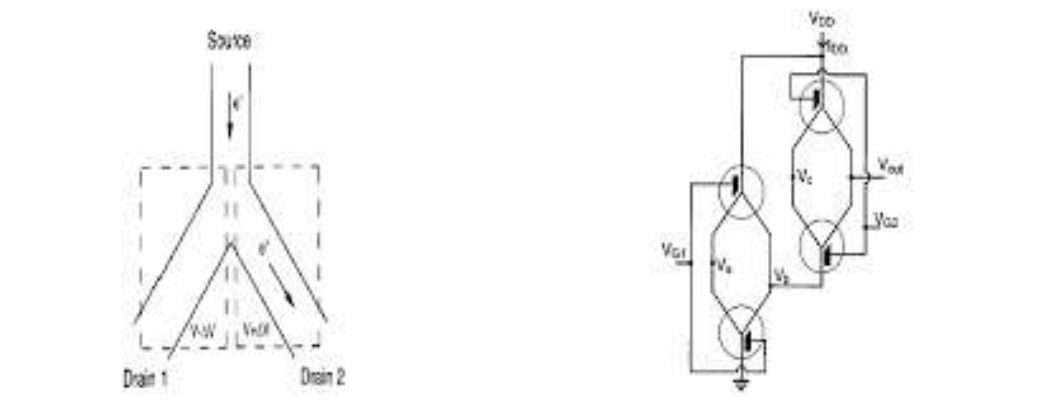

Figure 19: (left) template of a Y branch switch (right) design of a Y branch NAND gate using 2 inverters [10]

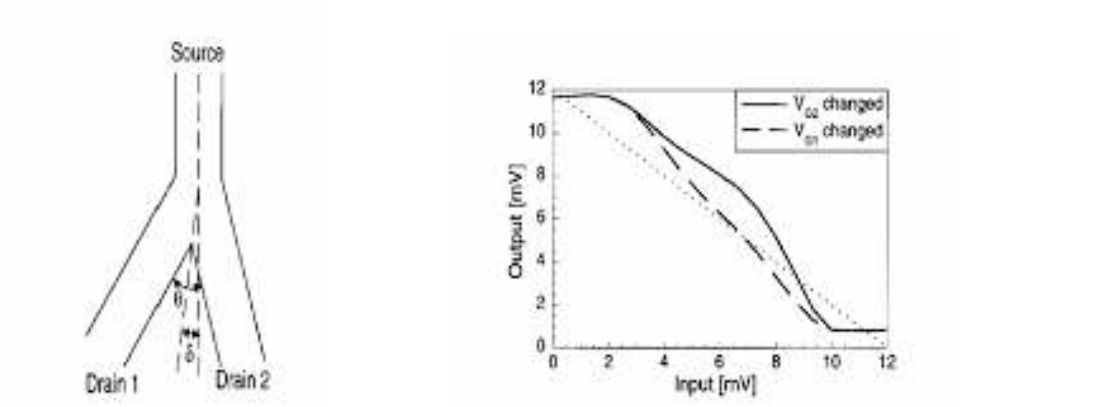

Figure 20: (left) asymmetric Y branch needed for NAND device (right) voltage characteristics of NAND gate [10]

The actual physical models in obtaining properties like current and voltage of these perturbed nanotubes is pretty advanced yet are becoming more accurate in their predicting nature. STM observations of Y branched carbon nanotubes produced by electric arc discharge method suggest that some of them are single walled Y branches [11], leaving us only to figure out better fabrication methods and to be able to refine the physics and measurement processes in order to build a functioning intramolecular NAND gate.

6 Y-Junction CNT NAND Gate Architecture and Fabrication

In this section we propose step-by-step the fabrication process to create our NAND logic gate device. We start with a silicon substrate and grow a $617.2nm$ thick layer of silicon dioxide by putting the substrate in 1050^0C and performing dry oxidation for 5 minutes, wet oxidation for 90 minutes, and dry oxidation again for another 5 minutes. The dry oxidation steps ensure the smoothness of the oxide layer. Using electron beam (e-beam) lithography, we pattern and expose the back-gate regions for the two NAND inputs. Wet etching techniques such as BHF (buffered hydrofluoric acid) can be used to etch away the exposed back-gate, oxide areas. The etch rate of BHF ranges from $10 - 100nm/min$ at room temperature and is temperature-dependent. Although wet etching techniques are usually isotropic, it is much faster than dry-etching processes and it is primarily used for etching away large areas. A $400nm$ thick layer of silicon is then deposited onto the substrate to fill in the etched regions. The excess silicon is etched away and smoothed using chemical mechanical polishing (CMP). The resulting structure is shown in Figure

21.

