Research Article

Analyses of Short Channel Effects of Single-Gate and Double-Gate Graphene Nanoribbon Field Effect Transistors

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Short channel effects of single-gate and double-gate graphene nanoribbon field effect transistors (GNRFETs) are studied based on the atomistic p_z orbital model for the Hamiltonian of graphene nanoribbon using the nonequilibrium Green's function formalism. A tight-binding Hamiltonian with an atomistic p_z orbital basis set is used to describe the atomistic details in the channel of the GNRFETs. We have investigated the vital short channel effect parameters such as I_{on} and I_{off} , the threshold voltage, the subthreshold swing, and the drain induced barrier lowering versus the channel length and oxide thickness of the GNRFETs in detail. The gate capacitance and the transconductance of both devices are also computed in order to calculate the intrinsic cut-off frequency and switching delay of GNRFETs. Furthermore, the effects of doping of the channel on the threshold voltage and the frequency response of the double-gate GNRFET are discussed. We have shown that the single-gate GNRFET suffers more from short channel effects if compared with those of the double-gate structure; however, both devices have nearly the same cut-off frequency in the range of terahertz. This work provides a collection of data comparing different features of short channel effects of the single gate with those of the double gate GNRFETs. The results give a very good insight into the devices and are very useful for their digital applications.

1. Introduction

In recent years, to resolve the severe limitations in scaling of conventional silicon transistors, many researchers have paid attention to one and two materials to be used as the channel of semiconductor devices especially nanoscale transistors, for examples, carbon nanotube (CNT) transistors [1], silicon nanowire transistors [2], FinFETs [3], and graphene nanoribbon transistors [4]. Due to excellent electronic properties of two-dimensional materials such as graphene and phosphorene, they are known as the promising substances as the electronic materials in the near future [5, 6].

Graphene is a one-atom-thick sheet of carbon atoms which are arranged in a hexagonal structure. The graphene nanoribbon (GNR) is a monolayer ribbon of graphene which is patterned along a specific channel transport direction, where its narrow channel width shows interesting electronic

properties theoretically and experimentally [7–9]. A GNR-FET is realized by connecting both sides of the channel to metals known as Schottky contacts and is called Schottky Barrier GNR-FET (SB-GNR-FET). In addition, ohmic contacts can be obtained by using heavily doped GNRs as source and drain regions. Therefore, such a device makes a doped contact GNR-FET which operates like a MOSFET.

Many undesirable quantum and short channel effects such as drain induced barrier lowering (DIBL) and threshold voltage roll-off appear when the channel length of the field effect transistor enters the nanometer regime. The short channel effects are referred to as deviations from an ideal long channel behavior due to decrease of channel length. However, partial neutralization of these effects can be done by amending the other parameters of device, such as doping concentration.

Comparison between the short channel effects of CNT-FETs and GNR-FETs are done using nonequilibrium Green's function (NEGF) formalism [10]. NEGF is an accurate full quantum transport method intended to study the devices in the nanoscale regime [11–13]. The short channel effects of SB-GNRFETs designed in three different structures including single gate (SG), double gate (DG), and wrapped gate have been investigated and their performances are compared [7]. In addition, the short channel characteristics of a doped contact DG-GNRFET are compared with those of SB-GNRFET [4], where the results show that the doped contact GNRFETs have better performance than the SB-GNRFETs. A larger maximum achievable on-off ratio, 50% larger on-current, a larger transconductance, and better saturation behavior with 60% smaller output conductance are known as the advantages of the doped contact GNRFETs over SB-GNRFETs. Moreover, switching and high frequency performances of the doped contact GNRFETs are also improved by 30% higher cut-off frequency and 20% faster switching speed compared to those of SB-GNRFETs [4].

Using linear and step-linear doping profiles for drain (source) in doped contact CNTFETs and GNRFETs can alleviate the short channel problems [14–16]. Dual- and triple-material gate structures which employ gate-material engineering with different work functions instead of doping engineering are another way to partially suppress the short channel effects in doped contact DG-GNRFETs [17].

