East West University

Thesis Title

Fundamental Study and Application of Carbon Nanotube in FET

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Declaration

We hereby declare that we have completed thesis on the topic entitled “Fundamental Study and Application of Carbon Nanotube (CNT) in Field Effect Transistor (FET)”as well as prepared as research report to the department of Electronics and Communication Engineering, East West University in partial fulfillment of the requirement for the degree of B.Sc in Electronics and Telecommunication Engineering, Under the course “Research/internship (ETE 498)”.

We further assert that this report in question is based on my original exertion having never been produced fully and/or partially anywhere for any requirement.

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Acceptance

This research report presented to the Department of Electronics and Communication Engineering, East West University is submitted in partial fulfillment of the requirement for degree of B.Sc in Electronics and Telecommunication Engineering, under complete supervision of the undersigned.

…………………………

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Acknowledgement

At first we are grateful to Almighty ALLAH for our good health, wellbeing and ability to complete this task.

We would like to express our gratitude to our Supervisor Dr. M. Mofazzal Hossain for his continuous support of our study, motivation, enthusiasm and sincere guidance. His guidance and support helped us to successfully completing this thesis.

We would also like to thanks our parents to give birth in this beautiful world and continuously supporting us to make our dream real.

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Abstract

Our goal is to investigate the fundamental properties and the applications of single-walled carbon nanotubes (SWCNT) in Field Effect Transistor. Due to the outstanding and exceptional properties of carbon nanotubes, many different types of CNTs have been produced at the industrial scale over the last two decades. In this study, types of carbon nanotubes, electrical properties of SWCNT and applications are analyzed. The theoretical formulations are briefly investigated for energy bandgap and I-V characteristics of SWCNT. Based on the theory, the I-V characteristics of SWCNT-based FET for different diameter of SWCNT have been analyzed. It is found that the energy gap of SWCNT decreases at increased diameter, and higher drain current was found for larger diameter SWCNT.

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Chapter 1

Introduction

Carbon nanotubes have unique physical and chemical properties. Because of the bonding characteristics of carbon atoms, the physical appearance of carbon nanotubes can often resemble rolled up chicken wire.

1.1 Background of CNT

In anticipation of mid-1980's pure solid carbon was thought to exist in only two physical forms (a) diamond and (b) graphite. They have different physical structures and properties. These two different physical forms of carbon atoms are called allotropes.

In 1985 a group of researchers led by Richard Smalley and Robert Curl of Rice University in Houston and Harry Kroto of the University of Sussex in England made an interesting discovery. They vaporized a sample of graphite with an intense pulse of laser light and used a stream of helium gas to carry the vaporized carbon into a mass spectrometer. The mass spectrum showed peaks corresponding to clusters of carbon atoms, with a particularly strong peak corresponding to molecules composed of 60 carbon atoms, C_{60}. The fact that C_{60} clusters were so easily formed led the group to propose that a new form or allotrope of carbon had been discovered. It was spherical in shape and formed a ball with 32 faces. Of the 32 faces, 12 were pentagons and 20 were hexagons exactly like a soccer ball. The soccer ball shaped C_{60} molecule was named "buckerminsterfullerene" or 'buckyball' for short.[6]

After this discovery, other related molecules (C_{36}, C_{70}, C_{76} and C_{84}) composed of only carbon atoms were also discovered and the 'buckyball' were recognized as a new allotrope of carbon. This new class of carbon molecules is called the fullerenes. Fullerenes consist of hexagons and pentagons that form a spherical shape. [6]

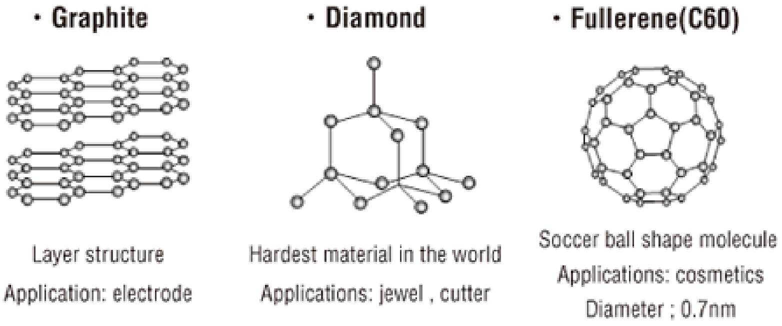


Figure.1.1 Structure of Graphite, Diamond and Fullerene

1.2 Invention of CNT

The unique geometric properties of this new allotrope of carbon did not end with soccer shaped molecules, it was also discovered that carbon atoms can form long cylindrical tubes. These tubes were originally called ‘buckytubes’ but now are better known as carbon nanotubes or CNT for short. These molecules are shaped like a tube similar to a sheet of graphite (‘graphene sheet’) or chicken wire rolled into a tube.[6]

Chapter 2

Carbon Nanotube

2.1 What is Carbon Nanotube (CNT)

A carbon nanotube is essentially one mono-atomic layer thick graphene sheet rolled-up into a seamless wrapped cylinder, caped at both ends with axial symmetry and spiral conformation, called chirality. Electrons in a CNT are confined in the radial and circumferential directions due to layer thickness and periodicity, respectively. This makes a CNT a one dimensional (1D) nanowire. [1]

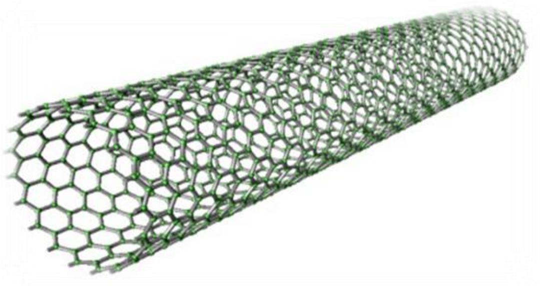


Fig.2.1 Carbon Nanotube.

- One type of carbon nanotube has a cylindrical shape with open ends, as shown in the following figure.

