Investigating the electrical characteristics of a single electron transistor utilizing graphene nanoribbon as the island

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Abstract

Single electron transistor (SET) is a fast device with promising features in nanotechnology. Its operation speed depends on the island material, so a carbon based material such as graphene nanoribbon (GNR) can be a suitable candidate for using in SET island. The GNR band gap which depends on its width, has a direct impact on the coulomb blockade (CB) and SET current. In this research, current-voltage characteristic for the SET utilizing GNR in its island is modelled. The comparison study shows the impact of GNR width and length on the SET current. Furthermore SET quantum capacitance is modeled and effect of GNR width and temperature on the quantum capacitance are investigated.

Keywords: Graphene nanoribbon (GNR), Tunneling, Single Electron Transistor (SET), Charge stability diagram.

1-Introduction

Tunneling based devices such as single electron transistor (SET) are attractive subjects for researchers. This nanoscale transistor has promising features such as very fast switching speed and its operation is based on quantum tunneling [1, 2]. A single electron tunnels from source electrode to the island and then leaves it to drain electrode [3, 4]. This process is prevented by coulomb blockade phenomena. It affects on the energy levels of the island as well as source and drain electrodes [5, 6]. If energy level of the electron in the island is between energy levels of drain and source (transfer window), the electron can tunnel and current flows [7]. The island shape and its material properties such as electron mobility have direct effect on the SET current and Coulomb Blockade (CB) range [8]. Its material can be graphene which is 2D structure of carbon atoms arranged in a hexagonal pattern [9]. The interesting characteristics of this 2D material is discovered by A. Geim and K. Novoselov from the University of Manchester at 2004 [10]. It has high carrier mobility, so graphene SET can operate with a high speed. A strip of graphene is called graphene nanoribbon (GNR) and it has one dimensional structure [11, 12]. Its edge configurations has two different types called armchair and zigzag [13, 14, 15]. The armchair configuration is classified to three families: 3p, 3p+1 and 3p+ 2 where "p" is an integer number indicating the number of atoms along the width [16]. The corresponding bandgaps with same "p"'s are different for each family, so the current which flows from graphene SET depends on the energy gap [16, 17]. In other words, GNR bandgap depends on its edge configuration and number of atoms along its width [18]. We derive the current-voltage characteristics for a SET utilizing graphene in this research and then study the impact of GNR width and length on the current.

2- Modelling the current flow in a GNR SET

A single electron transistor comprises of source, gate, drain electrodes and an island which is located between source and drain but not connected to them as shown in Fig. 1(a). The GNR island with the length of L can be assumed as a quantum well and the potential profile along the device is shown in Fig. 1(b). Schrodinger equation can be employed to derive the electron wave function and the corresponding current for this particular device.

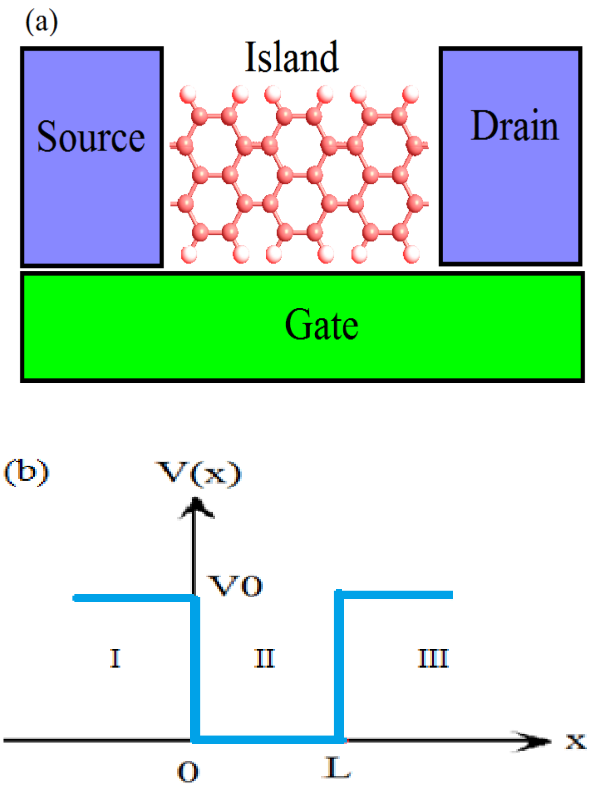


Figure 1: a) Graphene nanoribbon SET .b) potential profile along the device.