According to the best of our knowledge, global investigations of short channel effects and high frequency parameters on single-gate and double-gate doped contact GNRFET devices are not reported so far. In this work, we have included the effect of changes in channel length, oxide thickness, and channel doping on the device behavior. In order to investigate the short channel characteristics of the doped contact GNRFETs, we have applied a full quantum transport approach in mode space based on the NEGF formalism to solve the Schrödinger equation which is self-consistently coupled to a two-dimensional (2D) Poisson's equation. The quantum transport analysis based on the NEGF formalism is a well-known method that is widely used for simulation of nanoelectronic devices. The quantum transport analyses are in more correlation with the experimental results than that of semiclassical methods [18]. The current-voltage characteristics, I_{on} and I_{off} versus channel length, DIBL versus the channel length and oxide thickness, and the frequency responses of the SG- and DG-GNRFETs are investigated. In addition, the effect of channel doping concentration on the current and frequency response of both configurations are discussed. The NEGF and simulation method details are the same as those given in our previous research articles, so we do not include them here [13, 19].

2. Device Structure

The device structures of doped contact quasi-SG- and DG-GNRFETs are shown in Figure 1. In these structures, the GNRs are placed between two layers of insulator. The channel is intrinsic and the gate and channel lengths are equal to

FIGURE 1: The structure of simulated device: (a) SG-GNRFET and (b) DG-GNRFET. The SiO_2 gate insulator is 2 nm thick with a relative dielectric constant $\kappa = 3.9$. Armchair GNR with $N = 12$ and $E_g = 0.735$ eV is used as a channel material, which is 15 nm long and 1.35 nm wide.

15 nm which means the device is without overlap. The oxide thickness (t_{ox}) is assumed to be silicon dioxide, SiO_2 , of 2 nm thickness, where it is feasible because SiO_2 of 1.2 nm thickness is already reported [20], and the relative dielectric constant is $\kappa = 3.9$. The source (drain) region is a sheet of GNR that is doped with 15×10^{-3} dopants/atom. We have also used an armchair GNR (A-GNR) as the channel material with the number of carbon atoms across the width of GNR; N is equal to 12 (width of $W = 1.35$ nm) which confirms that the channel is a semiconducting material with energy bandgap $E_g = 0.735$ eV. To construct quasi-SG-GNRFET, the bottom oxide thickness of device can be chosen large enough to eliminate its effect; thus we choose the thickness of bottom oxide ten times larger than that of the top one. Such an approach has already been used for CNTFETs [21].

3. Theory and Simulation

In this section, a short description on the method and formulas used in our simulation is presented; however, one can find more details in the literatures [13, 19]. It is worth to note that each carbon atom in graphene in addition to having three bonds with its neighbor carbon atoms has one dangling bond called p_z orbital which is very effective on the energy diagram and electrical conduction [22]. We have included the carrier transport within three closer subbands to the Fermi level. The electronic band structure of the graphene nanoribbon is obtained from the band structure of graphene. The band energy throughout the entire Brillouin zone of the

FIGURE 2: The electronic band structure of $N = 12$ and $N = 19$ armchair GNRs with bandgap $E_g = 0.735$ eV and $E_g = 0.497$ eV, respectively. Three subbands with their minimum band gaps are illustrated.

graphene is based on the minimum energy of the structure and defined as [23]

$$E(\vec{k}) = \sqrt{\left(1 + 4 \cos \frac{\sqrt{3}\vec{k}_x a}{2} \cos \frac{\vec{k}_y a}{2}\right) + 4 \cos^2 \frac{\vec{k}_y a}{2}}, \quad (1)$$

where k in x and y directions are the wave vector in the transport (longitudinal) and transverse directions, respectively. Also, $t = -2.7$ eV is the nearest neighbor carbon-carbon (C-C) tight-binding overlap energy, and $a = \sqrt{3}a_{C-C}$, where a_{C-C} is the C-C bond length and is equal to 0.142 nm. In this paper, we have only considered nearest neighbor interaction in the tight-binding calculation for simplicity [24]. Figure 2 shows the energy diagram for A-GNRs with $N = 12$ and $N = 19$. We can see that the first three modes have minimum bandgaps and they contribute to carrier transport more than other higher order modes. Different approximation levels are proposed to determine and calculate the Hamiltonian and energy of atomic scale structures. The approximation levels depend on including the effects of neighboring atoms (e.g., first nearest neighbor or third nearest neighbor) on one atom at the center of a unit cell. The approximation levels and their validity for different applications are thoroughly investigated in [24]. Implementing the simple model (including only the nearest neighbors which are adequate for our analysis), based on using the given band structure and the geometry of the device, the Hamiltonian of the channel can be written as follows [19, 25]:

