Current Analysis of Single Electron Transistor Based on Graphene Double Quantum Dots

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Current Analysis of Single Electron Transistor Based on Graphene Double Quantum Dots

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The single electron transistors (SETs) as low power devices are suitable candidates for nanoscale circuit in future technology. These nanoelectronic devices operate based on an electron tunneling. However, coulomb blockade effect prevents single electron transfer between island and coulomb barriers in some conditions. This phenomenon causes zero-conductance region in low bias that is operation limitation of SET. This problem can be solved by using multiple islands in SET structure which their materials are two dimensional carbon based materials such as graphene. Increasing the number of islands effects on probability of electron tunneling. This factor not only rises speed of electron transfer but also it can reduce gap conductance in SET. In this research, current of graphene double quantum dots SET is analyzed and modeled. Moreover effects of graphene length, applied gate voltage and temperature on current SET are investigated. Furthermore effect of number of islands on SET current is evaluated with comparison their charge stability diagrams which are results of SET simulation by software.
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The semiconductor transistors have been an important element of electronic systems. Technology passes path of integrating devices very rapid which reduces device size with the passage of time. Therefore nanoscale devices such as Graphene Nanoribbon Field Effect Transistors (GNRFETs), Carbon Nanotube Field Effect Transistors (CNTFETs) and Single Electron Transistors (SETs) are among candidates for the replacement of traditional transistors in future.[1–5] The first SET device was fabricated by Fulton and Dolan in 1987.[6] SET contains drain electrode and source electrode that two tunnel junctions and an island are between them. Moreover gate electrode connects to the island by gate capacitance.[7–9] Materials of SET structure affect on electron transmission, thus fast operation of SET needs to choose new low dimensional carbon base materials such as graphene with fast electron transfer and high electron mobility with honeycomb lattice.[10,11] It is suitable choice for island material of SET because of its good stability in nanoscale. The structure of single electron transistor with two graphene islands (DQD SET) is shown in Fig. 1.

Hence by applying bias voltage, an electron tunnels from source to island and then it moves to drain.[12] However under some conditions, coulomb blockade effect prevents transfer electron, so current is zero.[13]

In this research, the coulomb blockade range is analyzed for SET with double graphene quantum dots using Atomistix ToolKit (ATK) software.[14] Moreover their charge stability diagrams are plotted and compared together with the aid of coulomb diamond patterns as shown in Fig. 2a. The blue diamonds represent CB regions where electron transfer stops, therefore the device current becomes zero.[15,16] The green diamonds are electron tunneling regions where electron tunnels from source to drain and current flows in SET.[17] The red diamonds show co-tunneling regions that two or more electrons move to island.[18] These diamonds depend on energy level of SET.[19] Energy level diagrams of our points are plotted in Figs. 2b –2e where electron transfer is shown and investigated in each figure. The point "I" is in CB region and the first energy level of the island is higher than the energy level in the source. Therefore electron can't tunnel to the island. Point "II" is between CB and electron tunneling region, thus the first energy level of the quantum dot is aligned with the energy level of the source. Therefore electron tunnels to the quantum dot and then it moves to the drain. Point "III" is located in tunneling region where the energy level of island is in the transfer window and electron can tunnel form source to quantum dot and eventually to the drain and current flows in SET. Point "IV" not only is in the CB region but also the gate voltage is zero.[20] Moreover, source and drain energy levels are equal and they are lower than the energy level in the quantum dot or island. In this case, electron can't tunnel to the quantum dot. The final result is that the current becomes zero.

Results and Discussion

The single-electron transistors (SETs) can switch electron to achieve desired current by the quantum mechanical effects. Quantum mechanics express wave function changes by varying space of regions; however it is same in border points of neighboring regions.[21] Also double quantum dots SET is divided to five parts that has two islands as determined in Fig. 3a. The energy vs SET channel length with two barriers is illustrated in Fig. 3b.[22]

The Schrodinger's equations for five parts of graphene SET with attention to their part are defined.[23]

$$-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi_I(x) = E\psi_I(x) \qquad \text{First region} \qquad [1]$$

$$\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V(x)\right]\psi_{II}(x) = E\psi_{II}(x) \qquad \text{Second region} \qquad [2]$$

$$-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi_{III}(x) = E\psi_{III}(x) \qquad \text{Third region} \qquad [3]$$

$$\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V(x)\right]\psi_{IV}(x) = E\psi_{IV}(x) \qquad \text{Forth region} \qquad [4]$$

$$-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi_V(x) = E\psi_V(x) \qquad \text{Fifth region} \qquad [5]$$

