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# A Computational Study on the Performance of Graphene Nanoribbon Field Effect Transistor

**Maedeh Akbari Eshkalak[*,1], Rahim Faez[2]**

[1] Young Researchers and Elite Club, Lahijan Branch, Islamic Azad University, Lahijan, Iran

[2] Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran

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**Abstract:** Despite the simplicity of the hexagonal graphene structure formed by carbon atoms, the electronic behavior shows fascinating properties, giving high expectation for the possible applications of graphene in the field. The Graphene Nano-Ribbon Field Effect Transistor (GNRFET) is an emerging technology that received much attention in recent years. In this paper, we investigate the device performance of Graphene Nanoribbon Field Effect Transistor (GNRFET) as a function of contact doping concentration and the gate insulator dielectric constant. The simulations are based on the Non-Equilibrium Green's function (NEGF) method coupled with a two dimensional Poisson equation in the ballistic regime. We assume a tight-binding Hamiltonian in mode space representation. By applying proper symmetric source and drain doping concentrations, It is observed that the GNRFET with low doping concentration has higher transconductance, lower Subthreshold Swing, lower Off-current ($I_{off}$), and higher ratio of On-current to Off-current ($I_{on}/I_{off}$). Moreover, The GNRFET with high doping concentration has smaller quantum capacitance, higher intrinsic cut-off frequency, and lower gate capacitance in comparison with low doping GNRFET. As we know, Selection of a suitable gate dielectric constant is important in determining device performance. The results indicate that the GNRFET with high dielectric constant has higher transconductance, lower Off-current, higher On-current and higher ratio of $I_{on}/I_{off}$ in comparison with low dielectric GNRFET. Furthermore, the GNRFET with low dielectric constant has smaller capacitances in gate, drain and source. The GNRFET with high dielectric constant has lower Sub-threshold Swing.

**Key words: Graphene Nanoribbon FET; Non Equilibrium Green's function (NEGF); Doping concentration; Gate Insulator.**

*** Corresponding author. E-mail: mde.akbari@yahoo.com**

## 1. INTRODUCTION

Graphene is a two dimensional single sheet of carbon atoms in $sp^2$ bonding configuration with a honeycomb structure. It has attracted tremendous research efforts due to its novel electronic characteristics [1, 2]. Large graphene sheets have no bandgap, therefore, are not suitable for logic applications. An energy bandgap can be prepared by lateral confinement of carriers in a graphene nanoribbon (GNR) [3, 4]. Nowadays, graphene is considered to be a viable alternative to Si for the channel of field-effect transistors (FETs). Transistors made of GNRs are called graphene nanoribbon field effect transistors (GNRFETs) [5, 6]. The scaling of device dimensions allows the integration of higher number of transistors on a chip. In the miniaturized transistors, in which scales are below 2 nm, leakage currents increase drastically due to tunnelling effect. In order to reduce transistor leakage current, researchers in both academia and industry studied on the doping concentration of source/drain contacts and gate insulator materials [7-9].

In this paper, we discuss the effects of symmetric doping concentrations at contact regions on the characteristics of GNRFET. A low subthreshold swing and a large $I_{on}/I_{off}$ ratio can be achieved by using the low doping concentrations in the source and drain contacts. We quantitatively study the dependence of transconductance, cut-off frequency and capacitances on the variations of doping concentrations. Furthermore, we investigate the effects of different dielectric constants on the operation of GNRFET. Double-gate GNRFET with doped source and drain is simulated and its electronic transport is studied. The model consists of an armchair graphene nanoribbon as the intrinsic channel material. Two metallic gates cover the channel region through two dielectric layers at the top and bottom of the ribbon. The source and drain extensions are highly doped with equal concentrations. Simulations are performed based on self-consistent solutions of the Poisson equation coupled with the Non-Equilibrium Green's Function (NEGF) formalism in mode space representation, assuming a tight-binding Hamiltonian [10, 11].

This paper is organized as follows: section 2 presents the device structure under study. Section 3 represents the simulation method for simulation of the aforementioned GNRFET. In section 4, the simulation results are shown and we discuss the results in this section. Finally, section 5 concludes this paper.

