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p-n Junction of 1.95 nm Carbon Nanotube: Fabrication, Properties and Performance

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Abstract: Carbon Nanotube (CNT) is the substitution of silicon material for designing of transistor device due to the shortcoming of silicon properties. In this study, 1.95 nm diameter of CNT is fabricated and characterized by analyzing of depletion width and I-V characteristics by realizing the p-n junction behavior. The p-n junction behavior of carbon nanotube is realized by applying self-consistency of the electrostatic potential and charge of CNT. The result shows that the variation of doping concentration happens in p-n junction due to the different cylindrical size of the carbon nanotube. Finally, the p-n junction current voltage transfer characteristics shows low current required for CNT device.

Keywords: p-n Junction, Self-Consistency, Nanotube

Introduction

A carbon nanotube is an active element that can be used in nanoscale Carbon nanotube attracted the researchers to open opportunities on the field of semiconductor research. Additionally, some other features are also growing interested for the further investigation on CNT, such as CNT channel width is in nanometer size which will enable the investigation of semiconductor devices in nanometer scale. Furthermore, the carrier concentration and effective mass of CNT is extremely with the good characteristics.

A carbon nanotube is a novel material for microelectronics components fabrication, such as a CNT-based Field-Effect Transistor (CNTFET). No other excellent choices rather than CNTFET are available for the replacement with CMOS device in nanometer length for digital device applications (Tulevski *et al*., 2014; Schroter *et al*., 2012). Basically, CNTs are connected with the silicon device with the metal contact embedded with the electronic device in nanometer regime. The contact electrodes consist of low resistance compare to other semiconductor devices (Franklin *et al*., 2014). Carbon nanotube resistance together with the contact electrode resistance interrupts the operating current of the electronics device. Therefore, experimental studies are required to verify and check the electrical properties of nanomaterial and its electrodes. However, some researches were carried out to understand the contact material electrical properties (Yam *et al*., 2015; Fediai *et al*., 2015; 2016). The lack of controlled diameter of the carbon nanotube is found from these research works. However, the hybrid of NEGF and DFT methods are observed for the nanotube specifications based electrical properties were simulated (Claus *et al*., 2013; Liu *et al*., 2015; Cao *et al*., 2013). In line with the theoretical simulation of NEGF and DFT methods, the Hamiltonian equation shows very effective results (Ryndyk, 2016). However, p-n junction analysis of CNT was absent in those researches to convey the FET in developing the electronics device. In addition, the tight-binding model of CNTs helps to calculate the analytical solution of 1D graphene (Schwierz, 2010) figure out from the electronic structure.

This work has been categorized into two divisions in the following sections. In the first section, a large quantity of CNTs is produced by using CVD process. Methane was used as the main source of the carbon nanotube. The continuous growing of CNTs can be observed by the deploying vertical reactor. In the second division, this research is dealing with the doping function of the p-n junction and analyzes the current-voltage characteristics of the carbon nanotube device.

Fabrication and Analysis of Carbon Nanotube

This section elucidates about the fabrication process of the carbon nanotube. The CNT fabricated in this research is aimed to have a particular diameter which allows the low bandgap and low energy consumption of the CNT device such as a field-effect transistor. The fabrication process consists of following steps, such as (i) growing of CNT, (ii) electrode production, (iii) removing oxide. CVD process was used to produce CNT.

Growing of CNT

Carbon nanotube growing method is elaborated here provided that the diameter of a nanotube is controlled due to get the particular nanotube. The manufacturing process of CNTs has been conducted using CVD process.

Figure 1 shows the experimental setup diagram for carbon nanotube growing process. In the experimental setup, gas low pipe, a pump, quartz tube which fitted electrical furnace, flow controllers are well equipped for experimentation. Flow controller and the pump are working together for controlling the gas flow rate. The product and the exhaust gas were released by the bottom line of the quartz tube. The temperature was controlled between 950°C and 1150°C due to stat CVD experimental process. The Nitrogen gas flow rate was controlled between 100 sccm and 250 sccm and methane flow rate was controlled between 950 and 2050 sccm.