$$H = \sum_{n=1}^p -e\varphi_{ch} |n\rangle \langle n| + \sum_{n=1, m \neq n}^p t |n\rangle \langle m|, \quad (2)$$

where e is the electron charge and φ_{ch} is the self-consistent electrostatic potential obtained by solving the 2D Poisson's

equation. Using the Hamiltonian of the system, we can write the corresponding Green's function as follows [26]:

$$G = [(E + i0^+)I - H - \Sigma_S - \Sigma_D]^{-1}, \quad (3)$$

where E is the energy, I is the identity matrix, and $\Sigma_{S(D)}$ is the self-energy matrix of the source (drain) which contains the effect of the doped reservoirs (source, drain) on the energy in the channel. It is notable that both source and drain leads operate as reservoirs and behave independently [26, 27]. The current flowing into the device from the source contact toward the drain contact versus the applied gate and drain voltages is computed using the Landauer formula (as given in (4)) once the self-consistency between the Schrödinger equation and the Poisson's equation is achieved [26]:

$$I = \frac{2q}{h} \int_{-\infty}^{+\infty} T(E) [f(E - \mu_S) - f(E - \mu_D)] dE, \quad (4)$$

where h is the Plank coefficient, f is the Fermi-Dirac function, μ_S (μ_D) is the source (drain) electrochemical potential, and $T(E)$ is the transmission coefficient computed from Green's formalism. Here we assumed that $\mu_S = E_f$ and $\mu_D = E_f - qV_{ds}$, where E_f is the Fermi energy of the GNR and is equal to zero as the reference energy level.

The intrinsic cut-off frequency, f_T , is an important parameter for high frequency performance of a transistor. Therefore, intrinsic cut-off frequency, f_T , of GNRFET is computed using the quasi-static approximation [28]. The value of f_T can be obtained from $f_T = g_m/2\pi C_g$ at $V_{ds} = V_{on} = 0.5$ V, where g_m is the transconductance and C_g is the intrinsic gate capacitance. The inherent delay, which specifies how fast a transistor intrinsically switches, is computed by $\tau_s = C_g V_{on}/I_{on}$ [29], where V_{on} is 0.5 V in our study and I_{on} are 2.90 μA and 3.72 μA for SG- and DG-GNRFETs, respectively.

FIGURE 3: The current I_{ds} versus V_{ds} for different channel length at $V_{gs} = 0.5$ V and 0.6 V. (a) SG-GNRFET. (b) DG-GNRFET.

4. Results and Discussion

Due to lack of measured data on the devices of this work we can compare our results with those from the other researches where required. First, we have calculated I_{ds} - V_{ds} characteristic of the doped contact SG- and DG-GNRFETs of various channel lengths at two different gate voltages. The simulated I_{ds} - V_{ds} for both devices are shown in Figures 3(a) and 3(b). It is shown that the DG-GNRFET has a higher ON current compared to the current of the SG-GNRFET, because in the DG-GNRFET the gate controls the channel conductance more effectively. As the channel length decreases from 15 nm to 10 nm, I_{ds} in the SG device increases more than that in the DG one. This means that the short channel effects in a SG structure appears at a higher channel lengths than that in a DG one. Thus, the SG structure senses the effect of changing the channel length much more than the DG structure, where this can be due to less control of the gate bias on the device behavior in the SG than in the DG. Moreover, the DG-GNRFET shows better saturation behavior than the SG-GNRFET, which is due to more control of V_{gs} in the DG than in SG and can also be considered to have the smaller output conductance g_d .

The input characteristics, I_{ds} - V_{gs} , of both devices of different channel lengths are represented in Figure 4 in both logarithmic and linear scales to show the threshold voltage clearly. It is shown that the decrease of channel length lowers the threshold voltage due to more contribution of the fixed drain bias to the depletion charges under the gate. This is more severe in shorter channel lengths as shown in Figure 4 when the channel length decreases from 15 nm to 5 nm.

We should note that I_{on} , I_{off} , and I_{on}/I_{off} ratio are among the most important device parameters for digital applications.

FIGURE 4: The current I_{ds} versus V_{gs} for different channel length at $V_{ds} = 0.5$ V in both logarithmic and linear scales.