## 2. DEVICE STRUCTURE

Fig. 1 illustrates a schematic representation of the dual-gated GNRFET under study. The channel material is chosen of a single layer armchair graphene nanoribbon (A-GNR). The length and width of this GNR channel are assumed to be $L$ = 10 nm and $W$ = 1.72 nm, respectively. The thickness of each insulating layer is chosen to be $t_{ox}$ = 1.3 nm. The channel is intrinsic and the source and drain regions are assumed to be heavily doped GNR. The whole simulated region is embedded between two dielectric layers at the top and bottom of the ribbon, and the two metallic gate electrodes are attached to the dielectrics above the intrinsic channel.

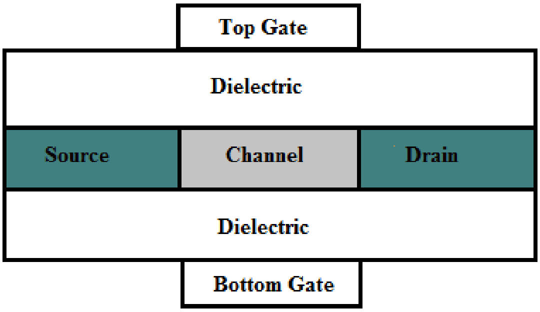


Fig.1. Schematic representation of the simulated dual-gated GNRFET.

## 3. METHOD

In this work, we study the behavior of double-gate GNRFETs by solving the quantum transport equation based on the NEGF formalism self-consistent with the 2D Poisson equation in mode space representation. The mode-space approach decouples the two-dimensional real space GNR lattice to one-dimensional lattice which reduces the computational cost. The source-drain current is computed using the Landauer formula once the self-consistency between the NEGF transport equation and the Poisson equation is achieved [10]. Ballistic transport is assumed [12]. In NEGF formalism the retarded Green's function of the device is defined as [4, 13-15],

$$G(E) = \left[(E + i0^{+})I - H - U - \Sigma_S - \Sigma_D\right]^{-1} \tag{1}$$

Where $H$ is the device Hamiltonian, which can be evaluated using a tight-binding model and $i$ is imaginary. $I$ is the identity matrix. $U = e\phi$ is on-site potential energy, where $e$ is the electron charge and $\phi$ is the electrostatic potential which is obtained by solving 2-D poisson equation. $\Sigma_S$ and $\Sigma_D$ are the self-energies of the source and drain, respectively. The transmission probability of the carriers through the device can be evaluated as,

$$T(E) = trace\left(\Gamma_S G \Gamma_D G^{+}\right) \tag{2}$$

Where $\Gamma$ is the contact broadening function obtained as,

$$\Gamma_{S(D)} = i(\Sigma_{S(D)} - \Sigma^{+}_{S(D)}) \tag{3}$$

The local density of states resulting from the source/drain injected states is calculated using,

$$D_{S(D)} = G\Gamma_{S(D)}G^{+} \tag{4}$$

Now, the current–voltage characteristic is obtained using $T$ (E) and the Landauer–Buttiker formula as follows [15],

$$I = \frac{2q}{h}\int_{-\infty}^{+\infty} dE.T(E)\{f(E,\mu_S) - f(E,\mu_D)\} \tag{5}$$

## 4. RESULTS AND DISCUSSION

In this section, we explore the calculated device characteristics. In part 4.A, we discuss the effects of symmetric doping concentrations at contact regions on the characteristics of GNRFET and in part 4.B, we study the effects of gate insulator materials with different dielectric constants on the performance of GNRFET.

### *A. Contact Doping*

In this part, we investigate the effects of contact doping concentration on the performance of GNRFET. We assume that the doping concentration of source and drain are equal. In this section, the dielectric constant of $K$=16 is considered. Fig. 2 shows the current characteristics ($I_{DS}$–$V_{GS}$) for GNRFETs with different doping concentrations at $V_{DS}$ = 0.6 V. The doping concentrations at the source and drain, $N_S$ and $N_D$, respectively, are uniform and symmetric. The amount of doping concentrations varied in this study to understand their effect on GNRFETs. As can be seen, the off-current decreases with decreasing of doping concentration.