Diameter-controlled carbon nanotubes were investigated using FFD experimentation. The investigation includes methane flow, nitrogen flow, temperature and tube pressure. The average diameter of the produced carbon nanotubes is shown in Fig. 2. A fine tuning was executed to have a variable base diameter of the nanotube based on the tuning of the parameters above. Table 1 shows the details elaboration of the diameter adjusted experimentation data. The average diameter of the nanotubes has been captured by SEM investigation.

The oxidized silicon surface deposited catalyst was processed at 900°C with the hydrogen gas flow rate of 700 sccm. Finally, methane was applied with the flow rate of 1100 sccm at the temperature of 900°C to complete the CVD process. The CVD process was continued for 15 min. The produced carbon nanotube was analyzed by AFM and SEM. From the experiment, 1.5~2 nm diameter of CNTs is found where the average diameter is 1.95 nm was determined. Figure 2a SEM view of CNTs in micrometer scale and Fig. 2b shows enlarged SEM view of CNT in nanometer scale. From the SEM analysis, the average diameter 1.95 nm is found for carbon nanotube. Contacts are required for the CNTs to make the connection between source and drain of a field-effect transistor.

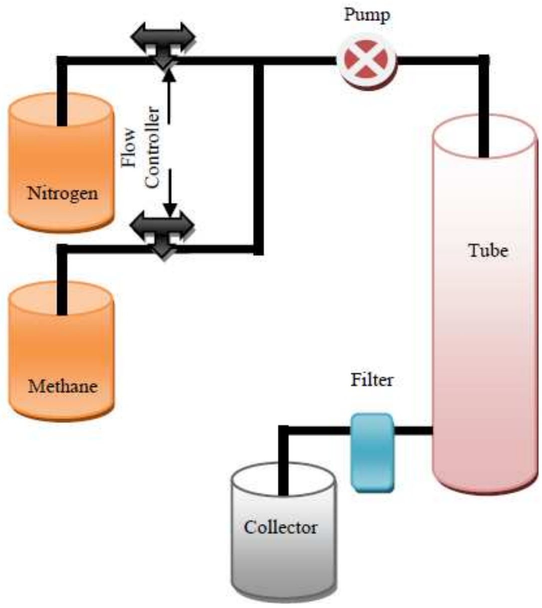
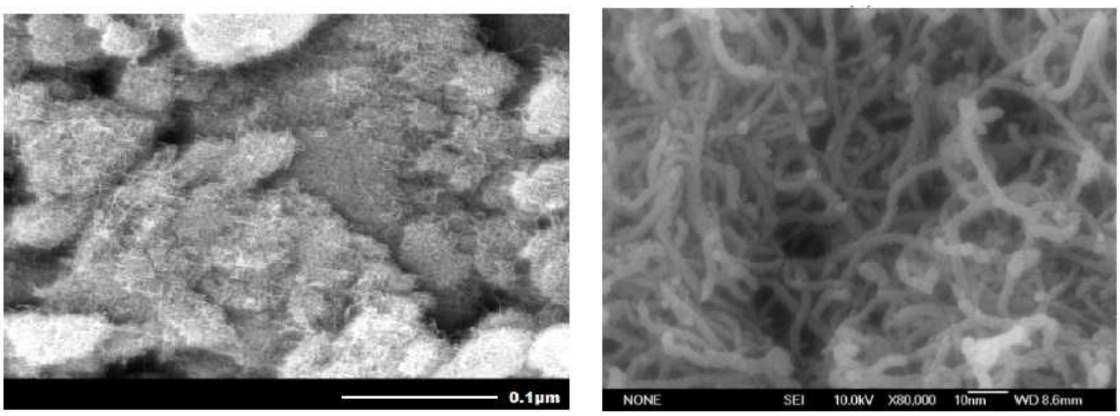


Fig. 1. Carbon nanotube growing schematic diagram



(a) (b)

Fig. 2. SEM micrographics view of the CNTs in (a) micrometer length, (b) nanometer length, the average diameter is 1.95 nm