Off current is related to the short channel effects directly. Figure 5 shows the simulated I_{on} and I_{off} as functions of the channel length for both the SG- and DG-GNRFET devices. I_{on} (I_{off}) is I_{ds} in the on-state and $V_{ds} = 0.5$ V and $V_{gs} = 0.5$ V (off-state, $V_{ds} = 0.5$ V and $V_{gs} = 0$ V). According to Figure 5, decreasing the channel length increases I_{on} and I_{off} especially for the channel lengths less than 10 nm in SG structure. As the channel length decreases, the short channel effects become more important, and at the same biasing conditions shorter

FIGURE 5: The current I_{on} and I_{off} of GNRFETs versus the channel length.

devices show larger ON currents, which is due to their lower channel barriers. The on-state current is $3.72 \mu\text{A}$ in the DG and $2.90 \mu\text{A}$ in the SG. The off-state current, on the other hand, is 188 pA in the SG and 55.5 pA in the DG devices. I_{on}/I_{off} current ratio is 6.7×10^4 in the DG and 1.54×10^4 in the SG. As Figure 5 indicates, the short channel effects occur more significantly in the SG device than in the DG device. In fact, in a DG device, the gate affects the channel conductance more seriously. However, this is not true for I_{off} , since I_{off} directly depends on the potential barrier between the source and the channel which is lower in the SG structure.

If the drain voltage increases, the potential barrier in the channel of the device decreases. This effect is referred to as DIBL. Electrons can flow between the source and drain across a lowered barrier height which result in subthreshold current even if V_{gs} is lower than V_{th} . The DIBL can change the channel from the pinch-off state to the conduction state when the gate-to-source voltage is not high enough and results in leakage current. DIBL as functions of channel length and oxide thickness are plotted in Figure 6(a). In the DG device, the gate surrounds the channel and affects DIBL more significantly than the SG-GNRFET. Therefore, DIBL has a lower value in the DG device compared to that in the SG in good agreement with previous research [7]. In addition, decreasing the channel length of the SG-FET causes a larger increase in DIBL compared to that of the DG-FET and confirms that the short channel affects the SG-GNRFET more than the DG-GNRFET. At a channel length of 5 nm , the short channel effect is severe and the drain voltage affects the barrier at the beginning of the channel significantly. However, as the channel length increases, DIBL decreases drastically but remains approximately constant beyond $L_{ch} = 25 \text{ nm}$. On the other hand, when the thickness of SiO_2 increases, DIBL also increases in both structures, since the gate does not control the channel effectively. DIBL is less than 50 mV/V for both devices as t_{ox} decreases from 9 nm to 1 nm and the channel length is equal to 15 nm . Because the DIBL depends

TABLE 1: The transconductance and cut-off frequency of SG- and DG-GNRFETs for several channel lengths in ON state at $V_{gs} = V_{ds} = 0.5 \text{ V}$.

Device type	Channel length (nm)					
	5	10	15	20	25	30
$g_m (\mu\text{S})$, SG	16.88	15.88	14.26	13.19	12.77	12.57
$f_T (\text{THz})$, SG	4.79	2.85	2.03	1.58	1.3	1.13
$g_m (\mu\text{S})$, DG	19.92	18.38	18.06	18.05	18.04	18.04
$f_T (\text{THz})$, DG	4.57	2.58	1.85	1.46	1.21	1.03

on both channel length and t_{ox} , the optimum values for them should be considered to have DIBL less than 60 mV/V .

A small value of inverse subthreshold slope (SS) or subthreshold swing is one of the important parameters which ensures fast switching operation in MOSFET devices. The subthreshold swing, defined as $SS = (d(\log I_{ds})/dV_{gs})^{-1}$, highly depends on the threshold voltage (V_{th}) and the ratio of depletion capacitance in the channel to the gate oxide capacitance. This capacitance strongly depends on the device dimension, its fabrication, and its quality of the materials. The designers of nanoscale transistor for digital application try to minimize SS in such devices for operation at lower bias voltages to alleviate the short channel problems effectively [30]. Figure 6(b) shows the variations of SS in GNRFETs versus the channel length and oxide thickness for the gate-to-source voltages in the range of $V_{gs} = 0.2\text{--}0.3 \text{ V}$. These results are in good correlation with previous research [7].