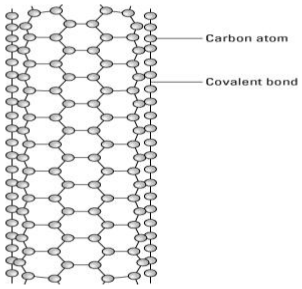


Fig.2.2 A carbon nanotube with open end.

- Another type of nanotube has closed ends, formed by some of the carbon atoms combining into pentagons on the end of the nanotube, as shown in the following figure.

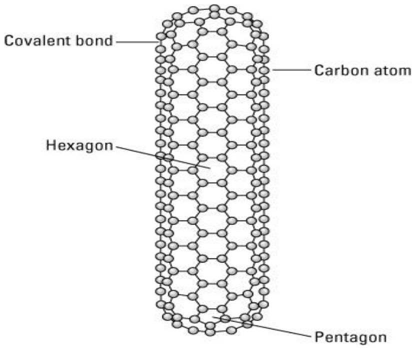


Fig.2.3 A carbon nanotube with closed ends.

2.2 Types of CNT

Carbon Nanotubes (CNTs) are cylindrical shells made, in concept, by rolling graphene sheets into a seamless cylinder. CNTs exist as**,**

(a) SWCNT (Single Walled Carbon Nanotube)

(b) MWCNT (Multi Walled Carbon Nanotube).

2.2.1 SWCNT

A single-walled nanotube is defined by a cylindrical graphene sheet with a diameter of about *0.7 - 10.0 nm*, though most of the observed single-wall nanotubes have diameters *<2 nm*. If we neglect the two ends of a carbon nanotube and focus on the large aspect ratio of the cylinder (i.e., length/diameter which can be as large as 10^4-10^5), these nanotubes can be considered as one-dimensional nanostructures.

SWNT are more pliable yet harder to make than MWCNT. They can be twisted, flattened, and bent into small circles or around sharp bends without breaking.

SWNT have unique electronic and mechanical properties which can be used in numerous applications, such as field-emission displays, nanocomposite materials, nanosensors, and logic elements. These materials are on the leading-edge of electronic fabrication, and are expected to play a major role in the next generation of miniaturized electronics. [2, 3]

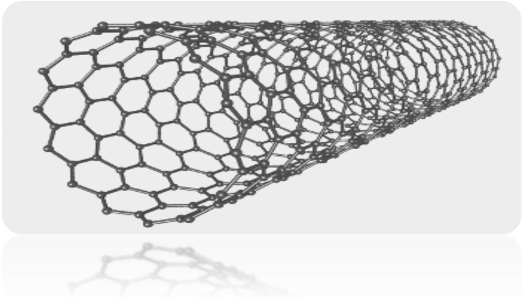


Fig.2.4 Single Walled Carbon Nanotube.

2.2.2 MWCNT

Multi-walled nanotubes (MWCNTs) consist of multiple rolled layer (concentric tubes) of graphene. In the Russian Doll model, sheets of graphite are arranged in concentric cylinders, e.g., a (0, 8) single-walled nanotube (SWCNT) within a larger (0, 17) 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 newspaper. The interlayer distance in multi-walled nanotubes is close to the distance between graphene layers in graphite, approximately 3.4 Å. The Russian Doll structure is observed more commonly. Its individual shells can be described as SWNTs, which can be metallic or semiconducting. [4]

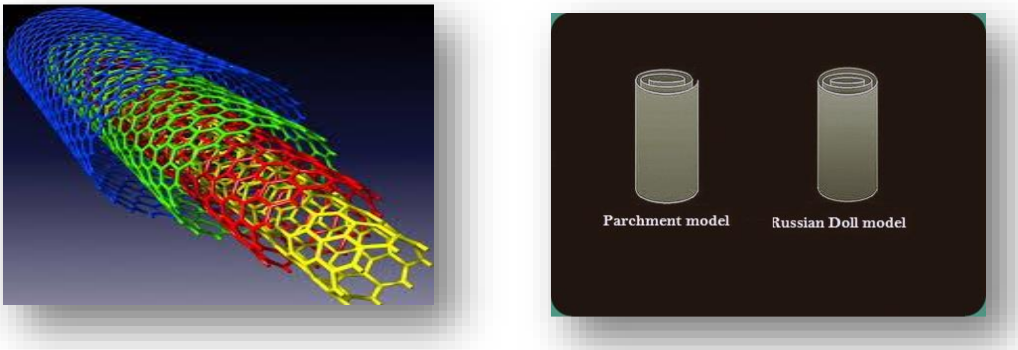


Fig.2.5 Multi Walled Carbon Nanotube.

2.3 Geometrical Structure of SWCNT

The graphene sheet can be rolled in different ways to get the three geometrical types of CNTs:

1. Armchair ($n = m$)

2. Zigzag ($m = 0$)

3. Chiral ($n \neq m$)

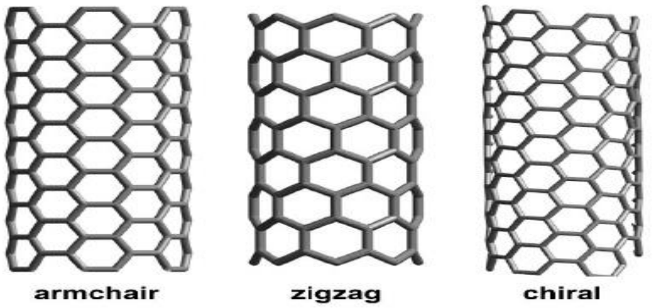


Fig.2.6 The outlines of three types of nanotube: (a) a (*10, 0*) zigzag nanotube; (b) a (*5, 5*) armchair nanotube; (c) a (*7,3*) general chiral nanotube.

These three types of SWCNT are classified on the chiral vector:

1. Zigzag

   In these the graphene sheet is rolled up along a vector greater than the chiral angle ($\theta=30^\circ$).

2. Armchair

   In these the graphene sheet is rolled up along the vector smaller than the chiral angle ($\theta=0^\circ$).

3. Chiral

   In these it is rolled up on the chiral vector ($0^\circ< \theta<30^\circ$).