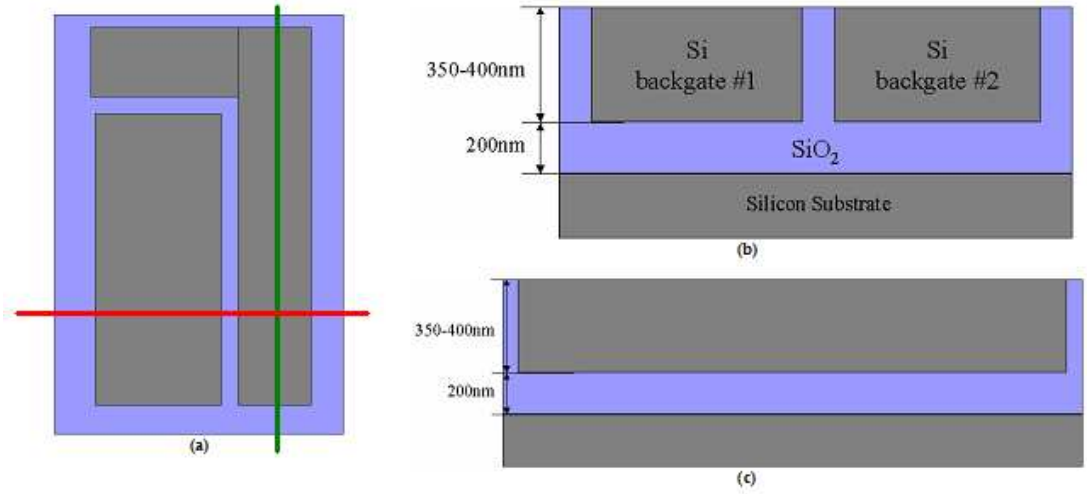

Figure 21: The patterned silicon back-gates. (a) Top-down view (b) Cross-section along the red line (c) Cross-section along the green line.

A $140nm$ thick layer of silicon dioxide is then grown via dry oxidation for approximately 2.6 hours. After this step, CMP can be used again to smooth the surface of the wafer, however it is not necessary. E-beam lithography is then used to define the gold contact regions that will allow us to easily bias the back-gate voltages. Gold is then sputtered or evaporated onto the sample. Although gold makes an excellent contact due to its stability against oxidation, it is a fast diffuser and produces deep-level recombination centers in silicon that tend to reduce the lifetime of carriers significantly. However, for experimental purposes, gold is sufficient. The gold is then patterned via e-beam lithography to create three electrodes that will connect to G_{ND} , V_{DD}, and V_{out}.

A semiconducting, asymmetric Y-nanotube is transferred (using a charged atomic force microscope tip) onto the oxidized silicon substrate prepatterned with gold electrodes. The Y-branch nanotube is placed such that the stem lies on both back-gates and each of the branches lie on different back-gate regions (Fig. 22).

We now apply a technique first proposed by V. Derycke, et al to create n-type field-effect transistors [2]. PMMA, a polymer-based mask material, is deposited on top of the substrate fabricated above. E-beam lithography then exposes the region of the device where the inherently p-type nanotube will then be doped with potassium to become n-type. The PMMA is a common resist that can help keep the device stable over time and through environment changes. It can also help protect the nanotube against the potassium doping. The doping concentration can be controlled such that the threshold voltages of the n-type FETs and the PMMA-protected p-type FETs overlap. The dis-

