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Research Article

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Current Analysis of Single Electron Transistor Based on Double Carbon nanotube Quantum Dots Island

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Abstract

The single electron transistor (SET) as fast electronic device operates with tunneling of single electron. It contains a quantum dot island that it's material impacts on speed of SET operation. In this study, carbon nanotube (CNT) as low dimensional carbon base material with high electron mobility is selected for island material. Moreover, increasing the number of islands effect on probability of electron tunneling. Therefore, SET with CNT double quantum dots (DQD) is modeled. Furthermore, impacts on CNT length, temperature and applied gate voltage on CNT DQD SET are investigated. Additionally, the impact of number of islands on SET current is evaluated with comparison charge stability diagrams of two SETs. Finally, SET with better and faster operation is defined.

Key words: carbon nanotube, Double quantum dots, island, output current, single electron transistor.

Introduction

Single electron transistor (SET) is a nanoscale device that replacement traditional transistor in electronic systems [1]. The first SET device was fabricated by Fulton and Dolan in 1987[2]. SET has three electrodes that island and tunnel junctions located between them [3]. Gate electrode contacts to the island by gate capacitance [4]. The SET works by single electron tunneling phenomenon as electron an electron from source electron to island and then move to drain electrodes [5,6].

The tunneling electrodes stops with coulomb blockade phenomenon [7]. The conditions of coulomb blockade are the charging energy (The essential energy for moving an electron to the island) is higher than thermal energy. Furthermore, thermal resistance is more than quantum

resistance [8]. When this phenomenon occurs, then current flows stops and output current is zero in SET [9].

The island material effects on speed of tunneling single electron transistor on SET [10]. Therefor SET quantum dot can be selected from materials with high electron mobility [11].

A carbon nanotube (CNT) is rolled up from a graphene sheet [12-14]. CNT is one dimensional material which discovered by Iijima in 1991[15, 16]. Its special properties are high electron mobility and thermal conductivity [17,18]. Moreover, it has high surface-to-volume ratio [19]. The graphene sheet and quantum dot CNT are illustrated in Figure 1 that were protected with Atomistic Toolkit software (ATK) [20].

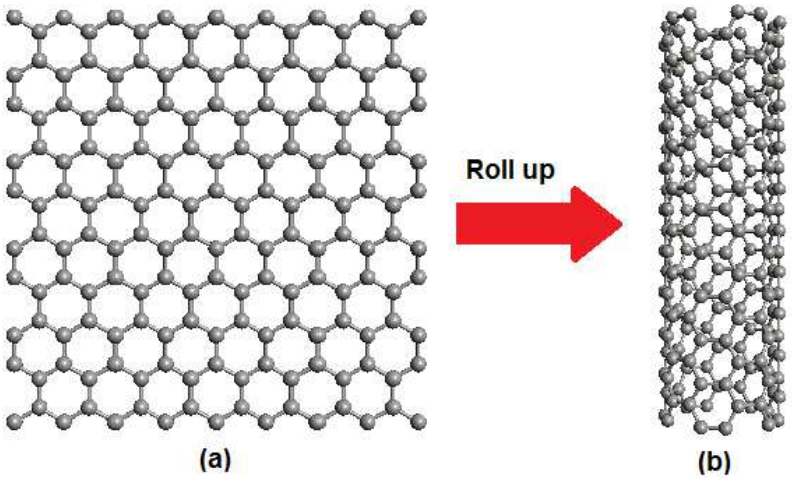


Figure 1. (a) Graphene sheet. (b) carbon nanotube (CNT).

On the other hand, increasing number of quantum dots (QDs) can reduce some limitations of SET operation such as cryogenic temperature and leakage current in SET [21]. Therefore, in this research, CNT DQD are utilized in SET channel. Mathematical current model for CNT DQD SET is written. The MATLAB codes for proposed current model are implemented. The current behavior diagrams for investigation of some parameters are plotted and compared with together.