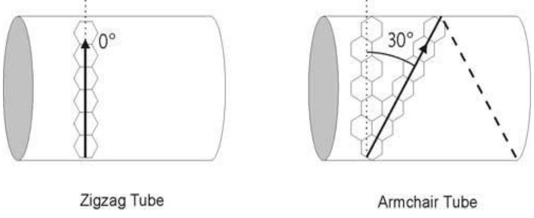


Figure.2.7 Chiral angle

2.4 Types of CNTFETs

There are two main types of CNTFETs that are being currently studied, differing by their current injection methods,

a) Schottky barrier CNTFETs (SB-CNTFETs) with metallic electrodes which form Schottky contacts.
b) MOSFET-like CNTFETs with doped CNT electrodes which form Ohmic contacts.

In SB-CNTFETs, tunneling of electrons and holes from the potential barriers at the source and drain junctions constitutes the current. The barrier width is modulated by the application of gate voltage, and thus, the transconductance of the device is dependent on the gate voltage.

The other type of the CNTFETs takes advantage of the *n*-doped CNT as the contact. Potassium doped source and drain regions have been demonstrated and the behavior like MOSFETs have been experimentally verified. [19]

2.5 Important Aspects of CNTFETs

One of the important aspects of nanotube transistors is the ambipolarity or unipolarity of their current-voltage characteristics. SB-CNTFETs exhibit strong ambipolar behavior. For high enough gate voltages the tunneling probability of electrons through the source.

In MOSFET-like CNTFETs with heavily doped source and drain regions, when applying a negative gate voltage, the band to band tunneling may lead to ambipolarity. [19]

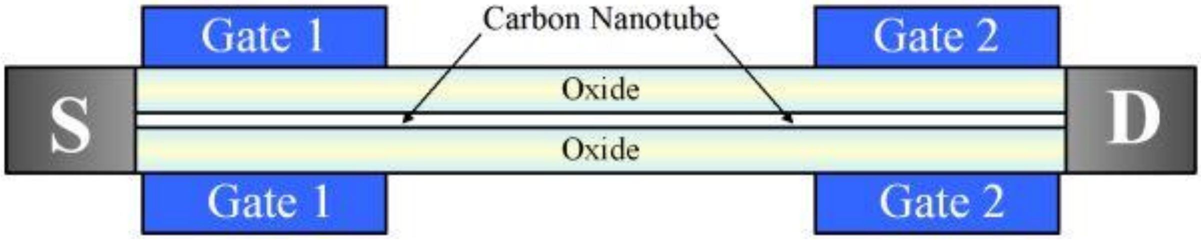


Figure 2.8 Diagram of MOSFET-like CNFET.

It is possible to use SWNT to make a Field Effect Transistor. By applying a different gate voltage, one can change the conduction by many orders of magnitude. [25]

Multi-wall carbon nanotubes (MWNTs) have been used as channels of field-effect transistors (FETs) to obtain information on their transport characteristics. MWNTs-FETs show metallic or semiconducting behavior depending on the tube diameters. All the semiconducting MWNTs have exhibited both *p*-type and *n*-type characteristics, the so-called ambipolar behavior which is absent in normal SWNTs-FETs. Comparisons between the subthreshold swing (s) factor of MWNTs and that of SWNTs indicate that MWNTs are better FET channels than SWNTs. [26]

Chapter 3

Methodology

3.1 Introduction

For fundamental study and to know the application of carbon nanotube in FET, it is necessary to know the mathematical formulations for chirality of CNT, chiral angle, diameter, relation between diameter and energy gap, Electronic structure of a graphene layer, energy dispersion relations and also the IV characteristics of CNTFETs. By the help of E_g vs d, it is more easier to find out the mathematical relation between V_{gs} vs I_d for different diameter, V_{ds} vs I_d for different diameter and also V_{ds} vs I_d for for different V_{gs}. The simulation of MATLAB codes, the result and discussions will be found in Chapter 4.

3.2 Mathematical Formulations

Different types of nanotubes that can be described by the tube chirality, defined by chiral vector ($\boldsymbol{C}_h$) and the chiral angle θ The chiral vector can be described in terms of the lattice translational indices (n,m) and the unit vectors $\mathbf{a}_1$ and$\mathbf{a}_2$ as shown in eq. (3.1)

$$C_h=na_1+ma_2 \tag{3.1}$$

The chiral vector is determined by the diagram,

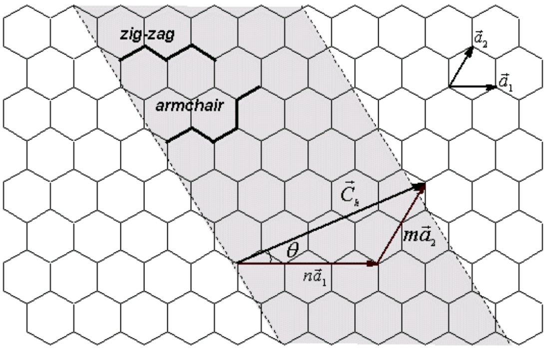


Fig.3.1 Schematic diagram showing how a hexagonal sheet of graphite is 'rolled' to form a carbon nanotube.

The chiral angle θ, determining the degree of “twisting" of the tube, is defined as the angle (θ) between the vectors and a_1, which varies in the $0^o \leq |\theta| \leq 30^o$ range. In terms of the integers (n,m), θ can be described by the equation below, [5]

$$Cos\theta = \frac{2n+m}{2\sqrt{n^2+nm+m^2}} \quad \textbf{(3.2)}$$

The given lattice translational indices (n,m), the diameter of a carbon nanotube can be expressed by using the relationship,

$$d = \frac{a}{\pi}\sqrt{n^2+nm+m^2} \quad \textbf{(3.3)}$$

The electronic properties of these nanotubes are determined by their (n, m) chiral indices according to the rules:
If, $(n-m)/3=$ integer, then CNT is called Metallic
If, $(n-m)/3\neq$ integer, then CNT is called Semiconducting

This pair of indices (n,m) determine whether CNT is a metal, semiconductor, semimetal and also it’s band gap.