The wave functions for different parts of SET (regions I, II, III) is given by:

$$\Psi_I = A_1 e^{k_1 x} + B_1\, e^{-k_1 x} \quad (1)$$

$$\Psi_{II} = A_2 e^{ik_2 x} + B_2\, e^{-ik_2 x} \quad (2)$$

$$\Psi_{III} = A_3 e^{ik_3 x} \quad (3)$$

where $k_1 = k_3 = \frac{\sqrt{2m(V_0 - E)}}{\hbar}$ and $k_2 = \frac{\sqrt{2mE}}{\hbar}$.

Continuity of the wave functions and its derivative for the neighbouring parts gives the boundary conditions at $x = 0$ and L as:

$$A_1 + B_1 = A_2 + B_2 \quad (4)$$

$$k_1A_1 - k_1B_1 = ik_2A_2 - ik_2B_2 \quad (5)$$

$$A_2e^{ik_2L_1} + B_2\, e^{-ik_2L_1} = A_3e^{k_1L_1} \quad (6)$$

$$ik_2A_2e^{ik_2L_1} - ik_2\, B_2\, e^{-ik_2L_1} = k_1A_3e^{k_1L_1} \quad (7)$$

Therefore transmission coefficient of GNR SET can be calvulated as [19]:

$$T = \frac{1}{1+\frac{(\mathrm{h}^2+ta'm)E-\hbar^2E_g}{2\sqrt{ta'\mathrm{h}mE(E-E_g)}}sinh^2(k_2L)} \quad (8)$$

where "L" is the GNR length, $k_2 = \frac{\sqrt{2mE}}{\hbar}$, "$E$" is the electron energy level , "m" is the electron effective mass, "h" is the Planck's constant, "$a' = 3a_{c-c}$" , and $a_{c-c} = 1.42A^0$ is the distance between neighbouring carbon atoms, "E_g" is the GNR band gap and "t=2.7 eV". The current of GNR SET is modeled by using transmission coefficient and landauer equation [19]. On the other hand the relation between bandgap and GNR width (w) for 3p+1 family is [20, 21]:

$$E_g = \frac{1.04eV}{w(nm)} \quad (9)$$

Therefore current of GNR SET is modeled as:

$$I = \int_0^{\eta} \frac{AK_BTx\,(K_BTx + \frac{1.04}{w})}{AK_BTx\left(K_BTx + \frac{1.04}{w}\right) + (B\left(K_BTx + \frac{1.04}{w}\right) + CAK_BTx)^2[\left(B\left(K_BTx + \frac{1.04}{w}\right)L^2\right)^{\frac{1}{2}} + \frac{\left(B\left(K_BTx + \frac{1.04}{w}\right)L^2\right)^{\frac{3}{2}}}{6}]^2} \cdot \frac{dE}{e^{x-\eta}+1} \quad (10)$$

where $A = \left(\frac{16m}{3\hbar ta_{c-c}}\right)$, $B = \left(\frac{2m}{\hbar}\right)$,$C = \left(\frac{2}{3ta_{c-c}}\right)$, $x = \frac{E-E_g}{K_BT}$, $\eta = \frac{E_F - E_g}{K_BT}$, "E_F" is GNR Fermi energy, "K_B" is Boltzmann's constant, and other parameters were defined previously. It is worth noting that the GNR width is directly proportional to the number of carbon atoms along the ribbon width. In general, the relation between the width and the number carbon atoms in an armchair GNR is given by [20,21]:

$$w(nm) = \frac{0.246}{2}(N-1) \quad (11)$$

Fig. 2 represents an armchair GNR having 7 carbon atoms along the width. Since the current in Equation (10) is explicitly based on the GNR width, the SET current can be evaluated for different ribbon widths as shown in Fig. 3. This figure reveals the fact that the highest GNR width has the lowest coulomb blockade (CB) range and zero current. In the other words, increasing GNR width increases the probability of electron tunneling and this leads to increase in the current.

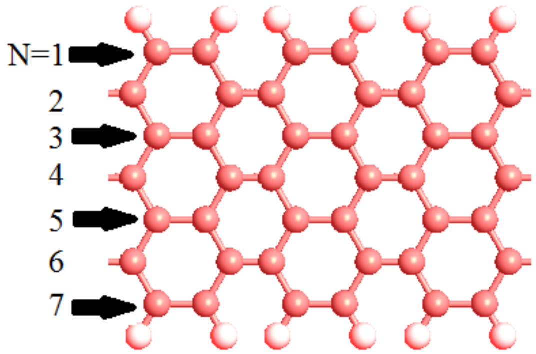


Figure 2: An armchair GNR with N=7.