Schrodinger's equations are solved as:[24]

$$\psi_I(x) = A_1 e^{k_1 x} + B_1 e^{-k_1 x} \text{ Where } k_1 = \frac{\sqrt{2m(V-E)}}{\hbar} \qquad [6]$$

$$\psi_{II}(x) = A_2 e^{ik_2 x} + B_2 e^{-ik_2 x} \text{ Where } k_2 = \frac{\sqrt{2mE}}{\hbar} \qquad [7]$$

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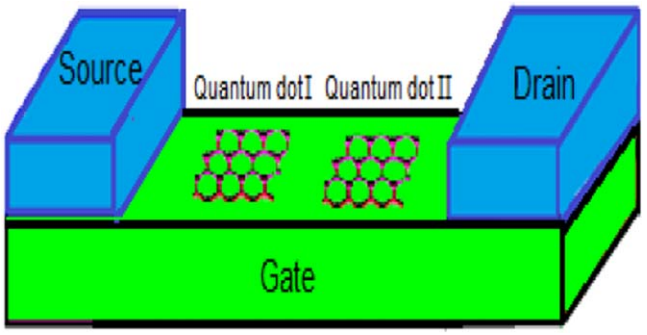

Figure 1. The single electron transistor with graphene double quantum dot (DQD).

$$\psi_{III}(x) = A_3 e^{k_3 x} + B_3 e^{-k_3 x} \text{ Where } k_3 = k_1 = \frac{\sqrt{2m(V-E)}}{\hbar} \quad [8]$$

$$\psi_{IV}(x) = A_4 e^{ik_4 x} + B_4 e^{-ik_4 x} \text{ Where } k_4 = k_2 = \frac{\sqrt{2mE}}{\hbar} \quad [9]$$

$$\psi_V(x) = A_5 e^{k_5 x} \quad \text{Where } k_5 = k_3 = k_1 = \frac{\sqrt{2m(V-E)}}{\hbar} \quad [10]$$

Graphene SET consists of two potential wells, in addition first well is from $x = 0$ to $x = a$ and also second barrier well from $x = a + L$ to $x = 2a + L$.Therefor boundaries condition must be consider to border points as

$$\psi_I(0) = \psi_{II}(0) \Rightarrow A_1 + B_1 = A_2 + B_2 \quad [11]$$

$$\psi'_I(0) = \psi'_{II}(0) \Rightarrow k_1 A_1 - k_1 B_1 = ik_2 A_2 - ik_2 B_2 \quad [12]$$

$$\psi_{II}(a) = \psi_{III}(a) \Rightarrow iA_2 e^{ik_2 a} + iB_2 e^{-ik_2 a} = A_3 e^{k_1 a} + B_3 e^{-k_1 a} \quad [13]$$

$$\psi'_{II}(a) = \psi'_{III}(a) \Rightarrow ik_2 A_2 e^{ik_2 a} - ik_2 B_2 e^{-ik_2 a} = k_1 A_3 e^{k_1 a} + k_1 B_3 e^{-k_1 a} \quad [14]$$