Moreover, charge stability diagrams for SET with double QD island are plotted using ATK software. These coulomb blockade ranges and coulomb diamond areas are compared.

The SET can be utilized in electron devices such as oscillator [22], sensor [23], single electron memory [24].

The Current model in CNT DQD SET

Theoretical Model

The single electron transistor (SET) works by tunneling single electron from source electrode to drain electrode. The electron passes from different regions that region has electron wave function. These electrons wave function can be written with Schrödinger equations. The SET can be divided to five parts which are two potential wells with equal length and three tunnel junctions. The CNT DQD SET and the schematic energy band diagram for the CNT SET is shown in Figure 2 [20].

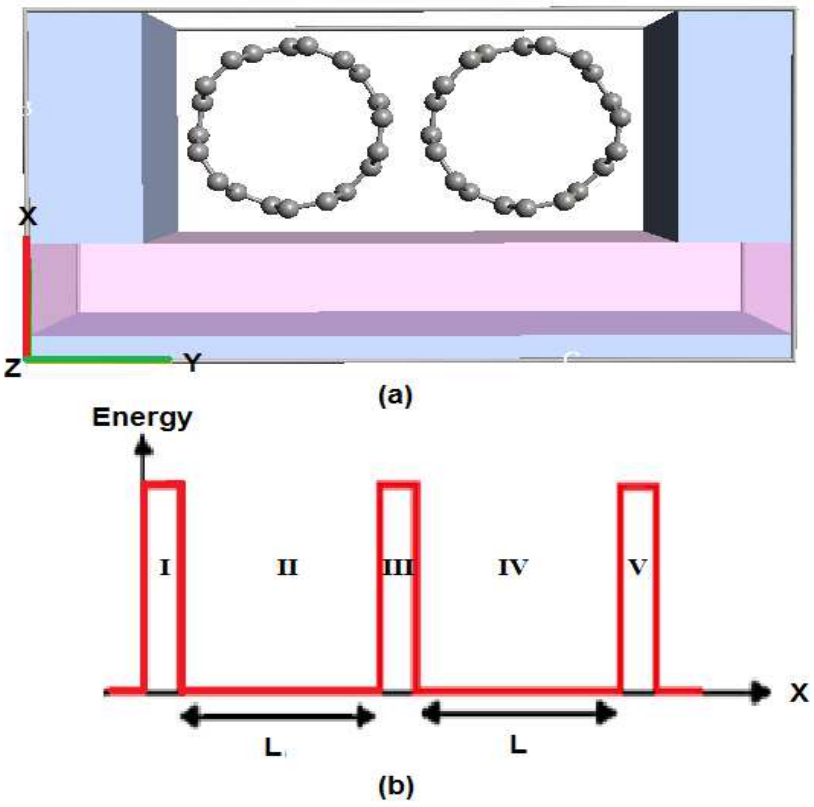


Figure 2.(a) The double CNT SET. (b) SET energy versus channel regions which indicates tunnel barriers.

These wave functions for three regions of SET with one CNT can be written with Schrödinger equations as

$$\frac{\hbar^2}{2m}\frac{\partial^2\psi_I(x)}{\partial x^2} + (\mathrm{E} - V)\psi_I(x) = 0 \qquad x \leq 0 \qquad \text{Region I} \qquad (1)$$

$$\frac{\hbar^2}{2m}\frac{\partial^2\psi_{II}(x)}{\partial x^2} + \mathrm{E}\psi_{II}(x) = 0 \qquad 0 < x < L \qquad \text{Region II} \qquad (2)$$

$$\frac{\hbar^2}{2m}\frac{\partial^2\psi_{III}(x)}{\partial x^2} + (\mathrm{E}-\mathrm{V})\psi_{III}(x) = 0 \qquad \mathrm{x} \geq L \qquad \text{Region III} \tag{3}$$

$$\frac{\hbar^2}{2m}\frac{d^2\psi_I(x)}{dx^2} + (E-V)\psi_I(x) = 0 \qquad x \leq 0 \tag{4}$$

$$\frac{\hbar^2}{2m}\frac{d^2\psi_{II}(x)}{dx^2} + E\psi_{II}(x) = 0 \qquad 0 < x < L \tag{5}$$

$$\frac{\hbar^2}{2m}\frac{d^2\psi_{III}(x)}{dx^2} + (E-V)\psi_{III}(x) = 0 \qquad x \geq L \tag{6}$$

$$\Psi_I = A_1 e^{k_1 x} + B_1\, e^{-k_1 x} \text{ و } k_1 = \frac{\sqrt{2m(V_0-E)}}{\hbar}$$