3.3 Energy gap and Diameter

Metallic zigzag nanotubes were found to have energy gap with magnitudes that depends inversely on the square of the tube radius where as isolated armchair tubes don’t have energy gap. That gap is called pseudo gaps. Band gap (Eg) is controlled by diameter (d_t). The semiconducting nanotubes shows that their energy gap depends upon the reciprocal nanotube diameter d_t independent of the chiral angle of the semiconducting nanotube, where $a_{c-c}=0.142nm$ is the nearest-neighbor C-C distance on a graphene sheet and graphite overlap integral taken as $|t|=3.13\ eV$, the eq^n (4.4) shows, [10]

$$Eg=|t|a_{c-c}/d_t \quad \textbf{(3.4)}$$

3.4 Energyband Structure of SWCNT

CNT is a rolled-up sheet of graphene. An appropriate boundary condition is required to explore the band structure. The E-k dispersion relation for graphene can be expressed as:

$$E(kx, ky)=\varepsilon_p \pm V_{pp\pi}\,[1+4\cos^2(k_y a/2)+4\cos(\sqrt{3}k_x a/2)\cos(k_y a/2)]^{1/2} \qquad \textbf{(3.5)}$$

For simplicity, here the electronic properties of semiconducting zigzag nanotubes are discussed only. The energy dispersion relation of an (n, 0) zigzag nanotube can be easily obtained from above equation by writing periodic boundary condition on k_y as:

$$K_y = \frac{2\pi}{na}p$$

Putting this value of k_y in Eq. (1) and writing $k_x = k$, the dispersion relation of an (n, 0) zigzag nanotube becomes:

$$E(k, p)=\varepsilon_p \pm V_{pp\pi}\,[1+4\cos^2(\pi p/n)+4\cos(\sqrt{3}k_a/2)\cos(\pi p/n)]^{1/2} \qquad \textbf{(3.6)}$$

Here $V_{pp\pi}$: is the π-bond energy (3.03 eV), $\varepsilon_p = 0.0$ eV and $p=1$ to $2n$. Positive and negative signs are taken for conduction band energy and valence band energy respectively.

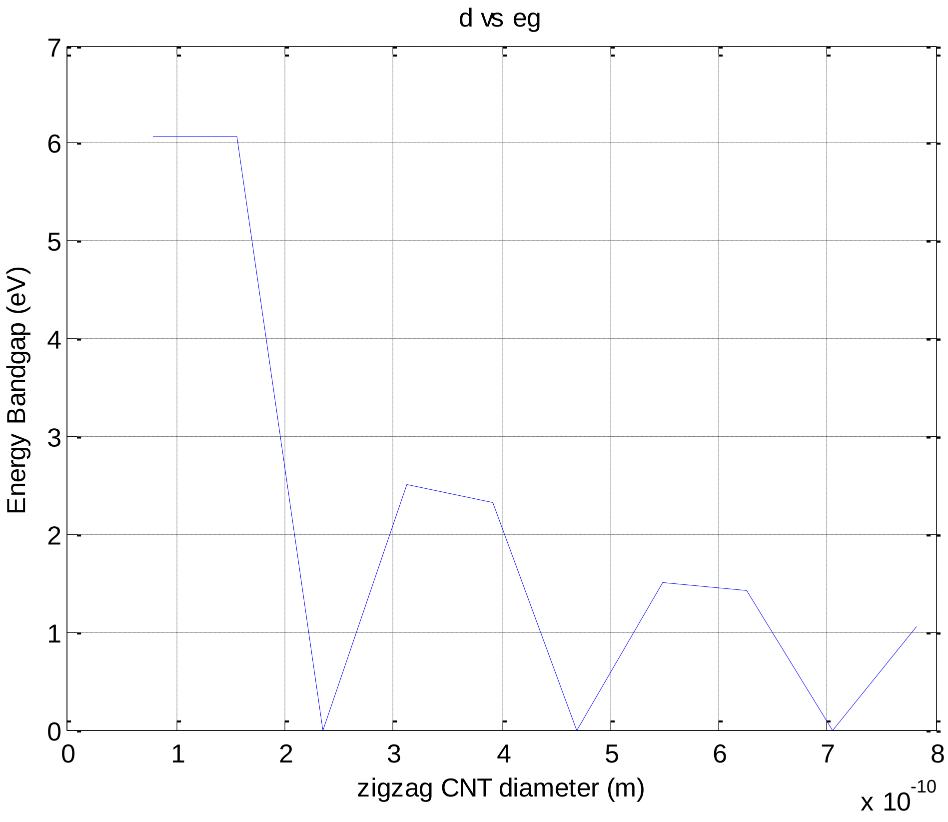
3.5 I-V Characteristics of CNTFETs

CNTFETs can act as ambipolar transistors and also acting as n-channel transistors. The source and drain Fermi levels can be moved in relation to the CNT band gap. With this fact, n-channel and p-channel IV characteristics can be equal for the absolute value of the applied voltages, $|V_{drain}-source|$ ($|V_{ds}|$) and $|V_{gate}-source|$ ($|V_{gs}|$). This means that *p*-channel or *n*-channel transistors can have the same current levels when their widths and process variations are equal and the V_{gs} and V_{ds} are equal and of opposite sign. [13]

$$Id= 4eKT/h[\ln(1+e^{(2eVgs-Eg)/2KT)}-\ln(1+e^{(eVgs-Eg-2eVds)/2KT}] \qquad \textbf{(3.7)}$$