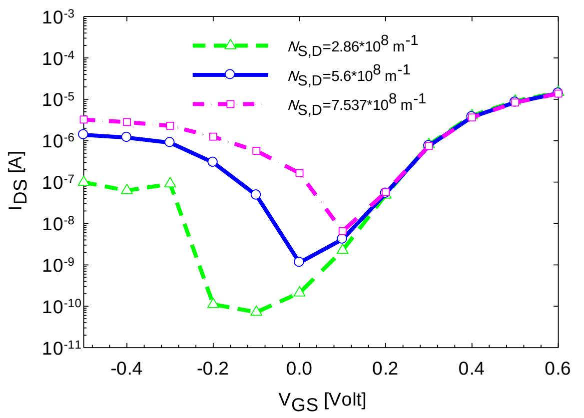


Fig.2. The $I_{DS}$–$V_{GS}$ characteristic of GNRFET with $N_S = N_D = 2.86$, 5.6 and $7.537\times 10^8$ $m^{-1}$ at $V_D$= .6 V.

Transconductance ($g_m$) is a figure of merit for perusing the change of output current versus the change of input voltage. It is the ratio of current variation to the gate voltage variation at On-state and is given by [2],

$$g_m = \frac{\partial I_D}{\partial V_G} \tag{6}$$

For a high transconductance, every small change in gate voltage causes a big change in drain current that shows transistor sensitivity. Fig.3 illustrates the transconductance for GNRFETs under different doping concentrations which show that the low doping GNRFET has higher transconductance.

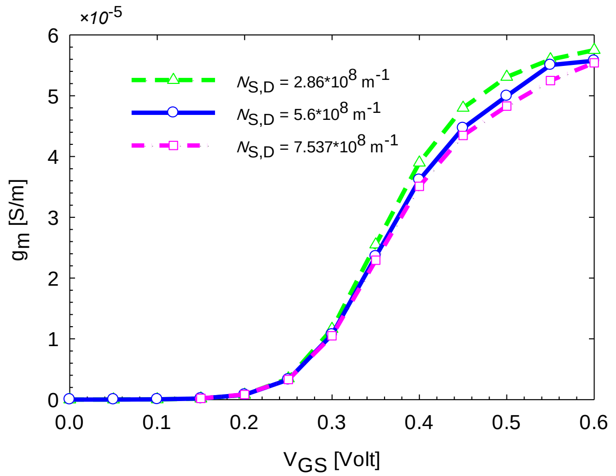


Fig.3. transconductance versus the gate voltage for GNRFET with $N_S = N_D = 2.86$, 5.6 and $7.537\times 10^8$ $m^{-1}$, $K$=16 and $V_D$= .6 V.

The subthreshold swing is a key parameter to transistor miniaturization. For FETs, a small subthreshold swing (SS) is desired for low threshold voltage and low-power operation and is defined as [2],

$$SS = \frac{dV_G}{d\left(\log(I_D)\right)} \tag{7}$$

Table I shows the subthershold swing and the ratio of $I_{on}/I_{off}$ for GNRFETs with different doping concentrations. We see that decreasing of doping concentration leads to the high ratio of $I_{on}/I_{off}$ and low subthershold swing.
Table II shows the calculated quantum capacitance ($C_Q$), gate capacitance ($C_G$) and intrinsic cut-off frequency ($F_T$) for different doping concentrations. Quantum capacitance is defined as the derivative of the total net charge of the GNR-channel with respect to applied electrostatic potential [15].

TABLE I

$I_{on}/I_{off}$ ratio and subthreshold swing (SS) of GNRFET with $N_S = N_D = 2.86$, 5.6 and $7.537\times 10^8$ m$^{-1}$.

| Doping Concentration $N_S = N_D$ (m$^{-1}$) | $I_{on}/I_{off}$ | Subthreshold Swing (SS) |
|---|---|---|
| $2.86\times 10^8$ | $2.0530*10^5$ | 77.79 |
| $5.6\times10^8$ | $1.2353*10^4$ | 95.79 |
| $7.537\times 10^8$ | $2.1194*10^3$ | 97.007 |

TABLE II

Cut-Off Frequency, Quantum and Gate Capacitances of GNRFET at $N_S = N_D = 2.86$, 5.6 and $7.537\times 10^8$ m$^{-1}$ .

| Doping Concentration $N_S = N_D$ | Cut-Off Frequency $F_T$ (THz. nm) | Quantum Capacitance $C_Q$ (pF/cm) | Gate Capacitance $C_G$ (pF/cm) |
|---|---|---|---|
| $2.86\times 10^8$ m$^{-1}$ | $3.96\times10^{-12}$ | 1.6220 | 1.1820 |
| $5.6\times10^8$ m$^{-1}$ | $1.46\times10^{-11}$ | 1.4621 | 1.0085 |
| $7.537\times 10^8$ m$^{-1}$ | $2.53\times10^{-11}$ | 1.2072 | 0.8436 |

The intrinsic cut-off frequency is an important parameter to determine the high frequency performance of the transistors [8]. It is observed that the intrinsic cut-off frequency increases with decreasing of contacts doping concentrations. Furthermore, for GNRFET with high doping concentration, the gate and quantum capacitances are smaller than high-doping GNRFET.