(7)

$$\Psi_{II} = A_2 e^{ik_2 x} + B_2\, e^{-ik_2 x} \text{ و } k_2 = \frac{\sqrt{2mE}}{\hbar}$$

(8)

$$\Psi_{III} = A_3 e^{ik_3 x} \text{ و } k_3 = \frac{\sqrt{2m(V_0-E)}}{\hbar} \tag{9}$$

Then boundary conditions is solved for $x = 0$ to $x = L$ as

$$\Psi_I(0) = \Psi_{II}(0) = A_1 + B_1 = A_2 + B_2 \tag{10}$$

$$\Psi_I{}'(0) = \Psi_{II}{}'(0) = k_1 A_1 - k_1 B_1 = ik_2 A_2 - ik_2 B_2 \tag{11}$$

$$\Psi_{II}(\mathrm{a}) = \Psi_{III}(\mathrm{a}) = A_2 e^{ik_2 L} + B_2\, e^{-ik_2 \mathrm{L}} = A_3 e^{ik_1 \mathrm{L}} \tag{12}$$

$$\Psi_{II}{}'(\mathrm{a}) = \Psi_{III}{}'(\mathrm{a}) = ik_2 A_2 e^{ik_2 L} - ik_2\, B_2\, e^{-ik_2 \mathrm{L}} = ik_1 A_3 e^{k_1 \mathrm{L}} \tag{13}$$

The transmission coefficient of tunnel barriers assumed to be one. The transition coefficient of a CNT island is written as

$$T_{CNT}(E) = \frac{1}{1 + K_{CNT}{}^2 sinh^2(k_2 L)} \tag{14}$$

$$K_{CNT} = \frac{(\hbar^2 + ta'm)E - \hbar^2 E_{g_{CNT}}}{2\sqrt{ta'\hbar mE(E - E_{g_{CNT}})}} \tag{15}$$

where "h" is the Planck's constant, "$a' = 3a_{c-c}$" , and $a_{c-c} = 1.42A°$ is the distance between neighboring carbon atoms, "E_g" is the CNT band gap, "E" is the electron energy level, "L" is the CNT length, $k_2 = \frac{\sqrt{2mE}}{\hbar}$, "$m$" is the electron effective mass and "$t = 2.7eV$" .

Then the transition coefficient of double CNT island are calculated as [15]

$$T(E) = (T(E)_{CNT})^2 \tag{16}$$

$$T(E) = \left(\frac{Ax\left(K_BTx + \frac{2a_{c-c}t}{d}\right)}{AK_BTx\left(K_BTx + \frac{2a_{c-c}t}{d}\right) + \left(B\left(K_BTx + \frac{2a_{c-c}t}{d}\right) + CAK_BTx\right)^2\left[\left(B\left(K_BTx + \frac{2a_{c-c}t}{d}\right)L^2\right)^{\frac{1}{2}} + \frac{\left(B\left(K_BTx + \frac{2a_{c-c}t}{d}\right)L^2\right)^{\frac{3}{2}}}{6}\right]}\right)^2 \quad (17)$$

where $A = \left(\frac{16m}{3\hbar t a_{c-c}}\right), B = \left(\frac{2m}{\hbar}\right), C = \left(\frac{2}{3ta_{c-c}}\right), x = \frac{E-E_g}{K_BT}, E_g = \frac{2a_{c-c}t}{d}$, "d" is CNT diameter , "E_F"is CNT Fermi energy, "K_B" is Boltzmann's constant, "T" is temperature and other parameters were defined previously.

