Microwave Spectroscopy of Carbon Nanotube Field Effect Transistor

Aziz N. Mina*, Attia A. Awadalla*, Adel H. Phillips†, and Riham R. Ahmed*

*Faculty of Science, Beni-Suef University, Beni-Suef, Egypt. E-mail: attiamd2005@yahoo.com
†Faculty of Engineering, Ain-Shams University, Cairo, Egypt. E-mail: adel_phillips@yahoo.com

The quantum transport property of a carbon nanotube field effect transistor (CNTFET) is investigated under the effect of microwave radiation and magnetic field. The photon-assisted tunneling probability is deduced by solving Dirac equation. Then the current is deduced according to Landauer-Buttiker formula. Oscillatory behavior of the current is observed which is due to the Coulomb blockade oscillations. It was found, also, that the peak heights of the dependence of the current on the parameters under study are strongly affected by the interplay between the tunneled electrons and the photon energy. This interplay affects on the sidebands resonance. The results obtained in the present paper are found to be in concordant with those in the literature, which confirms the correctness of the proposed model. This study is valuable for nanotechnology applications, e.g., photo-detector devices and solid state quantum computing systems and quantum information processes.

1 Introduction

Carbon Nanotubes (CNTs) have been discovered by Sumio Iijim of the NEC Tsukuba Laboratory in HRTEM study of carbon filaments [1]. Carbon-based materials, clusters and molecules are unique in many ways [2]. One distinction related to the many possible configurations of the electronic states of carbon atom, which is known as the hybridization of atomic orbital. Electrical conductivity of carbon nanotube depending on their chiral vector carbon nanotube with a small diameter is metallic or semiconducting [2, 3]. The differences in conducting properties are caused by the molecular structure that results in a difference band structure and thus a different band gap. The quantum electronic transport properties of carbon nanotubes have received much attention in recent years [4, 5]. This is due to the very nice features of the band structure of these quasi-one dimensional quantum systems. The quantum mechanical behavior of the electronic transport in carbon nanotubes has been experimentally and theoretically investigated by many authors [6, 7]. According to these investigations, the authors showed that carbon nanotube sandwiched between two contacts behaves as coherent quantum device. A microwave field with frequency, ω, can induce additional tunneling process when electrons exchange energy by absorbing or emitting photons of energy, $\hbar\omega$. This kind of tunneling is known as the photon-assisted tunneling [8]. The aim of the present paper is to investigate the quantum transport characteristics of a CNTFET under the microwave irradiation and the effect magnetic field.

2 CNTFET

A carbon nanotube field effect transistor (CNTFET) is modeled as: two metal contacts are deposited on the carbon nanotube quantum dot to serve as source and drain electrodes. The conducting substance is the gate electrode in this three-terminal device. Another metallic gate is used to govern the electrostatics and the switching of the carbon nanotube channel. The substrates at the nanotube quantum dot /metal contacts are controlled by the back gate. The tunneling through such device is induced by an external microwave field of different frequencies of the form $V = V_{ac}\cos(\omega t)$ where V_{ac} is the amplitude of the field and ω is its angular frequency, that is the photon-assisted tunneling process is achieved. One of the measurable quantities of the transport characteristic is the current which may be expressed in terms of the tunneling probability by the following Landauer-Buttiker formula [9]:

$$I = \left(\frac{4e}{h}\right)\int \left[f_{FD(s)}(E) - f_{FD(d)}(E - eV_{sd})\right]\Gamma_n(E)\,dE \qquad (1)$$

where $\Gamma(E)$ is the photon-assisted tunneling probability, $f_{FD(s/d)}$ are the Fermi-Dirac distribution function corresponding to the source (s) and drain (d) electrodes, while e and h are electronic charge and Planck's constant respectively. The tunneling probability $\Gamma_n(E)$ might be calculated by solving the following Dirac equation [7]

$$\left[i v_{F\hbar}\begin{pmatrix} 0 & \partial_x - \partial_y \\ \partial_x - \partial_y & 0 \end{pmatrix} - eV_{sd} + \right. \qquad (2)$$
$$\left. + (e\hbar B)(2m)^{-1} + eV_B + eV_{sd}\cos(\omega t)\right]\psi_{\frac{e}{\hbar}} = i\hbar\frac{\partial\psi_{\frac{e}{\hbar}}}{\partial E}$$

where v_F is the Fermi velocity corresponding to Fermi-energy E_F, V_g is the gate voltage, V_{sd} is source-drain voltage, B is the applied magnetic field, m^* is the effective mass of the charge carrier, $\hbar$ is the reduced Planck 's constant, ω is the frequency of the applied microwave field with amplitude V_{ac} and V_b is the barrier height. The index e/h refers to electron like (with the energy > 0 with respect to the Dirac point) and hole-like (with energy < 0 with respect to the Dirac point) solutions to the eigenvalue differential equation (2).