Chapter 4

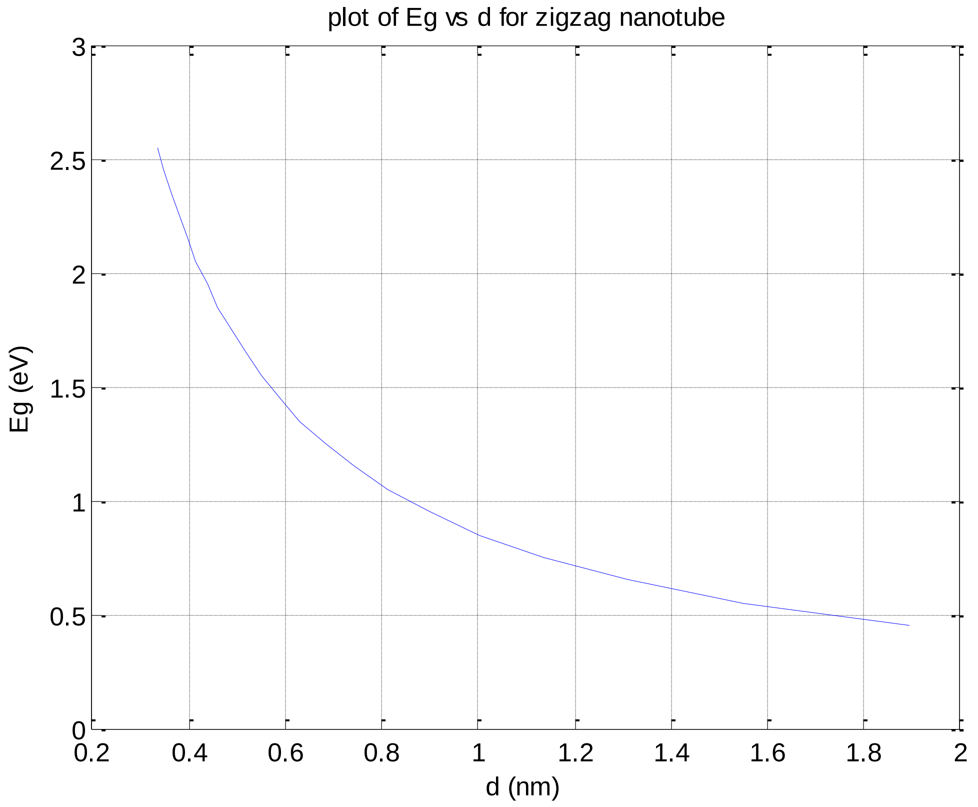
Result and Discussion



4.1. Energy band gap vs zigzag CNT diameter

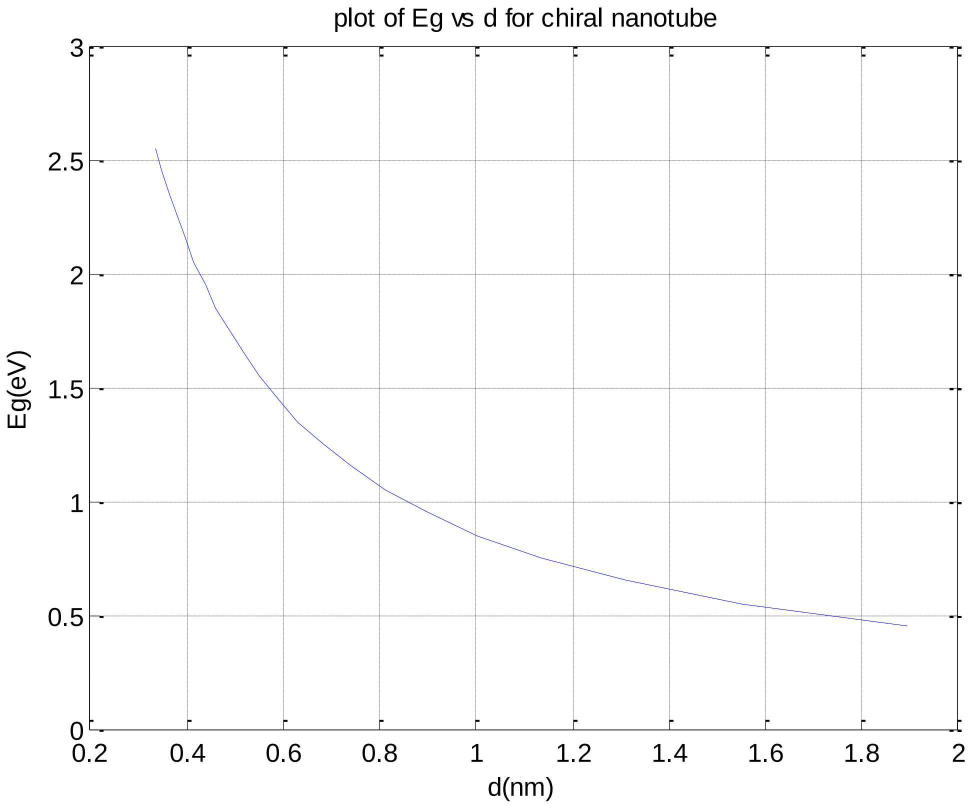
To establish the plot of Energy band gap versus zigzag CNT diameter, we considered *n*=1:1:10, *p*=1:1:2*n, *k*=0, γ_o= -3.03eV. The developed MATLAB code for figure 4.1 is included in Appendix A (A.1). If we ignore the decreasing value of energy gap (3, 6, 9), where metallic behavior found, it is seen that, energy gap is inversely proportional to diameter. Here the equation for electronic structure of a graphene layer is used.