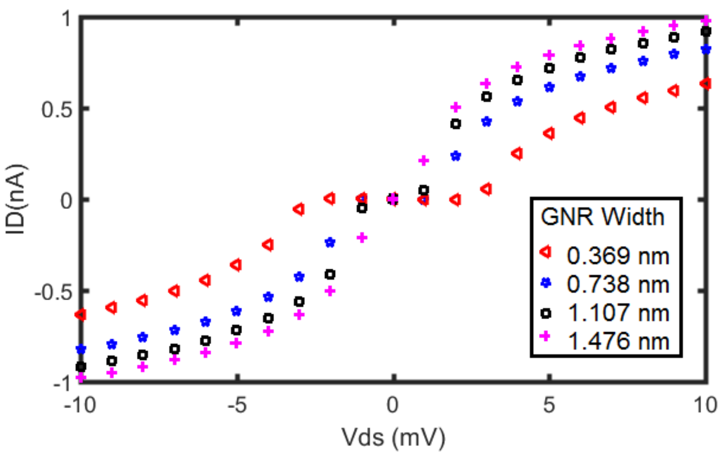


Figure 3: SET current versus drain voltage for different island widths, gate voltage is 1mV and GNR length is 0.492 nm.

Another factor affecting on the SET current is the gate voltage. SET current versus the drain voltage is plotted in Fig. 4 while the GNR length and width are selected as 0.396 nm and 0.492 nm, respectively. This figure clearly shows that increasing of the gate voltage has no significant impact on the coulomb blockade (CB) range. However, the gate voltage has a direct impact on the SET current for the V_{ds} outside from CB range. In order to evaluate the impact of gate voltage on the current, we simulated another device with the GNR width of 1.23 nm as shown in Fig. 5. Comparison of Fig. 4 and Fig. 5 indicates that the current in the device having wider GNR is almost 1.5 times more than the corresponding current of the other device. Furthermore,

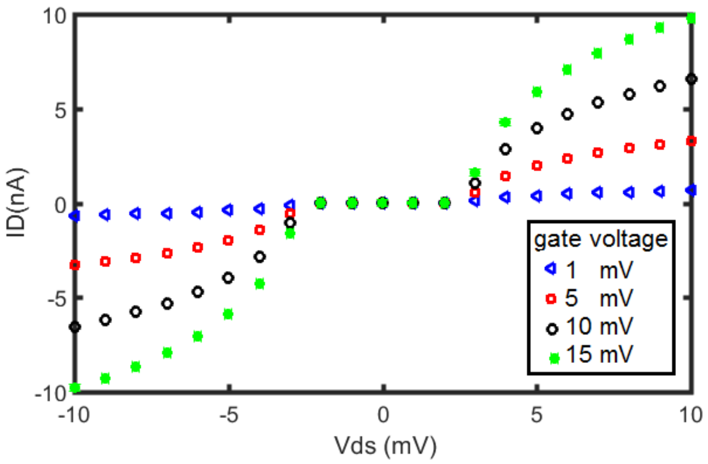


Figure 4: SET current versus drain voltage for different gate voltages. GNR width and length are 0.396 nm and 0.492 nm, respectively.

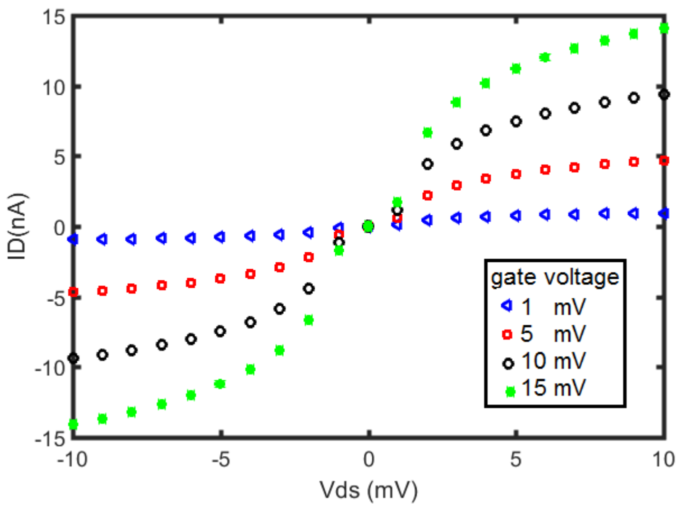


Figure 5: SET current versus drain voltage for different gate voltages. GNR width and length are 1.23 nm and 0.492 nm, respectively.

CB range is about one nanovolt for the device utilizing wider GNR but it is several millivolts for the device with smaller GNR width.

