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Simulation of Drain Currents of Double Gated Armchair Graphene Nanoribbon Field-Effect Transistors by Solving Dirac "Like" Equation and Using Transfer Matrix Method

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Abstract. We have modelled quantum mechanically the drain current in double gated armchair graphene nanoribbon field-effect transistors (AGNR-FETs). The Dirac 'like' equation was used to determine the electron wave functions in the AGNR. The electron transmittance and the drain current were calculated numerically by using a transfer matrix method (TMM). The results showed that the drain current of the AGNR-FET devices increases with the drain and gate voltages. In addition, the threshold voltage of the devices was obtained to be constant at about 0.3 V. Moreover, the drain current increased with decreasing the thickness of insulator. The different temperatures gave the different characteristics of the drain current.

1. Introduction

Graphene is a sheet of carbon atoms forming two dimensional material systems. Currently, it is still an interesting topic to be theoretically and experimentally studied. Large area graphene has semimetal properties with zero bandgap and high carrier mobility [1]. In addition, the dynamics of electron in graphene for low energy limit is described by the relativistic Dirac equation [2]. When graphene has width smaller than its length, it is called as a graphene nanoribbon (GNR) that has different electrical properties from graphene. Based on the edge shape, GNRs are divided into zigzag GNRs (ZGNRs) and armchair GNRs (AGNRs). The ZGNRs have metal properties for all widths, while the AGNRs can be either semiconducting or metal depending on their widths [3−4]. Because of these properties, GNRs can be applied for various nanoelectronic devices. High speed field-effect transistor (FET) is one of applications of graphene for the nanoelectronic devices [5].

The characteristics of graphene transistors including the tunneling current flowing from the source to the drain have been studied [6-9]. The Schrodinger equation has been used to obtain the characteristics of the devices. In addition, they used the WKB method [6,7] and the non-equilibrium Green's function [8,9] for calculating the drain current. In this paper, we report simulation results of drain current of armchair graphene nanoribbon field-effect transistors (AGNR-FETs) that have been obtained by

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solving the Dirac 'like' equation and using a transfer matrix method (TMM). The TMM has been employed to compute the tunneling current and it has been shown that the tunneling current calculated under the TMM is better than that done under the WKB [10,11]. The influences of gate and drain voltages, insulator thickness, and temperature on the drain current of (AGNR-FETs) will be discussed.

2. Theoretical Model

The schematic diagram of a double gated AGNR-FET device is shown in Fig. 1. AGNR is placed as a channel, whereas ZGNRs that have metal properties could be used as source and drain of the device.

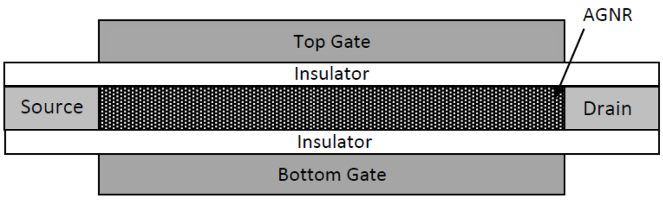

Figure 1. Schematic diagram of a double gated AGNR-FET device.

The electronic structure of AGNRs represented by the dispersion relation, $\varepsilon(\boldsymbol{k})$, is given by [3]

$$\varepsilon = s\hbar v_F \sqrt{k_x^2 + k_n^2}\,, \tag{1}$$

where the transverse momentum, $k_n = n\pi/3W$, is quantized by the ribbon width in which W is the width of AGNR and $n = \pm1, \pm2, \pm3, \dots$ $s = +1$ and $s = -1$ indicate the conduction and valence bands, respectively, $\hbar$ is the reduced Planck constant, and $v_F = 10^6$ m/s is the Fermi velocity. The potential profile of the AGNR near the source contact was obtained by solving the Laplace equation from Ref. [6] as given by

$$V(x) = \varphi_{SB} - \frac{2V_{GS}}{\pi} \arccos\left[\exp\left(\frac{-x\pi}{2t_{ins}}\right)\right], \tag{2}$$

where V_{GS} is the gate voltage and t_{ins} is the insulator thickness. The Schottky barrier height, φ_{SB}, was supposed to be half of the AGNR bandgap.
The electron behavior in graphene was described by the Dirac-like Hamiltonian as given by [2]

$$\hat{H} = -i\hbar v_F \sigma.\nabla\,, \tag{3}$$

where σ is the Pauli spin matrix. By solving the Dirac-like Hamiltonian equation, the wave functions in the source, channel and drain region could be found. Furthermore, by employing the TMM in which the potential profile of the AGNR channel was divided into N segments of rectangular form as given in Refs. [10,11] and applying the boundary conditions at each interface, the transmittance through the AGNR channel could be obtained. Finally, by using the Landauer formula which can be written as [6]

$$I_{DS} = \frac{2e}{h} \sum_n \int_{\varphi_{SB}-V_{GS}}^{\varphi_{SB}} T_n(E)\left[f(E) - f(E + eV_{DS})\right] dE\,, \tag{4}$$

where $T_n(E)$ is transmittance of the n^{th}-subband, V_{DS} is the drain voltage, V_{GS} is the gate voltage and $f(E)$ is the Fermi-Dirac distribution function, and by assuming ballistic transport within the AGNR channel, the drain current, I_{DS}, could be determined.