It can be seen that the subthreshold swing increases by the decrease/increase in channel length/oxide thickness, respectively. The reason for such a behavior is that SS directly depends on V_{th} , where V_{th} decreases by reducing the device length. However, for the case of oxide thickness, it operates inversely. Increasing of the oxide thickness decreases the oxide capacitance and increases SS significantly, while decrease of V_{th} due to thicker oxide is trivial. Comparing the SG and DG curves shown in Figure 6(b) indicates that, due to parallel oxide capacitances, the DG device has a lower SS than that of the SG one, where this is true at different channel lengths and oxide thicknesses. In addition, SS increases very quickly when the channel length decreases from 10 nm to 5 nm in both SG and DG devices.

The gate capacitance, transconductance, intrinsic switching delay, and intrinsic cut-off frequency versus the gate-to-source voltage (V_{gs}) at $V_{ds} = 0.5 \text{ V}$ are shown in Figure 7. The gate capacitance is very small for both devices; however, it is higher in the DG structure than in the SG one. Also, the transconductance in the DG device is higher than that in the SG one due to a better gate control in the DG structure [7]. The high cut-off frequency and the small delay shown in Figure 7 are due to the extremely short channel length (15 nm) and the usual assumption of ballistic transport, which makes these devices suitable for high frequency applications.

Furthermore, the transconductance and the cut-off frequency as functions of the channel length at on-state for both GNRFETs are calculated and tabulated in Table 1. According to the results, it is clear that a shorter channel length makes the transconductance and the cut-off frequency larger for

FIGURE 6: (a) The drain induced barrier lowering versus the channel length and oxide thickness of GNRFETs. (b) The subthreshold swing versus the channel length and oxide thickness of GNRFETs for $V_{ds} = 0.5$ V.

FIGURE 7: (a) The gate capacitance C_g and transconductance g_m and (b) the intrinsic cut-off frequency f_T and switching delay τ_s versus the gate bias voltage, all at $V_{ds} = 0.5$ V.

both devices. In general, f_T and g_m are inversely proportional to the channel length. Despite the larger transconductance of the DG-GNRFET, its cut-off frequency is smaller than that of the SG-GNRFET. According to f_T formula and the fact that the device with a larger oxide thickness has a smaller gate capacitance, the cut-off frequency of the SG device is larger.

According to the results obtained so far, the DG device has shown a better behavior than the SG one, so study of the role of doping on I_{ds} , g_m , and f_T of DG-GNRFET seems interesting. The cases of undoped, doped at 1×10^{-3} , and

doped at 1.5×10^{-3} dopants/atom (D/A) are simulated and the results are shown in Figures 8(a), 8(b), and 8(c), respectively. As we can see, increasing the doping of the channel increases I_{ds} , g_m , and f_T but decreases the threshold voltage.

Finally, from all the results and processes presented in this research, we can write the following closing items:

- (a) Quantum transport analyses of SG- and DG-GNRFETs give a very good insight into the nanoscale devices and reveal many physical points in nanoscale graphene based FETs.

FIGURE 8: The effect of different doping concentration of the channel on I_{ds} , g_m , and f_T . (a) I_{ds} versus V_{gs} gives the threshold voltage (V_{th}). (b) The transconductance g_m versus V_{gs} . (c) The intrinsic cut-off frequency f_T versus V_{gs} .

- (b) The properties of nanoscale graphene based devices show that they are promising electronic devices for future THz (10^{12} Hz) frequency applications.
- (c) DG-GNRFET can alleviate short channel effects more efficiently and is almost preferable over SG-GNRFET for high frequency applications.

5. Conclusion

In conclusion, short channel effects of quasi-SG- and DG-GNRFETs are investigated by solving the Schrödinger equation using the full quantum transport NEGF formalism self-consistently with Poisson's equation. A tight-binding Hamiltonian with an atomistic p_z orbital basis set is used to describe the atomistic details in the channel of GNRFETs. We compared these devices through the parameters such as transfer characteristic, I_{on}/I_{off} , threshold voltage, DIBL,

and subthreshold swing. It is shown that the double-gate structure exhibits very small short channel effects compared to those of the single-gate structure. The intrinsic cut-off frequencies of the two devices are calculated and both of them have almost the same f_T in the range of THz which are useful for digital and high frequency applications. It is shown that the increase in doping of the channel can be used to increase g_m and f_T and to decrease the threshold voltage of the device noticeably. We have shown that the short channel effects are trivial in DG-GNRFETs if compared to those in the SG-GNRFETs. This is because the DG structure controls the channel electrostatic more effectively than the SG one does. These results are very useful for designing of nanoscale devices for high frequency applications.

Competing Interests

The authors declare that they have no competing interests.

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