### *B. Gate Dielectric Constant*

Now, we discuss the effects of gate dielectric constant on the performance of GNRFET. The source and drain regions are assumed to be heavily doped GNR with doping concentration value of $2.82\times10^8$ m$^{-1}$. Fig. 4 shows the output $I_D$-$V_{DS}$ characteristics for GNRFETs with $K$ = 3.9, 12 and 25.

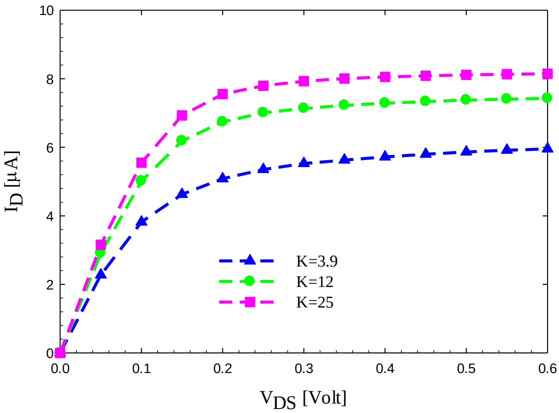


Fig.4. $I_D$-$V_{DS}$ characteristic for GNRFETs with dielectric constants of $K$= 3.9, 12 and 25 at $V_G$=.5 V.

It can be seen that the GNRFET with higher dielectric constant has the higher delivering capability due to increase of thermal emission current in comparison with a GNRFET of low dielectric constant. Fig. 5 shows the transfer $I_D$-$V_{GS}$ for GNRFETs with $K$ = 3.9, 12 and 25. As it can be seen, the increasing of dielectric constant in GNRFET lead to a lower Off-state current. This is due to more thermal emission current stems from superior control of the gate potential on the channel that helps reducing the Off-state current and increasing the On-state current.

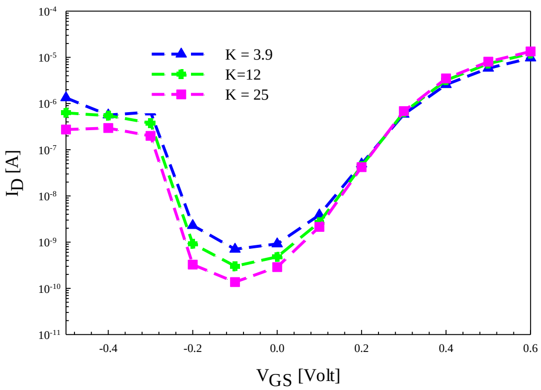


Fig.5. $I_{DS}$-$V_{GS}$ for GNRFETs with dielectric constants of $K$=3.9, 12 and 25 at $V_{DS}$ =.5 V.

Fig. 6 plots the transconductance versus gate voltage for three dielectric constants. We see that higher dielectric constant in GNRFET leads to more transconductance due to the more controllability of gate on the channel in comparison with low dielectric constant.

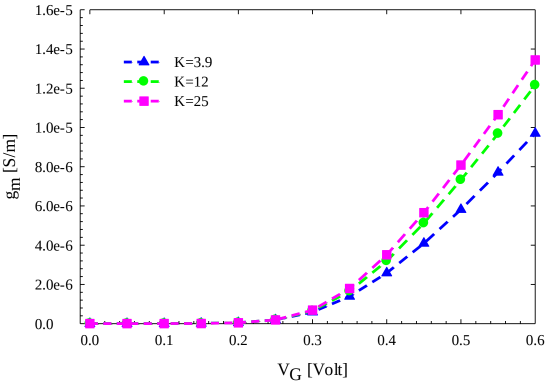


Fig.6.Transconductance versus the gate voltage for GNRFETs with $K$=3.9, 12 and 25 at $V_{DS}$ =.5 V.