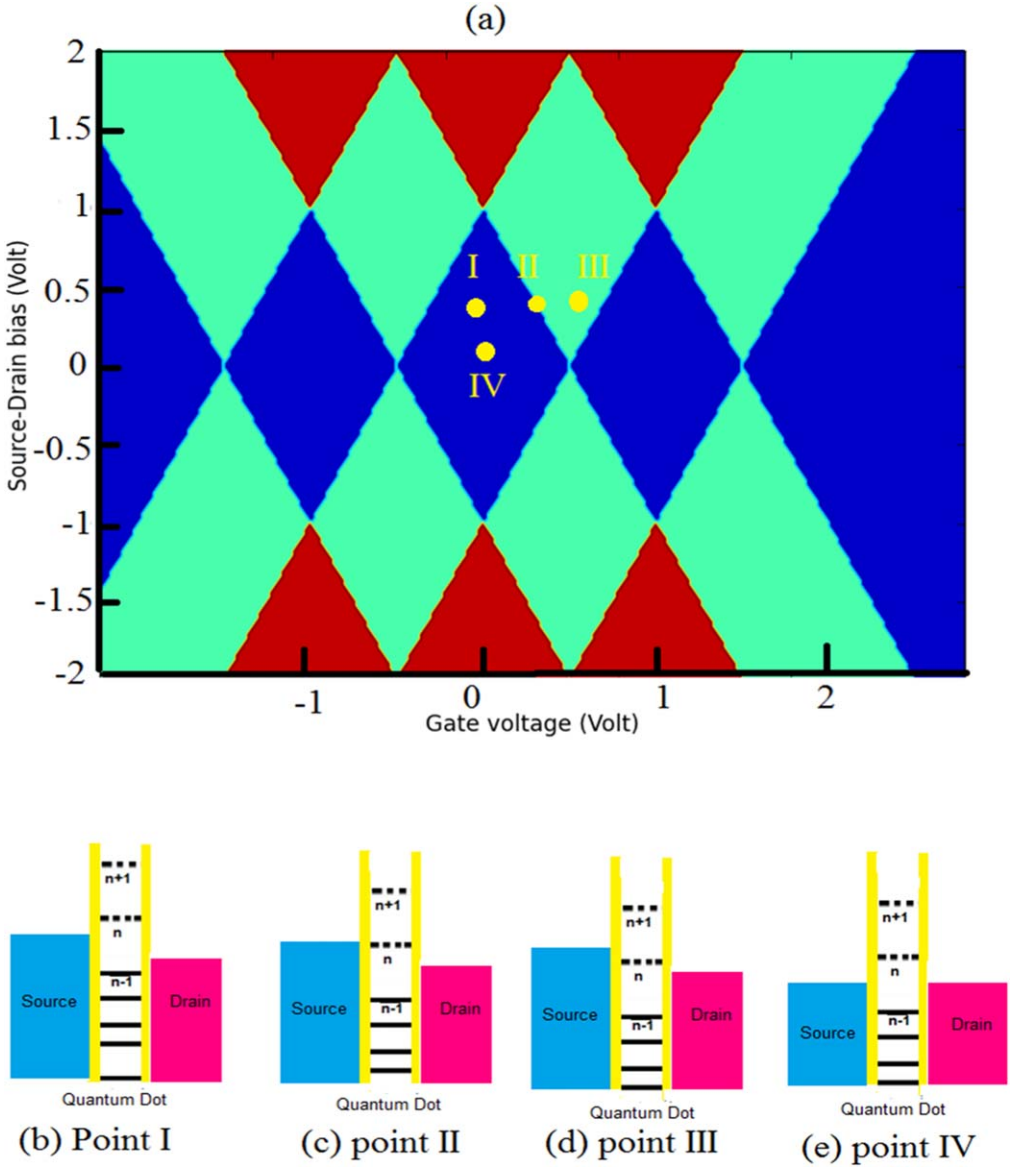

Figure 2. (a) A typical charge stability diagram of SET; (b)–(e) Energy levels of SET corresponding to different points in the charge stability diagram.

