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Coherent Photo-Electrical Current Manipulation of Carbon Nanotube Field Effect Transistor Induced by Strain

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Abstract

The quantum characteristics of the single walled carbon nanotube (SWCNT) quantum dot device are investigated under the effect of an external strain. This device is modeled as single walled carbon nanotube quantum dot connected to metallic leads. These two metallic leads operate as a source and a drain. 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 substances at the carbon nanotube quantum dot/ metal contact are controlled by the back gate. The electric current is deduced using Landauer-Buttiker formula. Numerical calculations are performed for armchair SWCNT and zigzag SWCNT and the obtained results show that both energy gap and the current are chiral dependent. So, results show that due to the effect of strain, the quantum transport characteristics of the present device are changed. Periodic oscillatory behavior of the current for both types of SWCNTs might be due Coulomb oscillation and the THz-photon assisted tunneling (PAT) of an electron in the SWCNT QD to the drain electrode. The present research is very important in the field of nanoelectronics devices and nanoelectromechanical system resonators.

Keywords

Armchair Single Walled Carbon Nanotube, Zigzag Single Walled Carbon Nanotube, Energy Gap, Strain, Ac-field and Magnetic Field

1. Introduction

Carbon nanotubes (CNTs) can be viewed as graphene sheets rolled up into cylindrical structures. Since their discovery in 1991 [1], the peculiar electronic properties of such hollow nanostructures have gained growing attention from scientists and researchers. CNTs show great potential for a variety of technological applications due to their novel physical properties. Depending on radius and chirality, a single walled carbon nanotube (SWCNT) can behave as either metallic or semiconducting [2]. The carbon nanotube (CNT) is one of the promising materials for the next generation of electronic devices because of its intrinsic nanoscale size, one-dimensional geometry, and excellent transport properties [1,3]. The high mobility, the large current density, and the controlled response to the gate voltage have been demonstrated in the nanotube-based field effect transistor (FET) [4-6]. Significant research efforts are now brought to the large-scale integration of CNT-FETs, especially on issues such as isolation of individual nanotubes, sorting the metallic and semiconducting nanotubes, and patterning and integration of the electrodes and nanotubes. CNTs are in great interest in electronic devices, gas sensors, biosensors, biomedical application, etc [7-10]. Metallic and semiconducting properties of CNTs depend on their diameter and chirality [11]. Application of CNTs in electronics includes use of semiconductor CNTs in the transistors and also use of metallic CNTs in the interconnections. Understanding tuning the electronic properties of SWCNTs has been a subject of interest to both experimental and theoretical researchers with the motivation of finding possible applications. In addition to doping with various types of foreign atoms [12-15] and adsorption of foreign atoms or molecules, [16,17] another effective way to widen their application possibilities is by applying external strain. Mechanical strain often gives rise to surprising effects on the electronic properties of carbon nanomaterials [18-20], often drastically changing the intrinsic properties of CNTs.

The purpose of the present paper is to investigate the quantum transport characteristics of carbon nanotube quantum dot field effect transistor (CNTFET) under the influence of an ac-filed (mid infrared region). The effect of tensile strain for zigzag CNT, armchair CNT will be taken into consideration.

2. The Model

The carbon nanotube field effect transistor (CNTFET) can be modeled as follows: A single walled carbon nanotube in the form of quantum dot is connected to two metallic leads. These two metallic leads operate as a source and a drain. 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 substances at the carbon nanotube quantum dot/ metal contact are controlled by the back gate. The Dirac fermion electron tunneling through CNTFET is induced by an external applied ac-field which is expressed as:

$$V = V_{ac} \cos \omega t \tag{1}$$

where V_{ac} is the amplitude of the ac-field and ω is its frequency. Using Landauer-Buttiker formula, the electric current, I, is given by [20-23].

$$I = \frac{4e}{h} \int_{E_F}^{E_F + n\hbar\omega} dE.[f_{FD(s)}(E) - f_{FD(d)}(E - eV_{sd})]\Gamma_{with\,Photon}(E) \tag{2}$$

where $\Gamma_{withphotons}(E)$ is the photon-assisted tunneling probability, $f_{FD(s)}$ & $f_{FD(d)}$ Fermi-Dirac distribution functions corresponding to source and drain leads respectively ,V_{sd} is the bias voltage, E is the energy of tunneled electrons and e is the electronic charge and h is the Planck's constant. The Photon assisted tunneling probability, $\Gamma_{withPhoton}(E)$ could be expressed in terms of the tunneling probability without photons, $\Gamma_{withoutPhotons}(E - n'\hbar\omega)$ as follows [20-24]:

$$\Gamma_{withPhoton} = \sum_{n'=1}^{\infty} J_{n'}^{2}\left(\frac{eV_{ac}}{n\hbar\omega}\right) \times f_{FD}\left(E - \left(\frac{C_{CNT}}{C}\right) eV_g - n'\hbar\omega - eV_{sd}\right) \times \Gamma_{withoutPhotons}(E - n'\hbar\omega) \tag{3}$$

where C_{CNT} is the capacitance of the carbon CNT quantum dot, C is the coupling capacitance between CNT quantum dot and the leads, V_g is the gate voltage, $\hbar\omega$ is the energy of the induced photon and $J_{n'}$ is the n'^{th} order Bessel function corresponding to the n'^{th} different side bands of nanostructure carbon nanotube. The tunneling probability without the induction of the photons, $\Gamma_{withoutPhotons}(E - n'\hbar\omega)$ could be determined using the WKB approximation method [25,26] as follows:

$$\Gamma_{withoutphoton}(E - n'\hbar\omega) = \exp\left[-2\int_{d}^{d+\Delta} dx \times \left(E_g / \sqrt{3} a \gamma_o\right) \times \sqrt{1 - \left(\left(E_1 - n'\hbar\omega + eV_{sd}(1 - x/L)\right) / (\varepsilon_g/2)\right)^2}\right] \tag{4}$$

where a is the lattice constant, γ_o is the nearest neighbor hopping integral, ε_g is the strained band gap energy, L is the length of CNT quantum dot , d is the diameter of CNT and , Δ , is its thickness. The energy, E_1 , (Eq.4) is given by:

$$E_1 = E_F + eV_g + V_b + \frac{N^2 e^2}{2C_{CNT}} + eV_{ac}\cos(\omega t) + \frac{\hbar eB}{2m^*} \tag{5}$$

Where E_F is the Fermi-energy, V_b is the barrier height at the interface between CNT and leads, N is the number of tunneled electrons and e is the electronic charge, B is the applied magnetic field and m^* is the effective mass of the charge carrier. The strained band gap energy, Eg, is expressed in terms of the induced strain, ε, as follows [27].

For armchair carbon nanotube, E_g, is given as:

$$E_g = \left| \left(\frac{\gamma_0 a^2}{16R^2} + \frac{ab\sqrt{3}}{2}\varepsilon \right) \sin(3\theta) \right| \tag{6}$$

And for zigzag carbon nanotube, E_g is expressed as:

$$E_g = \left| \frac{\pi^2 \gamma_0}{4n^2} + \frac{ab\sqrt{3}}{2}\varepsilon \right| \tag{7}$$

where b is the linear change in the transfer integral with a change in bond length due to strain, R is the radius of the carbon nanotube and θ is the chiral angle. The diameter, d, of SWCNT and the chiral angle, θ, are determined in terms of the chiral indices n and m [28, 29] using the following equations :

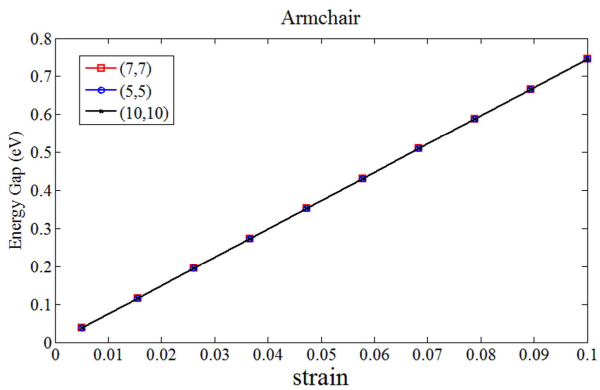
$$d = \frac{a}{\pi}(n^2 + nm + m^2)^{\frac{1}{2}} \tag{8}$$

and

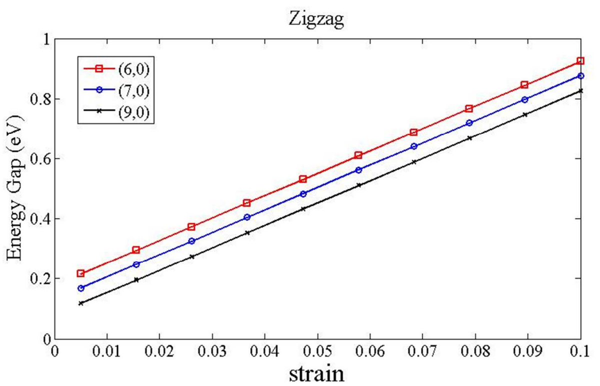
$$\cos\theta = \frac{2n+m}{2\sqrt{n^2+nm+m^2}} \tag{9}$$

In the present paper we consider only armchair carbon nanotube and zigzag carbon nanotube, that is, for armchair carbon nanotube n=m, while for zigzag carbon nanotube m=0 [11, 28].