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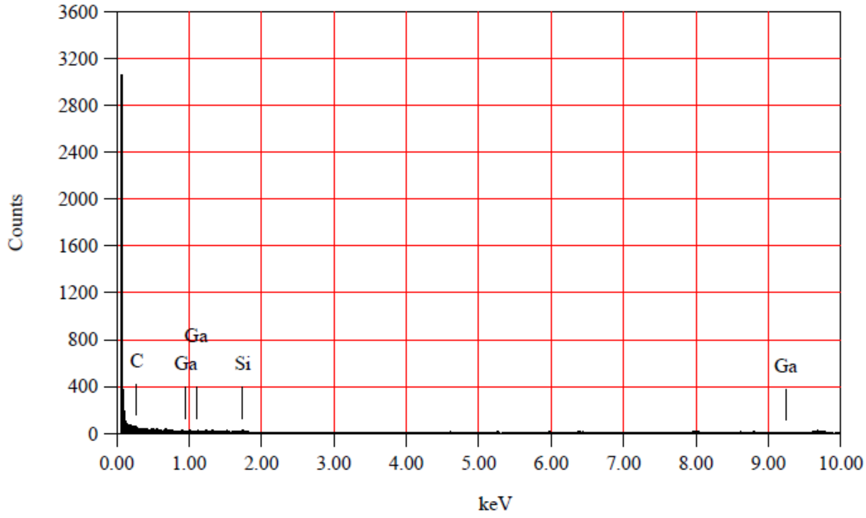

Fig. 3. Acquisition of CNT parameter data from SEM micrographs analysis

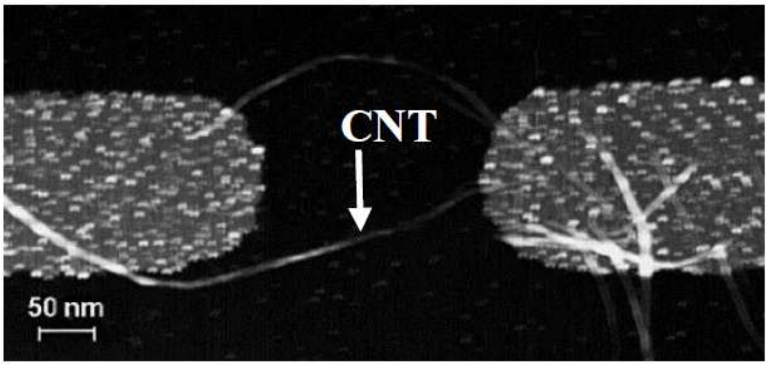

Fig. 4. Microscopic view of the fabricated CNT connected with two electrodes at the two terminals

Table 1. phi-rho-z method standardless quantitative analysis

Element	(keV)	mass%	Error%	At%	K
C K*	0.277	73.70	41.86	92.67	75.3119
Si K*	1.739	5.10	81.17	2.74	4.0246
Ga K*	9.241	21.19	743.54	4.59	56.7751
Total	100.00	100.00			

SEM analysis result is shown in Fig. 3. Carbon nanotube was counted from the raw material. Therefore, a quantitative analysis was imposed on the fabricated CNTs to segregate the carbon. Phi-rho-z Method was used for standard less quantitative analysis. Table 1 shows the quantity of mass and error of the carbon material.

Electrode Production

Photolithography was used to build gold electrode. The distance between the electrodes is around 1.5~2.5 μm. Electrodes are required in this experiment due to supply electrical power to the CNT through the conductor. Therefore, electrodes are connected with the CNTs as a conductor.

Removing Oxide

The last of the fabrication process is to remove oxide from CNTs to separate SiO_2. The etching process was used to remove oxides. Photolithography process was imposed to etch CNT. Finally, a complete CNT device is viewed in Fig. 4 where two electrodes are connected to the two terminal of the nanotube.

CNT Properties

CNT p-n Junction

The developed 1.95 nm carbon nanotube is characterized in the electrical point of view in deploying the design of optimum semiconductor device. The characterization of carbon nanotube includes charge, potential and energy in p-n junction of CNT. The electrical characteristic of the carbon nanotube is shown in Fig. 5 with respect to charge, potential and energy.