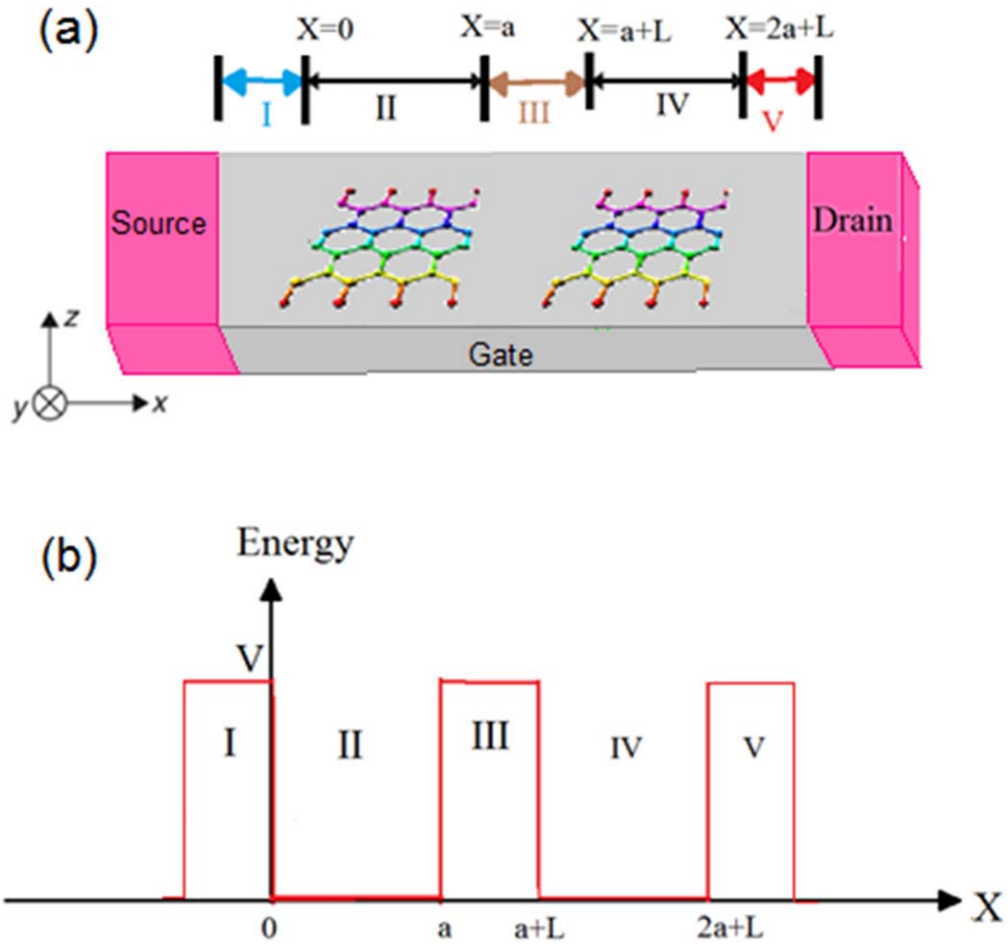

Figure 3. (a) Schematic presentation of double quantum dots SET regions. (b): double quantum dots SET energy vs channel region which indicates tunnel barriers.

$$\psi_{III}(a+L) = \psi_{IV}(a+L) \Rightarrow A_3 e^{k_1(a+L)} + B_3 e^{-k_1(a+L)} = A_4 e^{ik_2(a+L)} + B_4 e^{ik_2(a+L)} \quad [15]$$

$$\psi'_{III}(a+L) = \psi'_{IV}(a+L) \Rightarrow A_3 k_1 e^{k_1(a+L)} + B_3 k_1 e^{-k_1(a+L)} = A_4 ik_2 e^{ik_2(a+L)} + B_4 ik_2 e^{ik_2(a+L)} \quad [16]$$

$$\psi_{IV}(2a+L) = \psi_V(2a+L) \Rightarrow A_4 e^{ik_2(2a+L)} + B_4 e^{-ik_2(2a+L)} = A_5 e^{-k_1(2a+L)} \quad [17]$$

$$\psi'_{IV}(2a+L) = \psi'_V(2a+L) \Rightarrow ik_2 A_4 e^{ik_2(2a+L)} - ik_2 B_4 e^{-ik_2(2a+L)} = k_1 A_5 e^{k_1(2a+L)} \quad [18]$$

Above equations are solved.[25] As a result, transmission coefficient of graphene double quantum dots (DQD) SET is given as:

$$T_{Total} = \frac{1}{1 + k_G^4 k_2^2 L^2 + 0.027 k_G^4 k_2^6 L^6 + 0.33 k_G^4 k_2^4 L^4} \quad [19]$$

$$k_G = \frac{(\hbar^2 + ta'm)E - \hbar^2 E_g}{2\sqrt{ta'\hbar m E(E - E_g)}} \quad [20]$$

where "L" is graphene length, $k_2 = \frac{\sqrt{2mE}}{\hbar}$ and "E" is electron energy, E_g is band gap of graphene, "m" is the effective mass and "$\hbar$" is the Planck constant,"$a' = 3a_{c-c}$", a_{c-c} is the distance between neighbouring carbon atoms, "t" is the hopping energy.

Thus quantum drain current based on the Landauer formalism is:[26]

$$I_d = \int_0^{\eta} F(E).T(E)dE \quad [21]$$

That $T(E)$ is transmission coefficient of graphene DQD SET moreover $F(E)$ is Fermi probability function defined as:

$$f(E)\left(\frac{1}{\exp\left(\frac{E-E_F}{k_BT}\right)+1}\right) \quad [22]$$

Finally a model is suggested for drain current of graphene single electron transistor with double quantum dots which is calculated by:

$$I = \int_0^{\eta} \frac{1}{1 + k_G^4 (Ak_BT\,(x+d))^2 L^2 + 0.027 k_G^4 (Ak_BT\,(x+d))^6 L^6 + 0.33 k_G^4 (Ak_BT\,(x+d))^4 L^4} \cdot \frac{k_B T dx}{e^{x-\eta}+1} \quad [23]$$