Thus quantum drain current based on the Landauer formalism is

$$I = \int_0^{\eta} T(E).F(E)dE \quad (18)$$

$$F(E) = \frac{1}{\exp\left(\frac{E-E_F}{k_BT}\right)+1} \quad (19)$$

where $\eta = \frac{E_F-E_g}{K_BT}$, "$T(E)$" is the transmission coefficient of SET and "$F(E)$" is the Fermi probability function.

The current mathematical model is suggested for CNT DQD SET by solving Schrödinger equations and Landauer formalism as

$$I = \int_0^{\eta} \left(\frac{Ax\left(K_BTx + \frac{2a_{c-c}t}{d}\right)}{AK_BTx\left(K_BTx + \frac{2a_{c-c}t}{d}\right) + \left(B\left(K_BTx + \frac{2a_{c-c}t}{d}\right) + CAK_BTx\right)^2\left[\left(B\left(K_BTx + \frac{2a_{c-c}t}{d}\right)L^2\right)^{\frac{1}{2}} + \frac{\left(B\left(K_BTx + \frac{2a_{c-c}t}{d}\right)L^2\right)^{\frac{3}{2}}}{6}\right]}\right)^2 \cdot \frac{dE}{e^{x-\eta}+1} \quad (20)$$

These parameters are definded perviously. The proposed model is based on some parameters such as CNT length, gate voltage and temperature which is investigated in the following. The matematical model for current of CNT DQD SET is written with MATLAB codes. The curves of current vresus gate voltage with different CNT length are ploted in Figure 3.

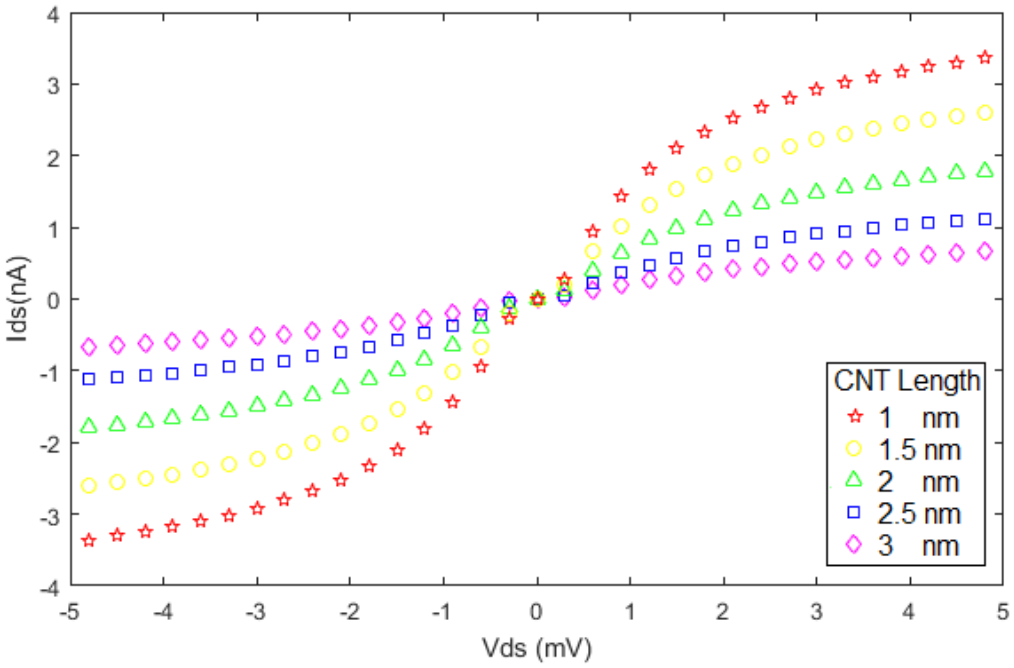


Figure 3. Current vs. voltage diagrams obtain from the proposed model for different CNT length. The applied gate voltage is 1mV and the temperature is 300°K.