3. Results and Discussion



(a)



(b)

***Fig. 1**. The variation of energy gap with strain for both types of CNT.*

Numerical calculations are performed for the strained energy gap energy, E_g, for both armchair CNT (Eq.6) and for zigzag CNT (Eq.7). The values of parameters are: the lattice constant a= 2.46Å & the nearest neighbor hopping integral γ_o= 2.6 eV [30]. The value of the parameter b= 3.5 eV/Å [27, 31]. The table (1) below shows the values of diameter, d, for the following armchair CNT and zigzag CNT:

***Table (1).** The values of diameter of zigzag CNT and armchair CNT with different chiral indices.*

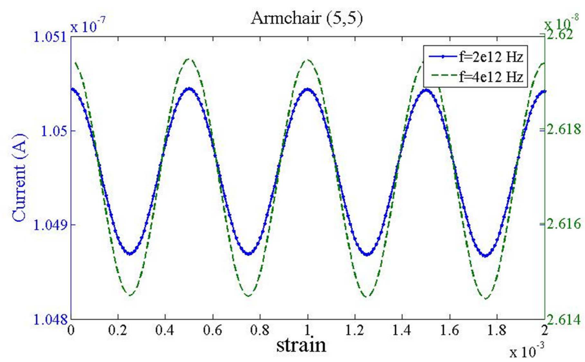
Zigzag CNT	(6,0) d= 4.69Å	(7,0) d= 5.48Å	(9,0) d= 7.04Å
Armchair CNT	(5,5) d=6.784Å	(7,7) d= 9.498Å	(10,10) d=13.569Å

It is well known that the chiral angle, θ, for zigzag CNT equals zero while for armchair CNT equals 30^0 [11, 28]. Also, armchair (n,n) single walled carbon nanotube (SWCNT) are expected to show metallic characteristic [11, 28]. While zigzag (n,0) single walled carbon nanotube (SWCNT) shows the metallic characteristics when n/3 is an integer; otherwise they semiconducting [11, 28].

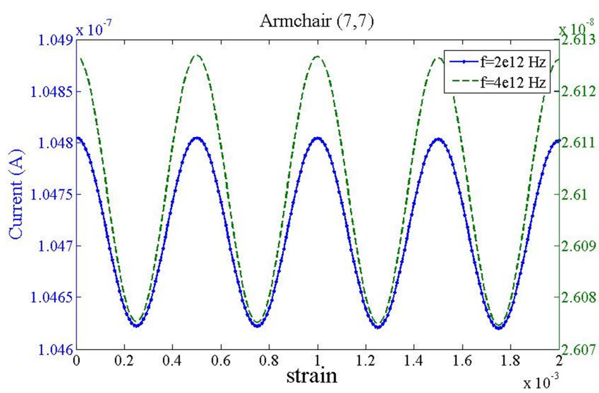
Fig.1 shows the variation of energy gap, E_g, for armchair CNT (Fig.1a) and zigzag CNT (Fig.1b) with strain. It shown from Fig.(1a) that the energy gap of armchair SWCNT varies with strain linearly. There is no difference in the values of energy gap for different chiral indices. While for zigzag SWCNT (n,0) (Fig.(1b), the energy gap varies linearly with strain. It is noted from this figure that the energy gap decreases as the chiral index, n, increases at the same value of strain. This is expected result for zigzag SWCNT according to Eq.7. The present results are found concordant with those in literature [11, 20, 27, 31]. The variation of energy gap of both SWCNT might be due to breaking the bond symmetry due to curvature of nanotube [20, 28, 32].

It is interesting to investigate the variation of the electrical current (Eq.2) with strain for both armchair CNT and zigzag CNT under the influence of the frequency of an ac-field in the mid-infrared region. So, numerical calculations are performed for the current, I, (Eq.2) for both types of CNT. The values of parameters: E_F= 0.125 eV, m^*= 0.054 m_e, C= 0.4 nF, C_{CNT}= 0.25 nF, eV_{ac}= 1 meV, L=20 nm and V_b= 0.3 eV [20, 22, 23]. The values of gate voltage, the source-drain voltage, magnetic field and temperature are 0.1 V, 0.2 V, 2T and 150K respectively.