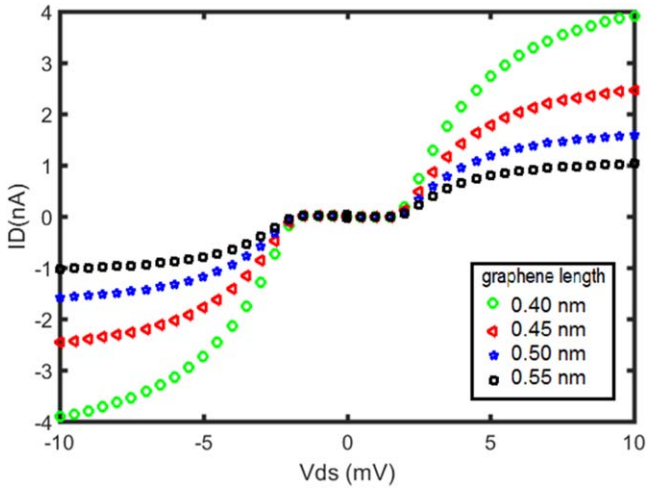

Figure 4. The current vs voltage curves of proposed model of DQD SET for different graphene lengths, applied gate voltage is 1 mV and temprature is 300 K.

where "L" is graphene length, $x = \frac{E - E_g}{k_B T}$, $\eta = \frac{E_F - E_g}{k_B T}$, $d = \frac{E_g}{k_B T}$, $A = \sqrt{\frac{2m}{\hbar^2}}$, "$E_F$" is Fermi energy, '$T$" is temperature and "$k_B$" is the Boltzmann constant and other parameters were defined previously.

The proposed model is based on graphene length that is investigated in Fig. 4. The quantum dot in SET is an important its part that its length effect on SET current. This parameter is investigated in Fig. 4. while graphene length changes from 0.4 nm to 0.55 nm. Analysis of its curves show that increasing graphene DQD lengths have indirect impact on current without regular factor. Furtheremore DQD with the lowest length has the most current because electron acrrosses shorter potantial barriers,so it transfers faster. Another efffective factor is gate voltage which its impact is investigated by proposed model in Fig. 5.

The gate voltage has direct impact on SET current therefore it is investigated in four different voltage values. Copmarision of curves in Fig. 5 indicates that increasing gate voltage increases current. When current increases 1 mV then SET current rises 5 mA. The physical reason can be transfers energy level to transfer window which high gate voltage increses its tranfer speed and then single electron tunneling phenomena ocuures.

The temperature effects on current SET,so this parameter is analysed in Fig. 6 at 100 K to 300 K. The current vs voltage curves

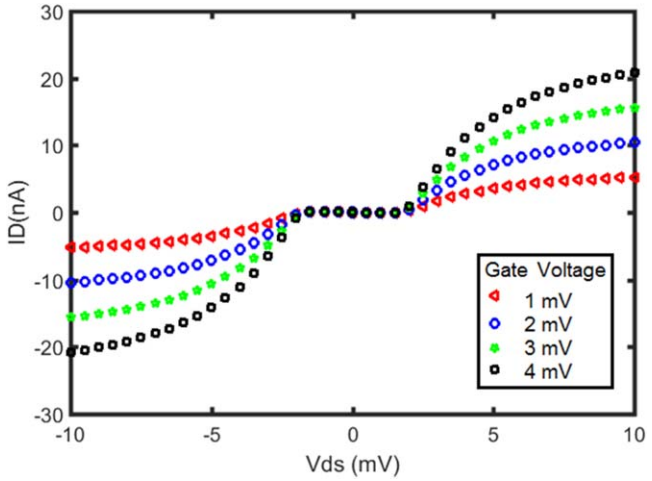

Figure 5. The current vs voltage curves of proposed model of DQD SET for different gate voltages, graphene lengths is 1 nm and temprature is 300 K.