The ratio of $I_{on}/I_{off}$ for GNRFETs with $K$ = 3.9, 12 and 25 is illustrated in Fig. 7. As it shown, GNRFET with higher dielectric constant has more $I_{on}/I_{off}$ ratio than GNRFET with low dielectric.

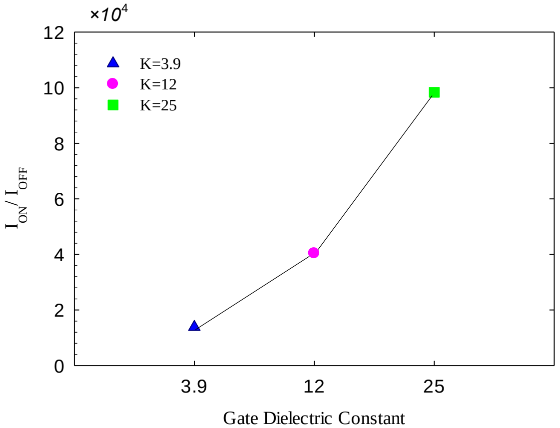


Fig.7. $I_{on}/I_{off}$ ratio for GNRFETs with dielectric constants of $K$=3.9, 12 and 25.

Fig. 8 shows Sub-threshold Swing for GNRFETs with $K$=3.9, 12and 25. We observe that Sub-threshold Swing decreases and is close to its theoretical limit with increasing $K$. The reason is that using the high gate Insulators reduce leakage current and afford low subthershold swing.

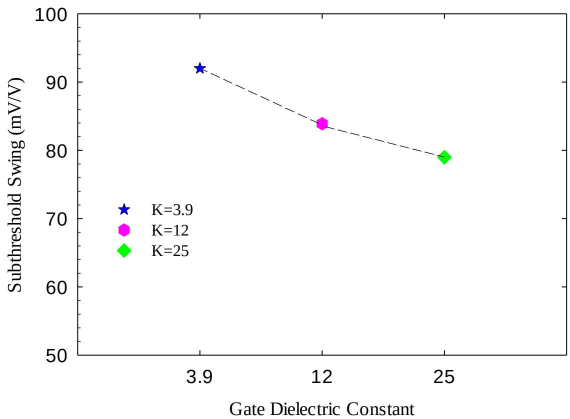


Fig.8. Subthreshold Swing for GNRFETs with *K*=3.9, 12 and 25

Table III shows calculated capacitances for GNRFETs with dielectric constant of *K*=3.9, 12 and 25. As can be seen, gate, drain and source capacitances are smaller for low dielectric constant due to weaker influence of gate potential on the channel.

TABLE III

gate, drain and source capacitances for GNRFETs with *K*=3.9, 12 and 25

| Dielectric Constant | Drain Capacitance | Source Capacitance | Gate Capacitance |
|---|---|---|---|
| $K = 3.9$ | $3.96\times10^{-12}$ pF | $9.60\times10^{-12}$ pF | $2.99\times10^{-11}$ pF |
| $K = 12$ | $1.22\times10^{-11}$ pF | $2.95\times10^{-11}$ pF | $8.17\times10^{-11}$ pF |
| $K = 25$ | $2.53\times10^{-11}$ pF | $6.15\times10^{-11}$ pF | $1.16\times10^{-10}$pF |

## 5. CONCLUSION

In this paper, we investigated the effects of contact doping and dielectric constant on the performance of a dual-gated armchair GNRFET. To investigate the transfer characteristics, a quantum model based on the non-equilibrium Green's function (NEGF) coupled with a two dimensional Poisson equation under the ballistic limits in the mode space is applied. By applying proper symmetric source and drain doping concentrations, It was observed that the GNRFET with low doping concentration has higher transconductance, lower Subthreshold Swing, lower off-current ($I_{off}$), and higher ratio *of On-current to*

*Off-current* ($I_{on}/I_{off}$). Moreover, The GNRFET with high doping concentration has smaller quantum capacitance, higher intrinsic cut-off frequency, and lower gate capacitance in comparison with low doping GNRFET. As we know, Selection of a suitable gate dielectric constant is important in determining device performance. The results show that the GNRFET with high dielectric constant has higher transconductance, lower Off-current, higher On-current and higher ratio of $I_{on}/I_{off}$ in comparison with low dielectric GNRFET. Furthermore, the GNRFET with low dielectric constant has smaller capacitances in gate, drain and source. The GNRFET with high dielectric constant has lower Sub-threshold Swing.

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