The solution of equation (2) is given by [7]:

$$\Psi^{(ac)}_{+,n}(x,t) = \sum J_n\left(\frac{eV_{ac}}{\hbar\omega}\right)\Psi^{ac}_{0,e/h}(x,t)\,e^{(-in\omega t)} \tag{3}$$

where

$$\Psi^{(in)}_{0,e/h}(x,t) = \Psi^{(ac)}_{0,e/h}(x)\,e^{\mp iEt/h}\,. \tag{4}$$

Accordingly equation (2) will take the following form.

$$\left[iv_{F\hbar}\begin{pmatrix} 0 & \partial_x - \partial_y \\ \partial_x - \partial_y & 0 \end{pmatrix} - \varepsilon\right]\Psi^{ac}_{0.e/h} = \pm E\Psi_{0.e/h} \tag{5}$$

where the letter ε denotes the following

$$\varepsilon = E_F + eV_g + eV_{sd} + \left(\frac{e\hbar B}{2m^*}\right) + V_b + eV_{ac}\cos\omega t\,. \tag{6}$$

In Eq. (3), J_n is the n^{th} order Bessel function. Since in ballistic transport from one region of quantum dot to another one, charge carriers with a fixed energy (which can be either positive or negative with respect to the Dirac point) are transmitted and their energy is conserved. The desired state represents a superposition of positive and negative solution to the eigenvalue problem Eq. (5). The solution must be generated by the presence of the different side-bands, n, which come with phase factors $\exp(-in\omega t)$ that shift the center energy of the transmitted electrons by integer multiples of $\hbar\omega$ [8]. The complete solution of Eq. (5) is given by [7]:

(i) The incoming eigenfunction

$$\Psi^{(ac)}_{icome}(x,t) = \sum_{n=-\infty}^{\infty} J_n\left(\frac{eV_{ac}}{\hbar\omega}\right)\times \tag{7}$$
$$\times\Psi^{ac}_{0,+}\exp\left(i\left(\varepsilon + E + n\hbar\omega\right)t/h\right)$$

(ii) The reflected eigenfunction

$$\Psi^{\alpha}_{r}(x,t) = \sum_{n=-\infty}^{\infty} R_n(E)\,J_n\left(\frac{eV_{ac}}{\hbar\omega}\right)\times \tag{8}$$
$$\times\Psi^{ac}_{0,-}\exp\left(i\left(\varepsilon + E + n\hbar\omega\right)t/h\right)$$

where $R_n(E)$ is the energy-dependent reflection coefficient.

(iii) The transmitted eigenfunction

$$\Psi^{ac}_{tr}(x,t) = \sum_{n=-\infty}^{\infty} \Gamma_n(E)\,J_n\left(\frac{eV_{ac}}{\hbar\omega}\right)\times \tag{9}$$
$$\times\Psi^{in}_{+,n}\exp\left(i\left(\varepsilon + E + n\hbar\omega\right)t/h\right)$$

where $\Psi^{(ac)}_{0,+}, \Psi^{(ac)}_{0,-}$ are respectively given by

$$\Psi^{(ac)}_{0,+} = \frac{e^{iq_n y + ik_n x}}{\sqrt{\cos\alpha_{ac}}}\begin{pmatrix} \exp\left(-\frac{\alpha_{ac}}{2}\right) \\ -\exp\left(\frac{\alpha_{ac}}{2}\right) \end{pmatrix} \tag{10}$$

and

$$\Psi^{(ac)}_{0,-} = \frac{e^{iq_n y - ik_n x}}{\sqrt{\cos\alpha_{ac}}}\begin{pmatrix} \exp\left(\frac{\alpha_{ac}}{2}\right) \\ -\exp\left(-\frac{\alpha_{ac}}{2}\right) \end{pmatrix} \tag{11}$$