Figure 3 shows the current versus voltage plots for device when the length of CNT DQD varies from 1nm to 3nm. The comparison study indicates that CNT length has indirect. The impact on SET current therefore increasing CNT length decreases value of output current. Moreover, coulomb blockade for the lowest CNT length has lower range. Because electron crosses shorter potential barrier, so it transfers faster. Another important parameter in SET current is applied gate voltage which is investigated in Figure 4.

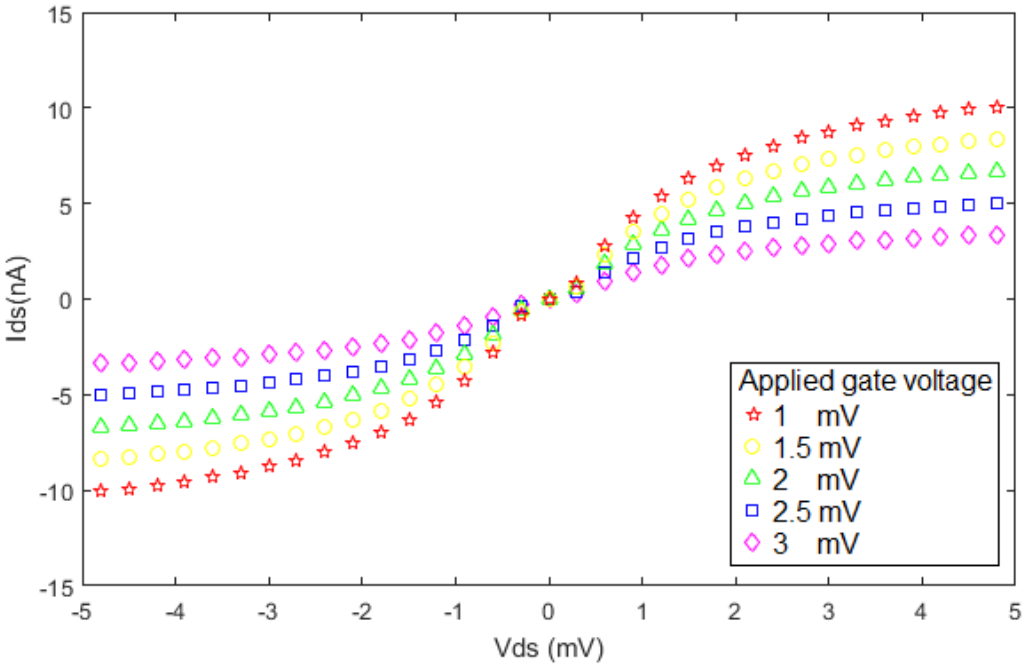


Figure 4. Current vs. voltage diagrams obtain from the proposed model for different applied gate voltages. The temperature is 300°K.

The curves in Figure 4 show that increasing applied gate voltage increases current of CNT DQD SET. Furthermore, the highest applied gate voltage has lowest coulomb blockade range. Because energy level transfer to transfer window and single electron can tunnel to tunnel barriers and electron flow with high speed in CNT DQD SET. The impact of ambient temperature on double CNT SET is investigated in Figure 5.