4.1. Result and Discussion



4.2. Energy gap versus diameter for zigzag nanotube

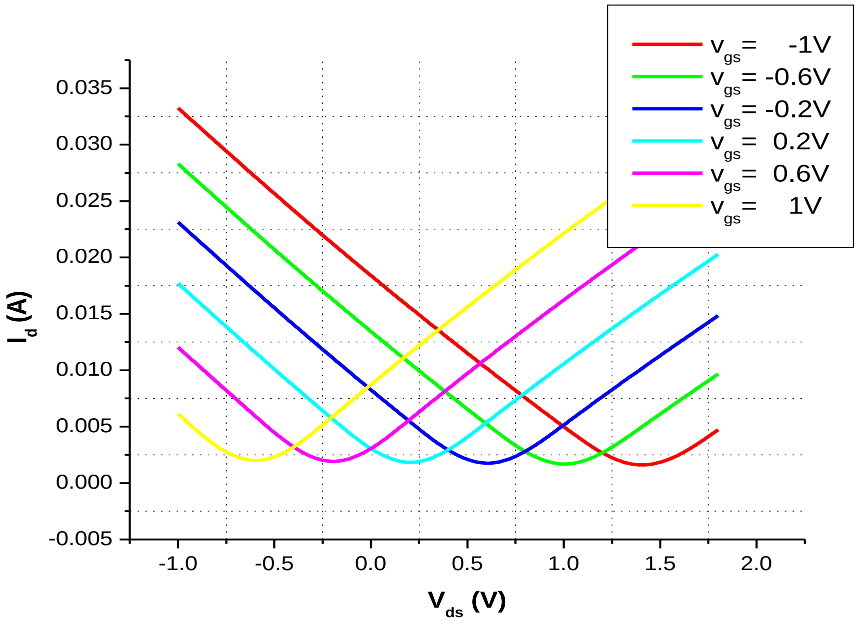
To implement the plot of energy gap versus diameter for zigzag nanotube, we considered indices (*m*,*n*)=(9,0), a_{c-c}=0.142nm, *t*=6eV and diameter range, *d*=0.45:0.1:2.55, the developed MATLAB codes for figure 4.2 is included in Appendix A (A.2).



4.3. Energy gap versus diameter for chiral nanotube

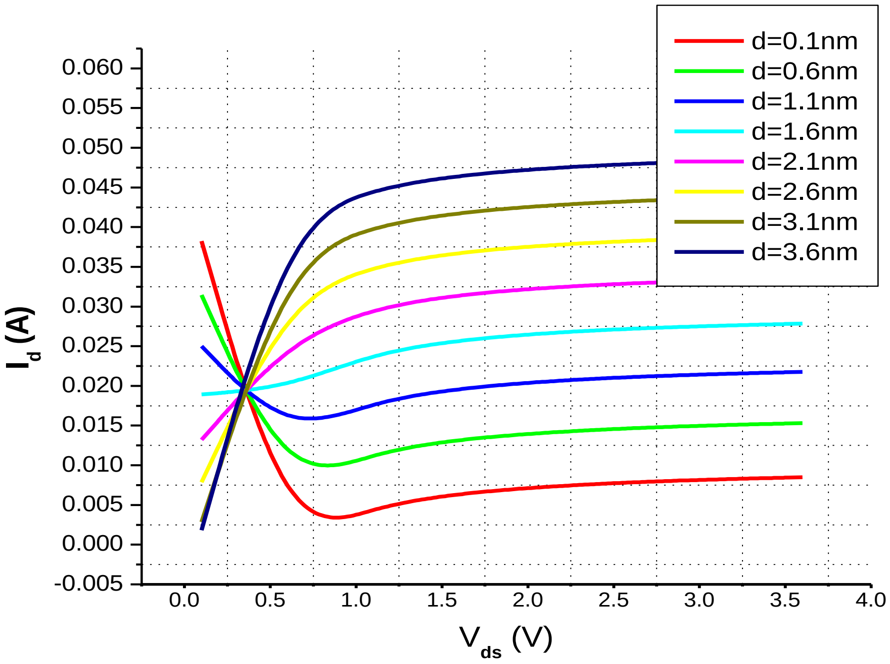
To implement the plot of energy gap versus diameter for armchair nanotube, we considered indices (*m*,*n*)=(9,7), a_{c-c}=0.142nm, *t*=6eV and diameter range, *d*=0.45:0.1:2.55, the developed MATLAB codes for figure 4.3 is included in Appendix A (A.3).

After completing this MATLAB simulation, it is seen that when energy gap increases, diameter of CNT decreases as we saw the given equation 3.4. It is now experimentally proved that energy gap depends upon the reciprocal nanotube diameter.



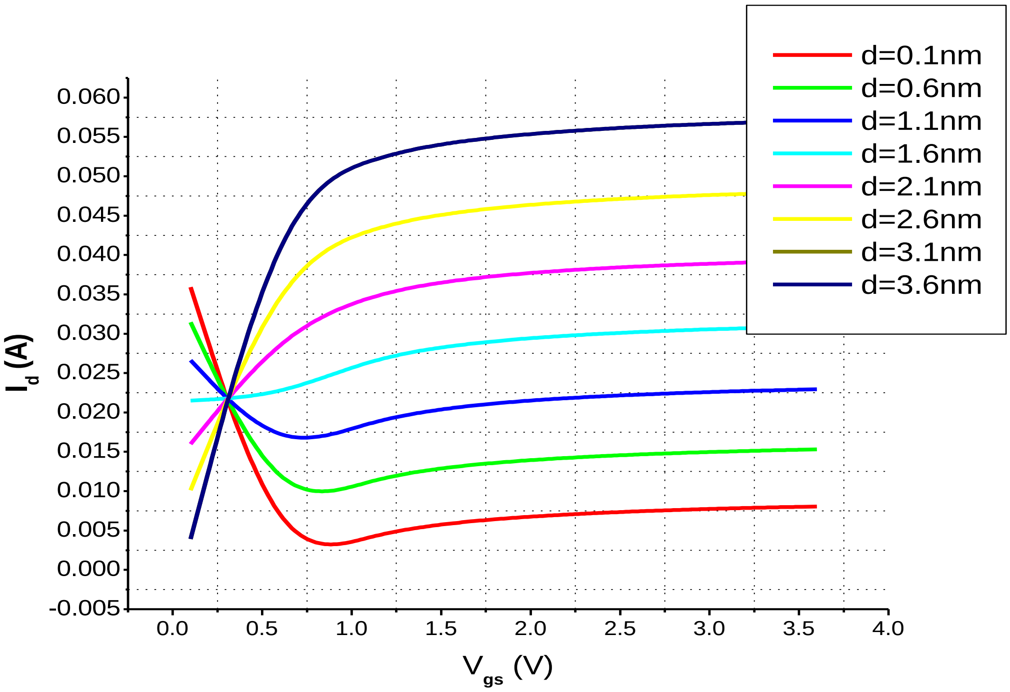
4.4. Current (I_d) versus Drain Source Voltage (V_{ds}) for different Gate Source Voltage

By considering V_{gs} and V_{ds} = -1:0.4:2, Current versus Drain Source Voltage for different Gate Source Voltage (V_{gs}) can be calculated. Here another parameter diameter was considered as 1. In the equation 3.7 for calculating I_d, the absolute values were considered and when V_{gs} increases, a greater value of drain current (I_d) results. The developed MATLAB code for figure 4.4 is included in Appendix B (B.1).