$\Psi^{(in)}_{+,n}$ in Eq. (9) is expressed as

$$\Psi^{(in)}_{+,n} = \frac{e^{iq_t y - ik_t x}}{\sqrt{\cos\alpha_{in,n}}}\begin{pmatrix} \exp\left(-\frac{\alpha_{in,n}}{2}\right) \\ \exp\left(\frac{\alpha_{in,n}}{2}\right) \end{pmatrix}. \tag{12}$$

In equations (10, 11, 12), the symbols α_{ac}, $\alpha_{in,n}$ are

$$\alpha_{ac} = \sin^{-1}\left(\frac{\hbar\nu q_n}{\varepsilon}\right) \tag{13}$$

and

$$\alpha_{in,n} = \sin^{-1}\left(\frac{\hbar\nu q_n}{\varepsilon + n\hbar\omega}\right) \tag{14}$$

where

$$q_n = \frac{n\pi}{W} \quad (n = 1, 2, 3, \ldots) \tag{15}$$

where W is the dimension of the nanotube quantum dot. The parameter k_n in Eqs. (10, 11, 12) is given by

$$k_n^2 = \left[\frac{V_b + eV_g + eV_{sd} + \frac{\hbar eB}{m^*}}{\hbar\omega}\right]^2 - q_n^2. \tag{16}$$

In order to get an explicit expression for the tunneling probability $\Gamma_n(E + n\hbar\omega)$ this can be achieved by applying the matching condition for the spatial eigenfunctions at the boundaries $x = 0$ and $x = L$. So, the tunneling probability $\Gamma_n(E+n\hbar\omega)$ will take the following form after some algebraic procedures, as

$$\Gamma_n(E + n\hbar\omega) = \tag{17}$$
$$= \left|\frac{k_n}{k_n\cos(k_n L) + i\left(\frac{eV_g + eV_{sd} + (\hbar eB/2m^*)}{\hbar\omega}\right)\sin(k_n L)}\right|^2.$$

The complete expression for the tunneling probability with the influence of the microwave field is given by [8]:

$$\Gamma_{withphoton}(E) = \sum J_n^2\left(\frac{eV_{ac}}{\hbar\omega}\right)\times$$
$$\times f_{FD}\left(E - \frac{C_g}{C}eV_g - n\hbar\omega - eV_{cd}\right)\Gamma(E - n\hbar\omega) \tag{18}$$

where C_g is the quantum capacitance of the nanotube quantum dot and C is the coupling capacitance between the nanotube quantum dot and the leads.

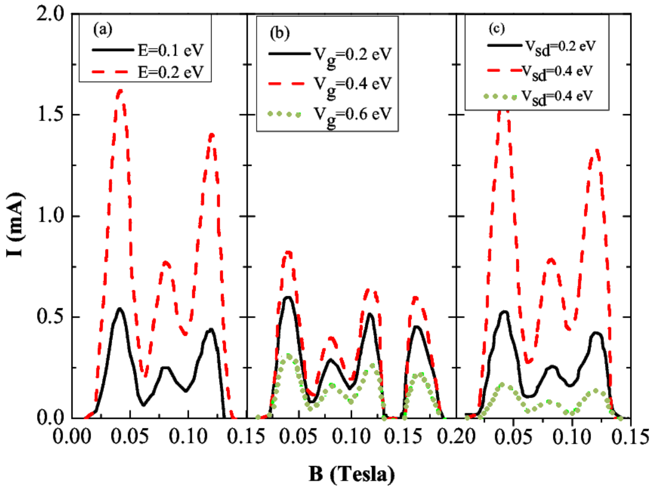

Fig. 1: The current as a function of the applied magnetic field (a) photon energy (b) gate voltage in energy units(c) source drain voltage in energy units.

3 Results and Discussions

Numerical calculations were performed according to the following:

(i) The electron transport through the present investigated device is treated as a stochastic process, so that the tunneled electron energy has been taken as a random number relative to the Fermi-energy of the carbon nanotube. The calculations had been conducted previously by the authors [9, 11].

(ii) The value of the quantum capacitance, C_g, is 0.25 nF.

(iii) The coupling capacitance between carbon nanotube quantum dot and the leads is calculated in the Coulomb blockade regime and in the charging energy of the quantum dot [9, 11]. Its value is found to be approximately equals $\sim$ 0.4 nF. The value of the Fermi energy, E_F is calculated using the values of the Fermi velocity, v_F, and it was found to be approximately equals $\sim$ 0.125 eV. This value of the Fermi energy, E_F, was found to be consisted with those found in the literature [12, 13]. The effective mass of the charge carrier was taken as 0.054 m_e [12, 13].