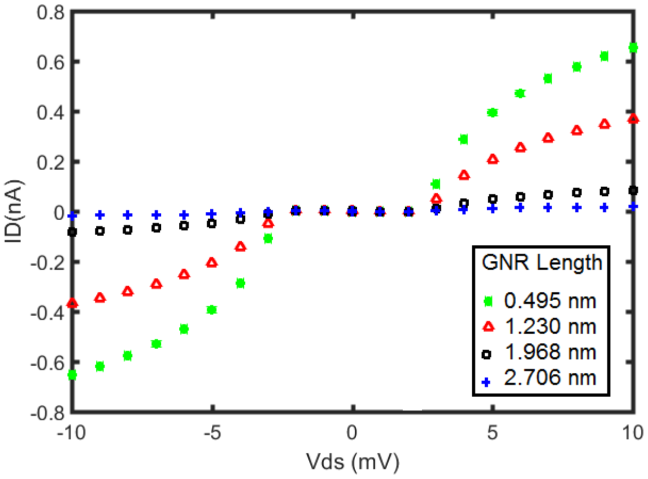


Figure 6: SET current versus drain voltage for different GNR lengths. Gate voltage is 1mV and GNR width is 0.396 nm.

The impact of GNR length on the SET current is investigated and shown in Fig. 6. It clearly indicates that variation in the GNR length, like the gate voltage, has no significant impact on the CB range. On the other hand, GNR length has a direct impact on the device current for the V_{ds} outside from CB range. The physical reason behind this behavior is that increasing the GNR length leads to a longer potential barrier in the island. This leads to decreased tunneling of electrons from source to drain and thus, the SET current is significantly reduced.

3- Investigating the quantum capacitance and charge stability diagram

The quantum capacitance is an important component in very small dimension electronic devices. It is modeled in our previous research [22] and given by:

$$c_Q = e^2 \frac{\partial n}{\partial E} = e^2 \frac{(ta')^{\frac{-1}{2}}}{2\sqrt{2}\pi} \cdot \frac{\left(E - \frac{1.04}{w}\right)}{\exp\left(\frac{E-E_F}{K_B T}\right)+1} \tag{12}$$

where "e" is charge of an electron and other parameters were defined previously as described in Eq. 8. Moreover, Eq. 9 is used to express the quantum capacitance as a function of GNR width. In this research, we investigate the impact of GNR width and temperature on the quantum capacitance. The proposed model is explicitly based on GNR width, and the effect of this parameter on the quantum capacitance is illustrated in Fig. 7. Analysis of Fig. 7 indicates that increasing GNR width decreases the maximum value of the quantum capacitance while its impact on the minimum value (which occurs around V_g=-0.2V) is not noticeable.

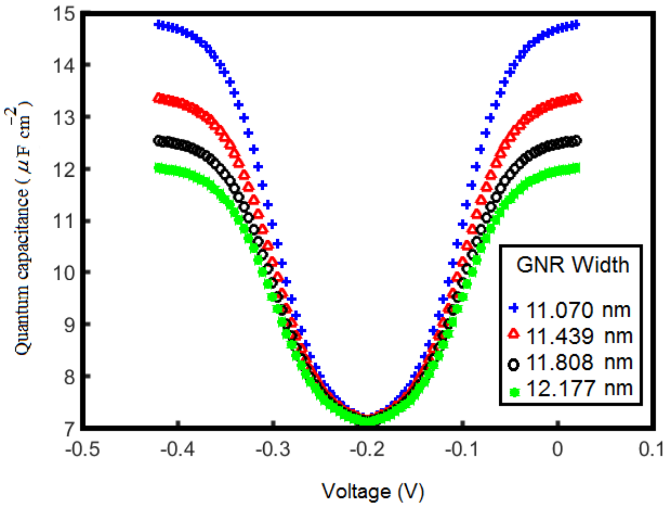


Figure 7: Quantum capacitance versus gate voltage for different GNR widths.

The impact of temperature on the quantum capacitance is depicted Fig.8. It reveals the fact that the temperature in neither influence on the maximum nor minimum value of the quantum capacitance. Instead, the quantum capacitance is broadened at higher temperatures. This behavior is due to the fact that the Fermi function is broadened at higher temperatures.