4.5. Current (I_d) versus Drain Source Voltage (V_{ds}) for different diameter

By considering V_{ds}= 0.1:0.5:4, plot for Current versus Drain Source Voltage for different diameter can be calculated. Here other parameters V_{gs} is considered as 0.6V and diameter range was 0.1:0.5:4. In the equation 3.7 for calculating I_d, the absolute values were considered. This indicates that larger diameter gives larger current. The developed MATLAB code for figure 4.5 is included in Appsendix B (B.2).



4.6. Current versus Gate Source Voltage for different diameter

By considering V_{gs}= 0.1:0.5:4 and temperature 300K, plot for Current versus Gate Source Voltage for different diameter can be calculated. Here other parameters V_{ds} is considered as *0.6V* and diameter range was 0.1:0.5:4. In the equation 3.7 for calculating I_d, the absolute values were considered. This indicates that larger diameter gives larger current. The developed MATLAB code for figure 4.6 is included in Appendix B (B.3).

After completing this MATLAB simulation, it is seen that when the value of drain voltage and gate voltage is 0.6V in two curves separately, the absolute value of current was exactly same at that point. Thus it is shown that *p*-channel or *n*-channel transistors can have the same current levels when their widths and process variations are equal and the V_{gs} and V_{ds} are equal and of opposite sign.

Chapter 5

Applications of CNT

Carbon nanotubes are currently being used or considered for a number of significant applications:

AFM probe tips. Single-walled carbon nanotubes have been attached to the tip of an AFM probe to make the tip "sharper". This allows much higher atomic resolution of the surface under investigation. Also, the flexibility of the nanotube prevents damage to the sample surface and the probe tip if the probe tip happens to "crash" into the surface. Piezomax a company started by Max Legally, director of MRSEC's IRG 1, that attaches carbon nanotubes to AFM probes for the purpose of increased resolution as well as decreased wear on sample and probe tip. [40]

Flat panel display screens. When a nanotube is put into an electric field, it will emit electrons from the end of the nanotube like small cannon. If those electrons are allowed to bombard a phosphor screen then an image can be created. Several companies (SI Diamond, Samsung) are using this technology to replace the bulky electron guns of conventional television sets with these significantly smaller carbon nanotube electron guns. When scientists instead use millions of carbon nanotubes as tiny electron guns, the required dimensions change and the creation of a flat panel display (that can hang on wall) becomes possible. In fact, some advertising billboards have already been made and are being used. [39]

Microelectromechanical devices. Dr. Morinobu Endo at Shinshu University mixed nylon with carbon fibers (not nanotubes) 100-200 nm in diameter creating a nanocomposite materials that could be injected into the world’s smallest (as of 2/6/2002) gear mold. The carbon fibers have good thermal conductivity properties that cause the nanocomposite material to cool more slowly and evenly allowing for better molding characteristics of the nanocomposite. The "improved" properties of the nanocomposite allow it more time to fill the tiny micron-sized mold than nylon would by itself. The tiny gears currently are being made in collaboration with Seiko for use in watches.[38]

Hydrogen storage. When oxygen and hydrogen react in a fuel cell, electricity is produced and water is formed as a byproduct. If industry wants to make a hydrogen-oxygen fuel cell, scientists and engineers must find a safe way to store hydrogen gas needed for the fuel cell. Carbon nanotubes may be a viable option. Carbon nanotubes are able to store hydrogen and could provide the safe, efficient, and cost-effective means to achieve this goal. [37]

Actuators/Artificial muscles. An actuator is a device that can induce motion. In the case of a carbon nanotube actuator, electrical energy is converted to mechanical energy causing the nanotubes to move. Two small pieces of "buckypaper," paper made from carbon nanotubes, are put on either side of a piece of double-sided tape and attached to either a positive or a negative electrode. When current is applied and electrons are pumped into one piece of buckypaper and the nanotubes on that side expand causing the tape to curl in one direction. This has been called an artificial muscle, and it can produce 50 to 100 times the force of a human muscle the same size. Applications include: robotics, prosthetics. [36]

Chemical sensors. Semiconducting carbon nanotubes display a large change in conductance in the presence of certain gases (e.g., NO_2 and NH_3). When compared to conventional sensors, carbon nanotubes provide the advantages of a smaller size, an increased sensitivity, and a faster response. [35]

Nanoscale electronics/nanocomputing Scientists have exploited the mechanical and electrical properties of carbon nanotubes to produce molecular electronic devices. When nanotubes are placed in a grid, the intersections of the nanotubes become bits of information that can be stored non-volatilely. [34]
Semiconducting nanotubes also can be used as single molecule transistors.

Nanothermometer. A carbon nanotube can be partially filled with gallium metal. When the temperature is changed, the gallium metal expands or contracts to fill or empty the carbon nanotube. The gallium level in the carbon nanotube varies almost linearly with temperature. This new device may find use in certain microscopies.

Flash photography and carbon nanotubes. Scientists have discovered that as-grown single-walled carbon nanotubes can be ignited by holding a conventional camera flash a few centimeters away and flashing the sample.[33]

Chapter 6

Conclusion

Rolled graphene sheet in different forms can create the types of nanotube. Different structures of nanotube create indices, angles that were helped to find the theoretical values of diameter and energy gap. From our analysis it is found that Energy gap is inversely proportional to diameter of single walled CNT. Again it is seen from I_d vs V_{ds} for different V_{gs} and a constant diameter that the V_{gs} increment effect will influence the drain current (I_d). That is, as V_{gs} increases, a greater value of I_d results. From the analysis of I_d vs V_{ds} and V_{gs} for different diameter it was found larger diameter gives larger current, current is strongly dependent on diameter, less dependent on V_{ds} and V_{gs} because if we change diameter range the changes of V_{ds} and V_{gs} is almost constant. The absolute value of current was taken for implementing different value of diameter and also different gate voltage.