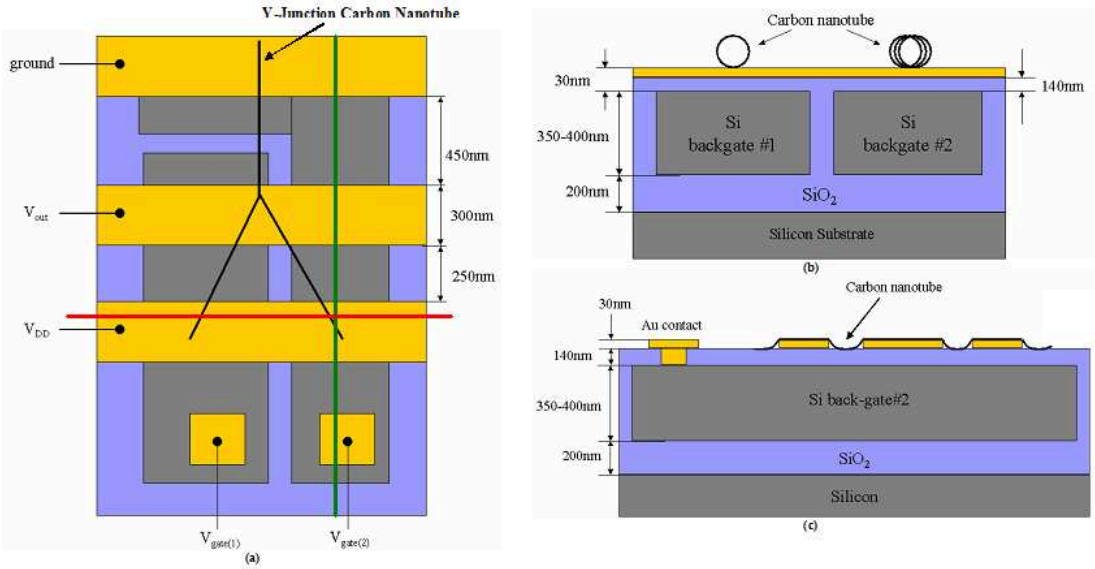

Figure 22: The final Y-branch NAND device. (a) Top-down view (b) Cross-section along the red line (c) Cross-section along the green line.

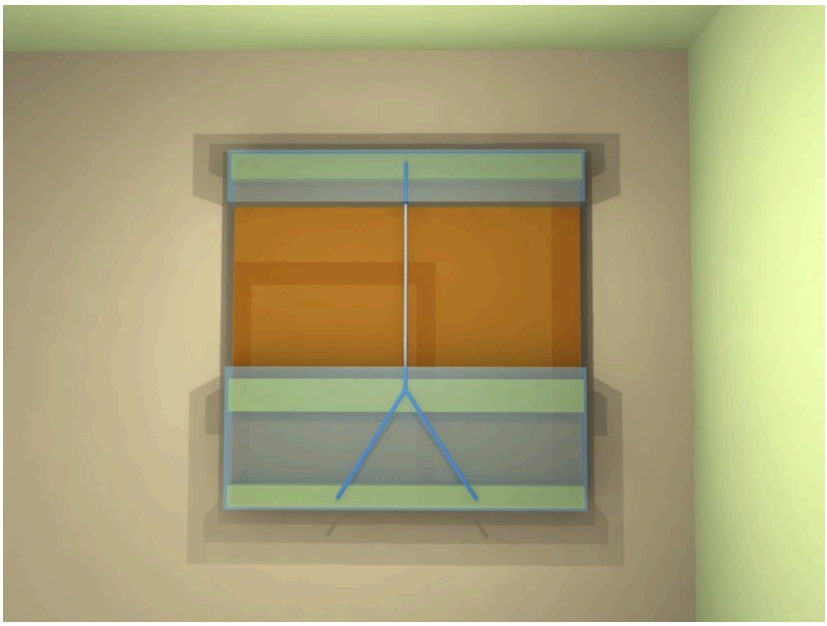

Figure 23: Top-down view of the PMMA-protected and potassium-doped nanotube NAND gate device

advantage of using PMMA is that when the nFETs are exposed to ambient temperature, the nFET is no longer stable and reverts back to a pFET. However, protecting the nFET with an additional 10nm thin layer of silicon dioxide can help eliminate this problem. The final device is shown in Figure 23.

7 Future Production Techniques

7.1 Using DNA for CNT Separation and Assembly

DNA, due to its flexible nature, has been the object of much research on molecular electronics. Nowadays, DNA sequences can be synthesized for specific purposes at reasonable cost and time. DNAs are highly charged, polar, and also sensitive to the environmental factors, such as temperature and pH value. So, what we can do with DNAs and carbon nanotubes?

Growing CNTs yield a mixture of both metallic and semiconducting nanotubes. Methods have been developed to separate between the two types; however, due to the CNT's poor polydispersabilty and solubility in both aqueous and non-aqueous solutions, the sorting of CNTs have become a big challenge [27].

Ming Zheng, et al finds that the binding of single-stranded DNA (ssDNA) to the carbon nanotube is fast and stable. He uses the ssDNA to assist in separation the nanotubes based on their electrical properties. Here is a list of advantages for DNA-coated nanotubes:

1. DNA-coated carbon nanotube (DNA-CNT) solutions are stable for months at room temperature.

2. Removal of free DNA by either anion-exchange column chromatography or nuclease digestion does not cause nanotube flocculation, indicating that DNA binding to carbon nanotubes is very strong.

3. DNA converts bundled CNT into individual tubes.

4. DNAs are easy to put on and easy to remove.

5. In comparison with other polymers that also disperse carbon nanotubes [28, 29] (CONVERT THESE REFS), DNA seems to be much more efficient.

6. DNA backbone is available to be solvated in solution, hence reducing the surface tension associated with the de-solvated nanotubes.

7. DNA offers the advantage of defined length and sequence, and well-developed chemistries for functionalization.

8. DNA-CNTs might be able to be sorted due to their different electronic properties, such as conductance (see next paragraph for more details).

They also find the optimal sequence (poly(T)) and length (30 mer) of DNA that gives maximum dispersion of nanotubes (fig. 24).