The features of the present results are the following:



(a)



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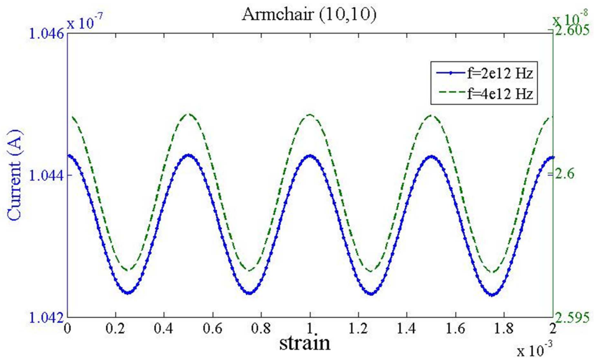


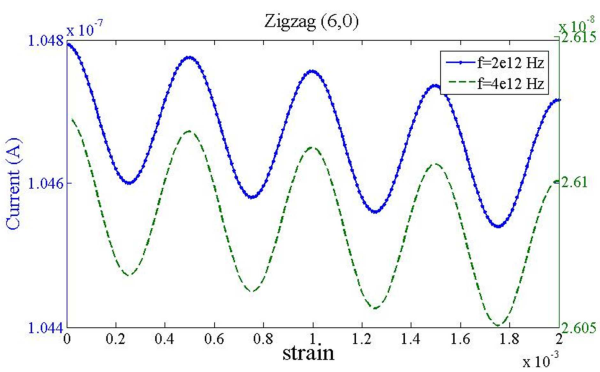
(c)

Fig. 2. *The variation of the current with the strain at different frequencies of the induced ac-field.*

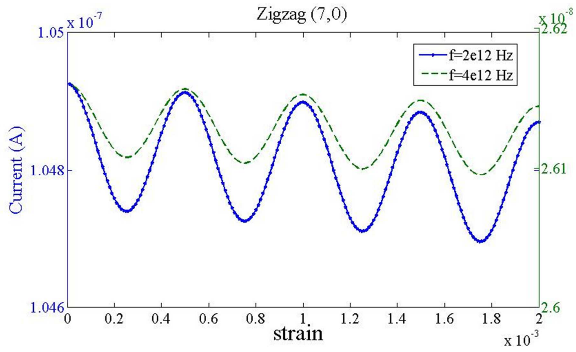
Fig.2 shows the variation of the current with strain for armchair SWCNT at different frequencies of the induced ac-field. These results show that the quantum transport characteristics are sensitive to the chirality nature of armchair SWCNT, that is, very sensitive to both the values of chiral indices and the corresponding diameters of CNT.

Fig.3 shows the variation of the current with strain for zigzag SWCNT at different frequencies of the induced ac-field. Also, for zigzag SWCNT, the results show that the quantum transport characteristics are sensitive to chiral index, n,.

As shown from Figs.(2, 3) that a periodic oscillation of the current with the strain at different frequencies of the induced ac-field. These oscillations are Coulomb oscillation [22, 23]. Also, according to the present model of nanoelectronics single walled carbon nanotube field effect transistor, the interaction of the tunneled electrons with the induced ac-field leads to photon-mediated transmission resonances. The interplay between the induced photons and the tunneled electrons leads to what it is known as Fano-resonance [33]. In general, the oscillatory behavior of the current might be due to Fano-resonance as the quantum transport of electrons is performed from continuum states of leads to the discrete states of nanostructure SWCNT [33]. The observed periodic oscillation of the current with strain for both types of SWCNT might be operated as single electron transistor [34, 35].



(a)



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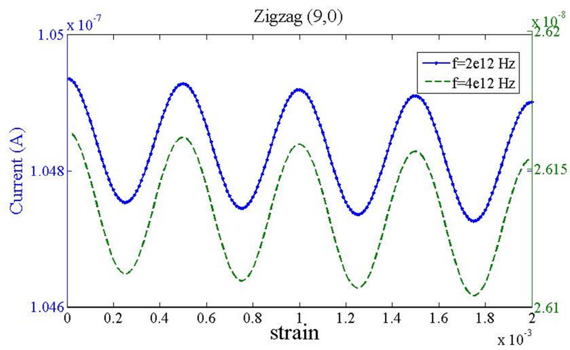

(c)

Fig. 3. *The variation of the current with strain at different frequencies of the induced ac-field.*

4. Conclusion

The quantum transport characteristics of single walled carbon nanotube quantum dot field effect transistor (SWCNTQDFET) under the effect of strain are investigated in the present paper. This investigation is performed under the influence of ac-field with frequencies in THz region. The strained energy gaps of armchair SWCNT and zigzag SWCNT are computed. Results show the variation of these energy gaps with strain might be due to breaking the bond symmetry due to curvature. Also, the electrical current for both types of SWCNT is computed under the effect of strain at different frequencies (THz-region) of the induced ac-field. Results show periodic oscillation of the current. These oscillations might be due Coulomb blockade and electron-photon interaction. Also, results show that the transport characteristics of the present investigated device are sensitive to the chirality nature of both armchair SWCNT and zigzag SWCNT. The present research is very important for nanoelectronics devices and for designing nanoelectromechanical systems needed for sensing.

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