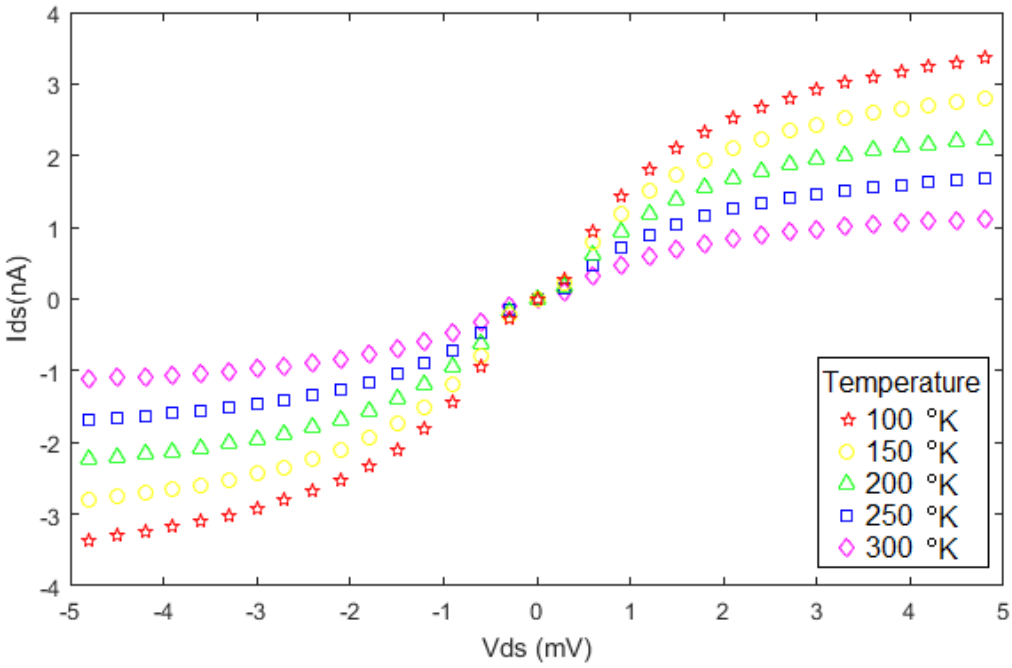


Figure 5. Current vs. voltage diagrams obtain from the proposed model for different temperatures. The applied gate voltage is 1mV.

The analysis of Figure 5 indicates that the ambient temperature has direct impact on SET current. Its curves show that the highest temperature has the highest output current value. In addition, increasing the temperature to room temperature value decreases coulomb blockade range and zero current in CNT DQD SET.

The SET operates with tunneling single electron in SET circuit that single electron transfer is prevented with coulomb blockade phenomena. The coulomb blockade range and coulomb diamond area can be shown in charge stability diagram. In this study, the similar CNT island with atoms where design with ATK software and xyz coordinates. The DFT method using local- density approximation (LDA) utilized for simulation. Finally, the charge stability diagram of CNT SET and CNT DQD SET can plot as shown in Figure 6. The important parameters are extracted from Figure 6 and these data are reported in Table 1.