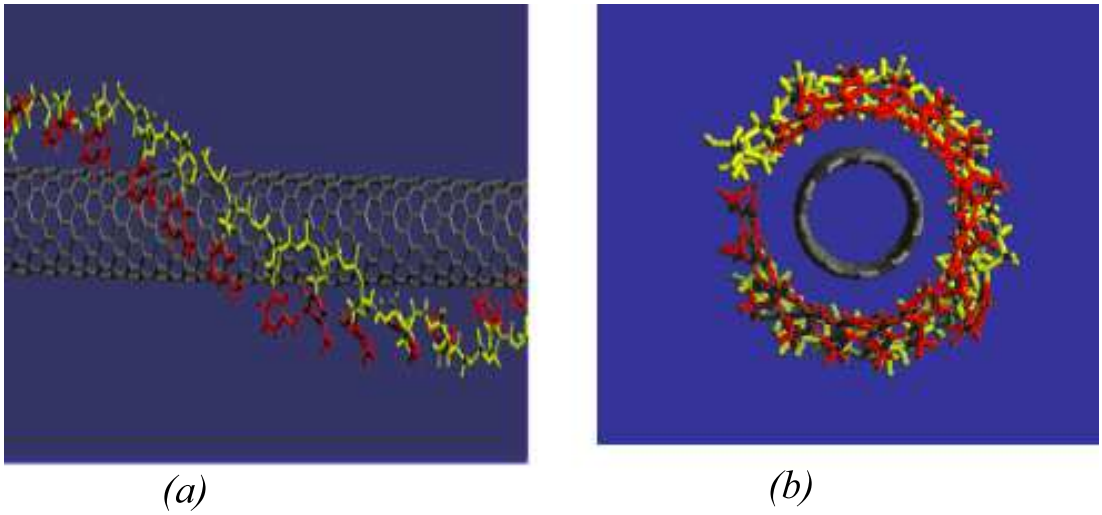

Figure 24: Poly(T) wrapping around nanotube

Due to the negative charge on the phosphate group of DNAs, DNA-CNTs are highly negatively charged. Since metal are conducting materials, DNA-metallic CNT is predicted to have less surface charge than DNA-semi-conducting CNT due to the opposite image charge created in the metallic tube. Therefore, Ming Zheng, et al, propose to use ion-exchange liquid chromatography to separate semi-conducting and metallic CNTs. Figure 25 shows a spectrum of the chromatography results.

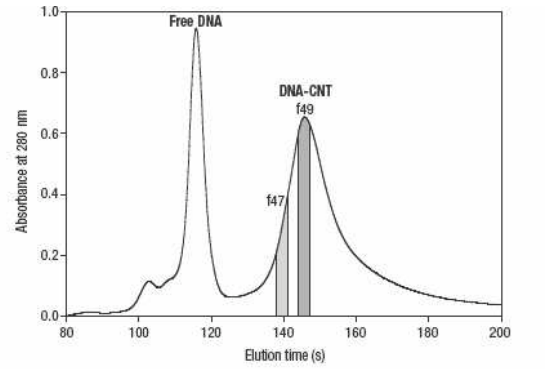

Figure 25: Chromatogram

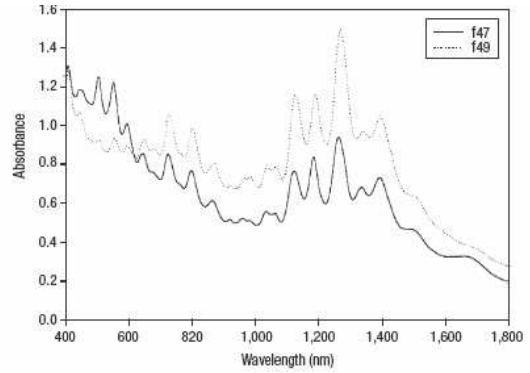

Figure 26: Electronic Absorption Spectrum

By measuring the electronic absorption spectra (fig. 26) for various fractions from the column, they found that f47 has more pronounced absorption in the metallic M11 (400-600 nm) band12, and weaker absorption in the semiconductor E11 band (900-1,600 nm) than f49. Therefore, f47 is enriched with metallic tubes. Semiconducting tubes can now be separated from metallic ones. Applying voltages on the DNA-coated carbon nanotubes can assist in aligning the nanotubes. This is useful for positioning the nanotubes at specific locations.

8 Conclusion

We have proposed an experiment to construct an intra-molecular carbon nanotube NAND gate. Also we've explored methods of fabrication and future techniques that may be used for possible mass production of such devices. Once this experiment is conducted, new nano-architectures should be investigated given the interesting properties that this along with the intra-molecular inverter present.

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