Chapter 7

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Appendix

Appendix A

A.1. Matlab codes for finding Enegy gap vs diameter for different energy level (zigzag nanotubes)

```
clc
n=[1:1:10];
w=length(n);
d=zeros(1,w);
eg=zeros(1,w);
for z=1:w
    p=[1:1:2*n(z)];
    k=0;
    a=0.246e-9;
    ep= 0.0;
vpp= -3.03;
    x=(pi.*p)./n(z);
    s=vpp.*(1+(4.*(cos(x)).^2)+(4.*(cos(x)))).^0.5;
egc=ep+s;
egv=ep-s;
eg(z)=min(egv-egc)
d(z)=(a.*n(z))./pi
end
plot(d,eg);
xlabel('zigzag CNT diameter (m)');
ylabel('Energy Bandgap (eV)');
title('d vs eg');
grid on;
fid=fopen('Vds_Id_cnt.doc','w');
fprintf(fid,'%10.10f\r\t\n',d,eg);
fclose(fid);
```

A.2. Matlab codes for finding Enegy gap vs diameter(zigzag nanotubes)

```
clc;
close all;
clear all;
n=9;
m=0;
t=6;
a=0.142;
d=(((sqrt(3)/pi)*a)*(sqrt(m^2+m*n+n^2)));
d=[0.45:0.1:2.55]
Eg=((t.*a)./d);
plot(Eg,d)
title(' plot of Eg vs d for zigzag nanotube'),grid on
xlabel('d (nm)')
ylabel('Eg (eV)')
fid=fopen('Eg_d.doc','w');
fprintf(fid,'%10.10f\r\t\n',d,Eg);
fclose(fid);
```

A.3. Matlab codes for finding Enegy gap vs diameter(chiral nanotubes)

```
clc;
close all;
clear all;
n=9;
m=7;
t=6;
a=0.142;
d=(((sqrt(3)/pi)*a)*(sqrt(m^2+m*n+n^2)));
d=[0.45:0.1:2.55]
Eg=((t.*a)./d);
plot(Eg,d)
title(' plot of Eg vs d for chiral nanotube'),grid on
```

```
xlabel('d (nm)')
ylabel('Eg (eV)')
fid=fopen('Eg_d.doc','w');
fprintf(fid,'%10.10f\r\t\n',d,Eg);
fclose(fid);
```

Appendix B

B.1. Matlab codes for finding drain voltage (Vds) vs current (Id) for different gate voltage(Vgs)

```
clc;
clear all;
close all;
vgs=[-1:0.4:2]
d=1;
Vds=[-1:0.4:2]
q=1.6.*exp(-19);
Eg=(0.8./d).*q;
K=1.38.*exp(-23);
T=300;
h=6.626.*exp(-34);
for i_Vg = 1:length(vgs)
 vgs_x = vgs(i_Vg);
C=((4*q*K*T)./h);
S=(((2*q*vgs_x)-Eg)./(2*K*T));
D=((2*q*vgs_x)-Eg-(2*q.*Vds)./(2*K*T));
Id(:,i_Vg)=abs(C.*abs(log((1+exp(S)))-abs(log(1+exp(D)))))
end
figure;
plot( vgs ,abs(Id),'LineWidth', 2);
title('Id(A) vs  vds (V) for different vgs');
xlabel('Drain voltage (Vds)');
ylabel('Id (A)');
legend(num2str(vgs'));
grid on;
fid=fopen('different_vg.doc','w');
fprintf(fid,'%10.10f\r\t\n',Vds,Id);
fclose(fid);
```

B.2. Matlab codes for finding drain voltage(Vds) vs current(Id) for different diameter(d)

```
clc;
close all;
clear all;
d=[0.1:0.5:4];
Vds=[0.1:0.5:4]
Vgs=0.6
q=1.6.*exp(-19);
Eg=(0.8./d).*q;
K=1.38.*exp(-23);
T=300;
h=6.626.*exp(-34);
for i = 1:1:length(Vds)
 Vds_x = Vds(i);
C=((4*q*K*T)./h);
S=(((2*q*Vgs)-Eg)./(2*K*T));
D=((2*q.*Vgs)-Eg-(2*q.*Vds_x)./(2*K*T));
Id(:,i)=abs(C.*abs(log((1+exp(S)))-abs(log(1+exp(D)))))
end
figure;
plot(Vds, abs(Id),'LineWidth', 2);
title('Id (A) vs Vds (V)for different diameter');
xlabel('Drain-source voltage(V)');
ylabel('Id (A)');
legend(num2str(d'));
grid on;
fid=fopen('Vds_Id_cnt.doc','w');
fprintf(fid,'%10.10f\r\t\n',Vds, Id);
fclose(fid);
```

B.3. Matlab codes for finding gate voltage(Vgs) vs current(Id) for different diameter(d)

```
clc;
clear all;
close all;
vgs=[0.1:0.5:4]
d=[0.1:0.5:4];
Vds=.6
q=1.6.*exp(-19);
Eg=(0.8./d).*q;
K=1.38.*exp(-23);
T=300;
h=6.626.*exp(-34);
for i_Vg = 1:1:length(vgs)
 vgs_x = vgs(i_Vg);
C=((4*q*K*T)./h);
S=(((2*q*vgs_x)-Eg)./(2*K*T));
D=((2*q*vgs_x)-Eg-(2*q.*Vds)./(2*K*T));
Id(:,i_Vg)=abs(C.*abs(log((1+exp(S)))-abs(log(1+exp(D)))))
end
figure;
plot(vgs, abs(Id),'LineWidth', 2);
title('Id(A) vs  vgs (V) for different diameter');
xlabel(' Gate-Source voltage(V)');
ylabel('Current(A)');
legend(num2str(d'));
grid on;
fid=fopen('vgs_vs_id.doc','w');
fprintf(fid,'%10.10f\r\t\n',vgs, Id);
fclose(fid);
```