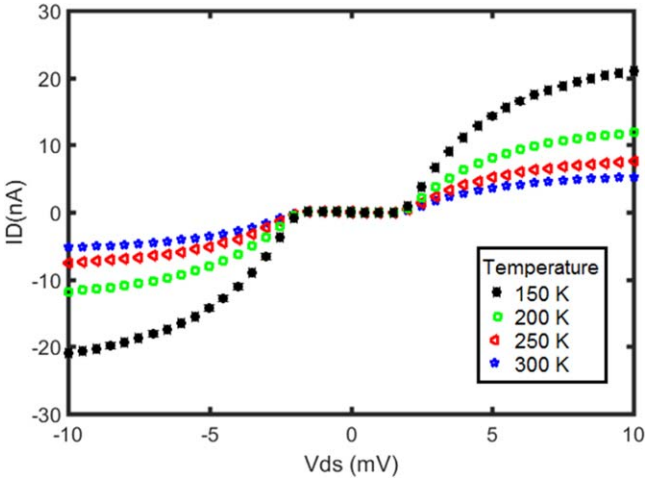

Figure 6. The current vs voltage curves of proposed model of DQD SET at different temprature, gate voltage is 1 mV and graphene lengths is 1 nm.

change at different temperature. The lowest temperature has highest current value because the current in SET depends on is Fermi probability function which increases in low temperature.

The results of current vs voltage curves in Figs. 4–6 confirm DQD length, applied gate voltage and also temperature effect on current and also they can control current in nano range and low bias. Another factor can show performance SET is coulomb blockade range which in our research a DQD SET is designed with Atomistix ToolKit (ATK) software.[14] The graphene nanoribbon with zigzag structure and 4 carbon atoms in xyz coordinates is designed as SET island. The DFT method using local-density approximation (LDA) is utilized for simulation and finally charge stability diagram of graphene DQD SET can plot as shown in Fig. 7. It's color bar represents the corresponding charge states in the diagram.

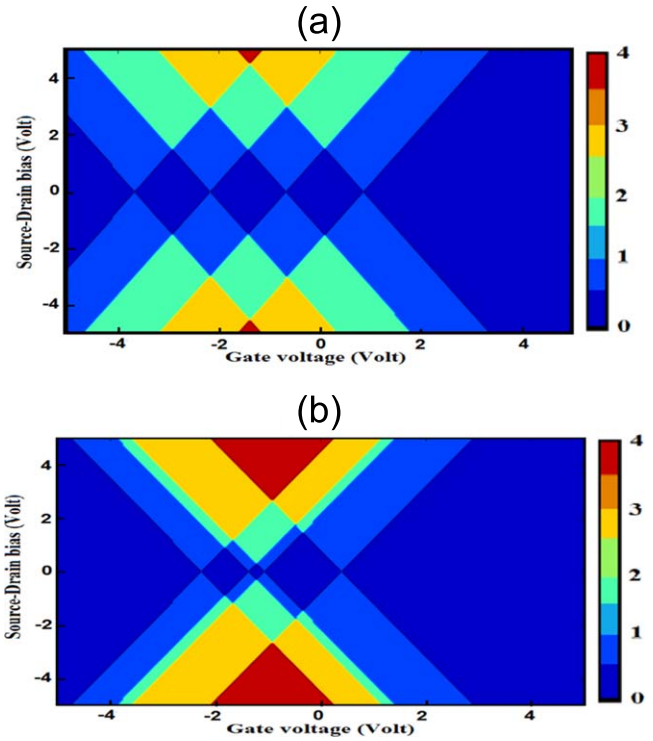

Figure 7. The charge stability diagrams of SET with graphene DQD as its islands (a): single QD (b):double DQD islands. (The color bar on the right represents the corresponding charge states in the diagram).

The number of islands has direct impact on coulomb blockade range in SET. Therefore SET with single graphene quantum dot (QD) and double graphene quantum dots (DQD) are investigated in Fig. 7. The compression their charge stability diagrams shows that single QD SET has longer coulomb blockade range and area of center diamond than DQD SET. As a result increasing QD can improve speed of electron transfer in SET.

Conclusion

Single electron transistor as a fast nano-device switches current by tunneling of electrons. Electron transfers by coulomb blockade effect, so it causes to zero current range in low bias. In this research, graphene with high electron mobility as material of SET island is selected and also a current model is suggested for graphene double quantum dots SET. The results show that graphene length and temperature have indirect impact on SET current but gate voltage effects on current directly. Moreover the SET with single graphene quantum dot and double graphene quantum dots are designed and also simulation results show that their charge stability diagrams has lower coulomb blockade rang and center diamond area. Therefore increasing number of quantum dot in SET can improve performance SET and its speed.

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