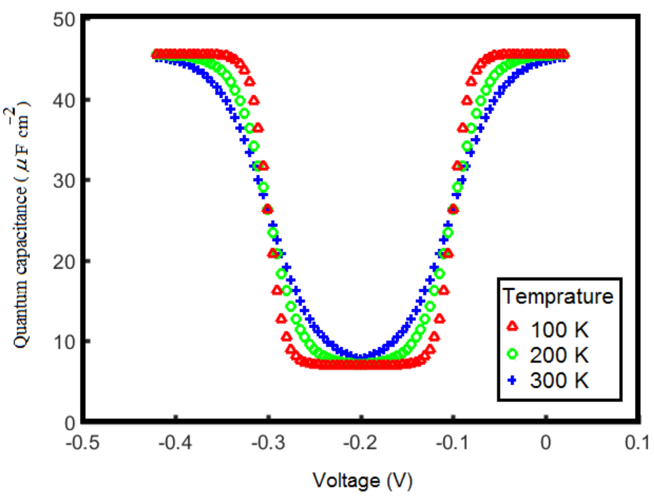
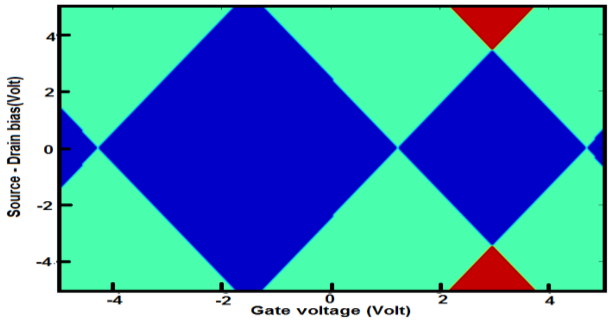
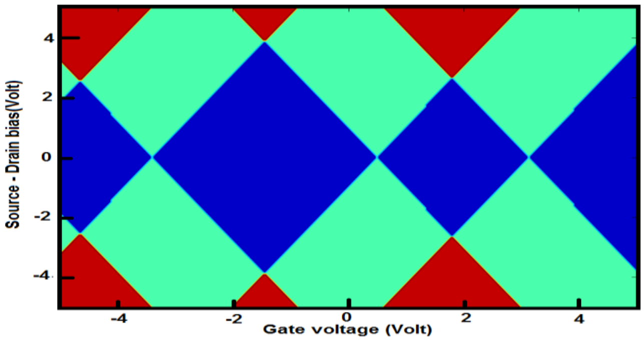


Figure 8: The curves of quantum capacitance versus voltage for different temperatures and GNR width is 11.07 nm.

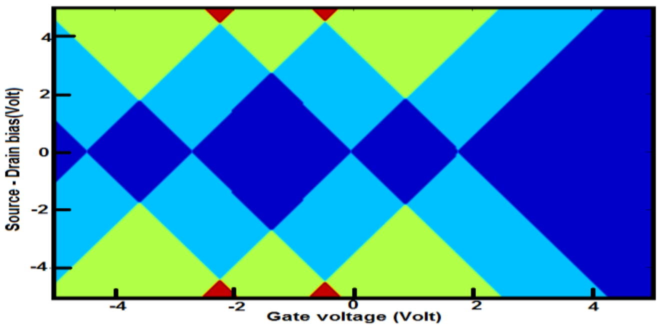
The GNR SETs with different GNR widths are designed and simulated with Atomistic Toolkit software [23]. Their charge stability diagrams are plotted in Fig. 9 (a, b, c) corresponding to 4, 7 and 10 carbon atoms along the GNR width, respectively. The blue diamonds in each figure presents regions where the tunneling is completely stopped due to coulomb blockade effect and thus, no current is flowing through the device.



(a)



(b)



(c)

Figure 9: The simulated charge stability diagrams for three GNR SETs: (a) GNR island with N=4, (b) GNR island with N=7, (c) GNR island with N=10.

Based on the charge stability diagrams shown in Fig. 9 for different GNR widths, it is concluded that increasing the number of carbon atoms along GNR width decreases the coulomb diamond area and coulomb blockade range. This result is in agreement with what we found from Fig. 3.

4- Conclusion

In this research, a single electron transistor utilizing graphene nanoribbon as the island was investigated. The emphasis was to model the current behavior versus ribbon geometry (width and length) and the gate voltage. The results revealed the fact that increasing GNR width leads to decrease of the coulomb blockade (CB) range. However, the GNR length and gate voltage did not have a noticeable impact on the CB range but these parameters showed a significant impact on the SET current for the drain voltages outside from CB range. Moreover quantum capacitance was modeled and the effects of GNR width and temperature was investigated. The charge stability diagrams were simulated and the results showed that increasing the number of carbon atoms along the GNR width has a direct effect on CB range and coulomb diamond area.

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