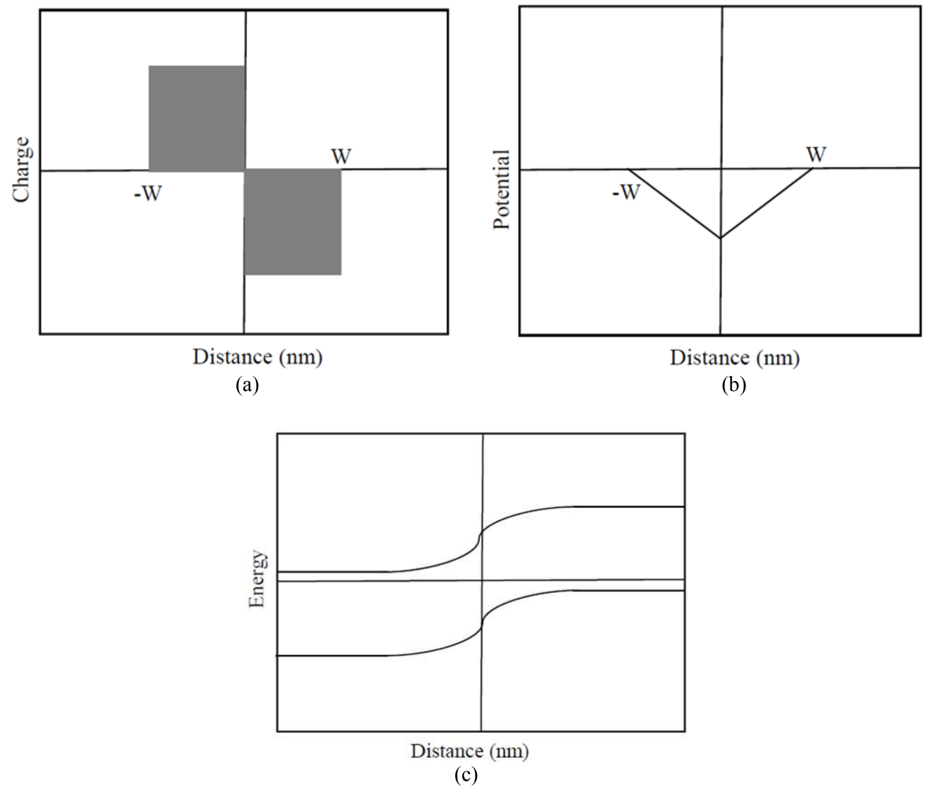

Fig. 5. Characteristics plot for a CNT p-n junction: (a) Charge (b) potential (c) energy

Charge can be calculated using Poisson equation:

$$V(z) = \frac{R}{4\pi\varepsilon_0} \int dz' \sigma(z') \int_0^{2\pi} \frac{d\theta}{\sqrt{(z-z')^2 + 2R^2 - sR^2 \cos\theta}} \quad (1)$$

Where:

R = The radius
ε_0 = permeability
θ = The angle
σ = CNT charge

$$\sigma(z') = \begin{cases} \rho & 0 < z < W \\ -\rho & -W < z < 0 \\ 0 & |z| > W \end{cases} \quad (2)$$

where, ρ is charge density, W is the depletion width. By integrating the direction, n-type side potential can be achieved:

$$V_n(z) = \frac{R\rho}{4\pi\varepsilon_0} \int_0^W dz' \int_0^{2\pi} \frac{d\theta}{\sqrt{(z-z')^2 + 2R^2 - 2R^2\cos\theta}} = \frac{R\rho}{4\pi\varepsilon_0} \int_0^{2\pi} d\theta \ln\left(\frac{z + \sqrt{2R^2(1-\cos\theta) + z^2}}{z - W + \sqrt{2R^2(1-\cos\theta) + (z-W)^2}} \right) \quad (3)$$

Similarly, P-type side potential can be obtained:

$$V_p(z) = -\frac{R\rho}{4\pi\varepsilon_0} \int_0^{2\pi} d\theta \ln \left(\frac{-z + \sqrt{2R^2(1-\cos\theta) + z^2}}{-z - W + \sqrt{2R^2(1-\cos\theta) + (z+W)^2}} \right) \quad (4)$$

Total voltage can be obtained by:

$$V(z) = \frac{R\rho}{4\pi\varepsilon_0} \int_0^{2\pi} d\theta \ln \left(\frac{z + \sqrt{2R^2(1-\cos\theta) + z^2}}{z - W + \sqrt{2R^2(1-\cos\theta) + (z-W)^2}} \times \frac{z + W - \sqrt{2R^2(1-\cos\theta) + (z+W)^2}}{z - \sqrt{2R^2(1-\cos\theta) + z^2}} \right) \quad (5)$$