The variation of the current, I, with the applied magnetic field, B, at difference values of the photon energy, E, gate voltage, V_g, and different values of the bias voltage, V_{sd}, is shown in Figs. (1a,b,c). It is known that the influence of an external magnetic field, B, will lead to a change in the energy level separation between the ground state and the first excited state [14] in the carbon nanotube quantum dot. We notice that the current dependence on the magnetic field oscillates with a periodicity of approximately equals $\sim$ 0.037 T. This value corresponds roughly to the addition of an extra flux quantum to the quantum dot. These results have been observed by the authors [12, 15]. The peak heights are different due the interplay between the tunneled electrons and the applied photons of the microwave field and also this flux quantum will affect on the photon–assisted tunneling rates between electronic states of the carbon nanotube quantum dot. The results obtained in the present paper are, in general, found to be in concordant with those in the literature [12–20].

4 Conclusion

We conclude from the present analysis of the proposed ccc theoretically and numerically that the present device could be used as photo-detector device for very wide range of frequencies. Some authors suggested that such mesoscopic device, i.e. cccc could be used for a solid state quantum computing system. Recently the investigation of the authors [20] shows that such carbon nanotubes (CNT's) could find applications in microwave communications and imaging systems.

Submitted on June 27, 2010 / Accepted on July 10, 2010

References

1. Iijma S. *Nature*, v.354, 1991, 56.
2. Harris F. Carbon nanotubes and related structures. Cambridge University Press, 1999.
3. Dresselhaus M. S. Dresselhaus G.,Eklund P. C., Science of fullerenes and carbon nanotubes. Academic Press, NY, 1996.
4. Javey A. and Keng Jing. Carbon nanotube electronics. Springer Science + Business Media LLC, 2009.
5. Dai Liming. Carbon nanotechnology Recent developments in chemistry, Physics, Materials Science and Device Applications. Elsevier, Amsterdam, 2006.
6. Saito R., Fujita M., Dresselhaus G., and Dresselhaus M. S. *Appl. Phys. Lett.*, v.60, 1992, 2204.
7. Tworzydlo J., Trauzett B, Titov M., Rycerz A., and Beenakker C. W. J. *Phys. Rev.Lett.*, v.96, 2006, 246802.
8. Platero G. and Aguado R. *Physics Reports*, v.395, 2004, 1.
9. Atallah A. S., Phillips A. H., Amin A. F. Semary M. A., *Nano 2006*, v.1, no. 3, 2006, 259 .
10. Phillips A. H., Mina A. N., Sobhy M. S., and Fouad E. A. *J. of Computational and theoretical nanoscience*, v.4 (1), 2007, 174 .
11. Phillips A. H., Aly N. A. I., Kirah K., El-Sayes H. E. *Chinese Physics Letters*, v.25, no. 1, 2008, 250.
12. Anantram M. P., Leonard F. *Rep. Prog. Phys.*, v.69, 2006, 507.
13. Durkop T., Getty S. A., Cobas E., Fuhrer M. S. *Nano Lett.*, v.4, 2004, 35.
14. Oosterkamp T. H., Kouwenhoven L. P., Koolen A. E. A., van der Vaart N. C. and Harmans C. J. P. M. *Semicond. Sci. Technol.*, v.11, 1996, 1512.
15. Meyer C., Elzerman J. M., and Kouwenhoven L. P. *Nano Lett.*, v.7, no. 2, 2007, 295.
16. Orellana P. A., Pacheco M. *Phys. Rev.*, v.B75, 2007, 115427.
17. Kim J., Hye–Miso, Kim Nam, Kim Ju–Ji, and Kicheon Kang. *Phys. Rev.*, v.B70, 2004, 153402.
18. Zhao Li–Na and Zhao Hong–Kang. *Phys. Lett.*, v.A325, 2004, 156.
19. Pan Hui, Li Tsung–Han, and Ya Dapeng. *Physica B*, v.369, 2005, 33.
20. Lin Y. M., Dimitrakpoulos C., Jenkins K. A., Farmer D. B., Chiu H. Y., Grill A., Avouris Ph. *Science, 2010*, v.327, no. 5966, 2010, 662.