3. Calculated Results and Discussion

The AGNR channel with length of 20 nm and width of 5 nm, the insulator thickness of 2 nm, and the temperature of 300 K were used. The calculated drain currents as a function of the drain voltage for various gate voltages are shown in Fig. 2. It is depicted that initially the drain currents increase with the drain voltage and then they will reach saturation values. It is also noticeable that the typical saturation characteristics are in accordance to the GNR-FETs ones [6-9].

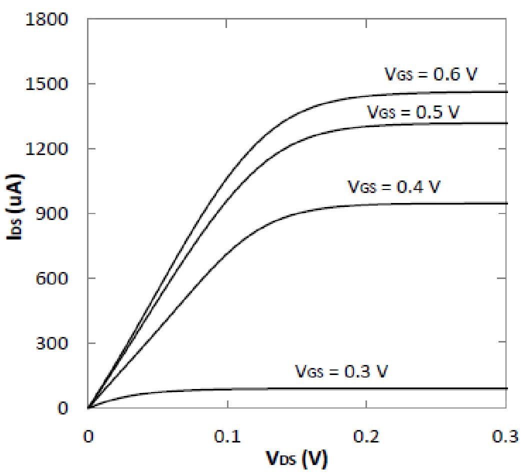

Figure 2. The drain current as a function of the drain voltage for various gate voltages.

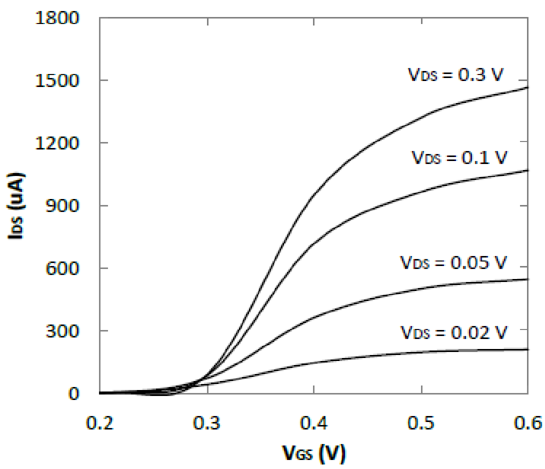

Figure 3. The drain current as a function of the gate voltage for various drain voltages.

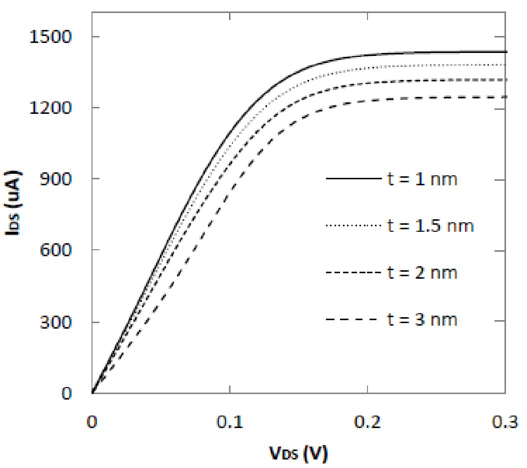

Figure 4. The drain current as a function of the drain voltage for various insulator thicknesses.

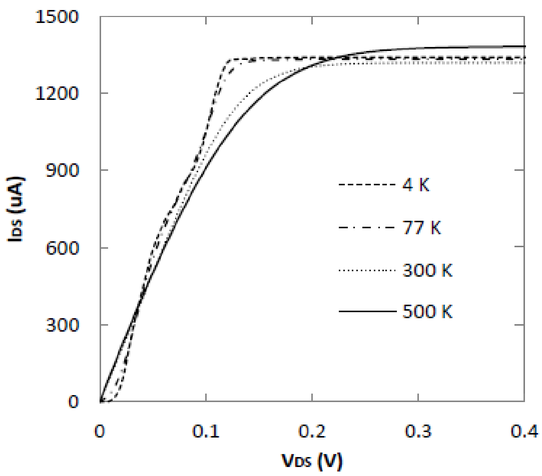

Figure 5. The drain current as a function of the drain voltage for various temperatures.

The dependence of drain current on the gate voltage for different drain voltages is given in Fig. 3. The drain current increases with increasing the gate and drain voltages. Furthermore, it is seen that the threshold voltage is constant about 0.3 V. This finding is in line with that obtained by Ref. [12].

Figure 4 shows the drain current as a function of the drain voltage for different insulator thicknesses. The gate voltage, the AGNR channel length, the AGNR channel width, and the temperature were 0.5 V, 20 nm, 5 nm, and 300 K, respectively. It can be seen that the thinner the insulator thickness the drain current of AGNR-FET becomes higher.

The dependences of drain currents on the drain voltage for various temperatures ranging from 4 K to 500 K are given in Fig. 5. It was taken that the gate voltage, the AGNR channel length, the AGNR channel width, and the insulator thickness were 0.5 V, 20 nm, 5 nm, and 2 nm, respectively. It is shown that the different temperatures give the different characteristics of the drain current of AGNR-FET.

4. Conclusion
The Dirac 'like' equation and the transfer matrix method have been successfully applied to obtain the drain current of AGNR-FETs. It has been found that the drain current increases as the gate and drain voltages increase. The threshold voltage of the devices has been obtained to be constant about 0.3 V. It has also been demonstrated that the drain current increases with decreasing the thickness of insulator. Moreover, the different temperatures give the different characteristics of the drain current of the devices.

5. Acknowledgments
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