An equation is considered at first for the built-in voltage by pretentious the step potential in the junction for the charge in depletion regions:

$$V_{bi} = \frac{R\rho}{4\pi\varepsilon_0} \int_0^{2\pi} d\theta \ln \left(\frac{\frac{W}{R} + \sqrt{2(1-\cos\theta) + \left(\frac{W}{R}\right)^2}}{\sqrt{2(1-\cos\theta)}} \right) \quad (6)$$

Thus for high doping, $W >> R$. So the potential becomes:

$$V_{bi} \approx \frac{R\rho}{\varepsilon_0} \ln\left(\frac{2W}{R}\right) \quad (7)$$

The depletion width become:

$$W_{NT} \sim \mathrm{Re}\,xp\left(\frac{\varepsilon_0 V_{bi}}{\rho R}\right) \quad (8)$$

Characteristics

The current-voltage characteristics of the carbon nanotube are analyzed to get the equation for discussing the nanotube p-n junctions. Ballistic conductor is considered for the extraction of current equation by:

$$I = \frac{4e^2}{h}\int T(E)\left[f_R\left(E - E_F^L\right) - f_L\left(E - E_F^R\right)\right]dE \quad (9)$$

Results

The depletion width is shown in Fig. 6 for the CNT p-n junction. Here, CNT p-n junction is acting as doping function. Different numbers of diameters of nanotubes were used to analyze the doping fraction of the nanotube.

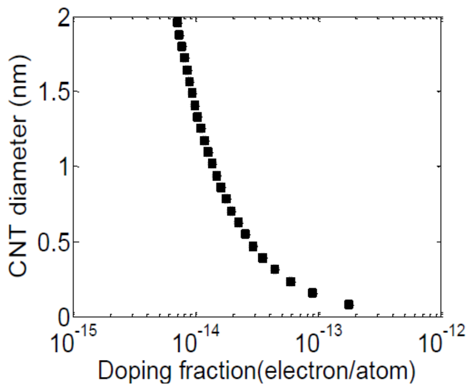

Fig. 6. Depletion widths for a nanotube p-n junction of doping

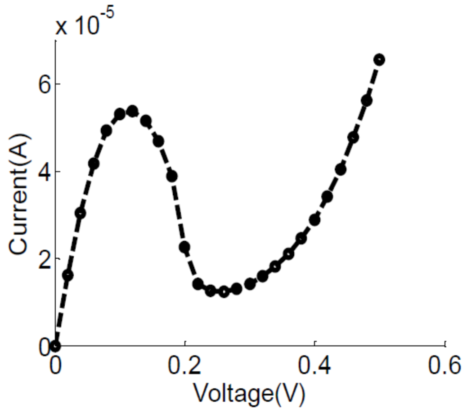

Fig. 7. CNT p-n junction current-voltage transfer characteristics

The lowest doping fraction value was found for the CNT with the diameter of 1.95 nm. This is considered as an optimal diameter for a single walled carbon nanotube to build a Field-Effect Transistor (FET).

Figure 7 shows the analysis of CNT p-n junction I-V characteristics analysis. The analysis consists of the ratio between the minimum and maximum current and differential resistance. As indicated by Equation 9, the built-in voltage varies logarithmically of the doping value. Therefore, doping function is varying very slowly. In addition, the doping depletion width is varying exponentially. In contrast, the lowest width is the sensitive doping function.

Conclusion

The fabrication of diameter controlled carbon nanotube is elucidated in this research. The brief analysis of Carbon Nanotube (CNT) is demonstrated the p-n junction charge, depletion width, current-voltage in this study. CNT is characterized to analyze the electrical properties of CNT. The results show that p-n junction of CNT is able to handle semiconductor device by operating low current. The self-consistent characteristics of CNT's of the charge and electrostatic potential determined the behavior of nanotube p-n junctions to act as semiconducting material. The result shows the different sizes CNT performs the different doping concentration.

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Author's Contributions

The experiment and article writing was prepared by Soheli Farhana. This project is mentored by Mohamad Fauzan Noordin.

Ethics

There is no ethical issue to be declared in this article.

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