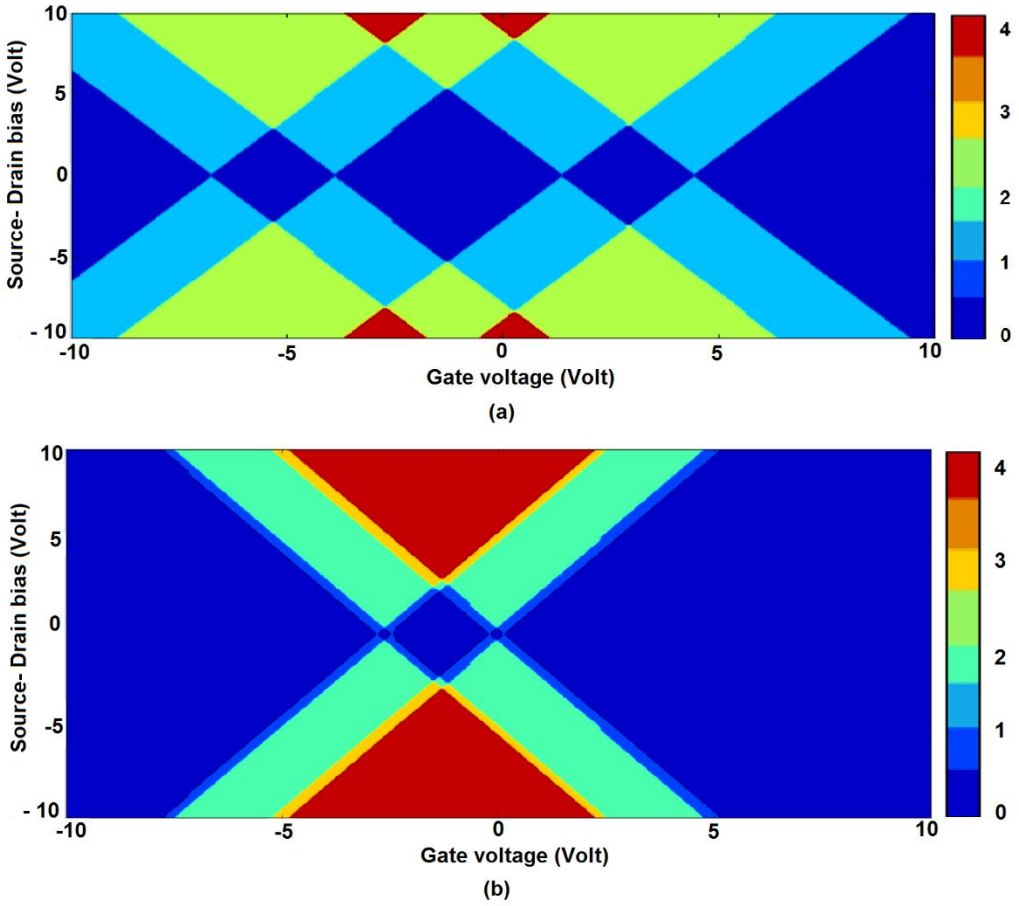


Figure 6. The charge stability diagrams of quantum dot island (a) single CNT with 20 carbon atoms (b) double CNT with 40 carbon atoms.

Table 1. Important parameters extracted from Figure 6.

Type of SET	Diamond	$V_{g_{min}}$ (v),$V_{g_{max}}$ (v)	ΔV_g(v)	$V_{ds_{min}}$(v), $V_{ds_{max}}$ (v)	ΔV_{ds}(v)	Diamond Area(v^2)	Total Diamonds Area(v^2)
CNT SET with 20 carbon atoms	diamond 1	(-6.726,-3.893)	2.833	(-5.328,-2.827)	2.501	3.542	40.555
	diamond 2	(-3.855,1.396)	5.251	(-5.282,5.282)	10.564	27.735	
	diamond 3	(1.396,4.438)	3.042	(-3.050,3.050)	6.100	9.278	
Double CNT SET with 40 carbon atoms	diamond 1	(-2.787,-2.515)	0.272	(-0.316,0.316)	0.632	0.085	5.294
	diamond 2	(-2.488,-0.229)	2.259	(-2.306,2.306)	4.612	5.209	
	diamond 3	(-0.199,0.144)	0.055	(0.390,0.409)	0.019	0.0005	

Analysis of charge stability diagrams in Figure 6 (a , b) show that double CNT SET has lower coulomb diamonds area than SET with single CNT. Comparison the data given in Table 1 indicates that that total coulomb diamond area of double CNT SET is smaller than CNT SET. Moreover, the coulomb blockade range and zero voltage region of double CNT SET are smaller than CNT SET. Therefore, SET with double CNT has higher conductance than another SET.

Conclusion

Single electron transistors (SETs) as nanoscale devices can be utilized in many electronic devices can be utilized in many electronic devices such as sensors and oscillators. The material of the SET island plays an important role in SET operation. Carbon nanotube (CNT) is selected for quantum dot island. Double quantum dots CNT were utilized as SET island. The current of double CNT SET is modeled by mathematical model and then analyzed. Impact of CNT length, applied gate voltage and temperature are explored. Moreover, the effect of numbers of island were investigated. The charge stability diagrams for two devices as CNT SET and double CNT SET were plotted and compared together. The results revealed the fact that the total area of coulomb diamonds for double CNT SET was smaller than CNT SET. Therefore, the zero voltage region and zero conductance region of double CNT SET were smaller than CNT SET in charge stability diagrams. The results of this study show that double CNT SET was better operation than CNT SET.

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