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Channel Length Modulation Effect on Monolayer Graphene Nanoribbon Field Effect Transistor

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Abstract**—**Recently, Graphene Nanoribbon Field Effect Transistors (GNR FETs) attract a great deal of attention due to their better performance in comparison with conventional devices. In this paper, channel length Modulation (CLM) effect on the electrical characteristics of GNR FETs is analytically studied and modeled. To this end, the special distribution of the electric potential along the channel and current-voltage characteristic of the device is modeled. The obtained results of analytical model are compared to the experimental data of published works. As a result, it is observable that considering the effect of CLM, the current-voltage response of GNR FET is more realistic.

Keywords**—**Graphene nanoribbon, field effect transistors, short channel effects, channel length modulation.

I. INTRODUCTION

GRAPHENE NANORIBBON (GNR) with remarkable electronic properties such as width-tunable energy band gap, high conductance and high carrier mobility, is known as a futuristic material to be used in next generation nanoelectronics devices [1]. It is observed that properties of GNR are similar to carbon nanotubes (CNTs), also GNR commonly has been created by unzipping multiwall carbon nanotubes (MWNTs) [2] as illustrated in Fig. 1.

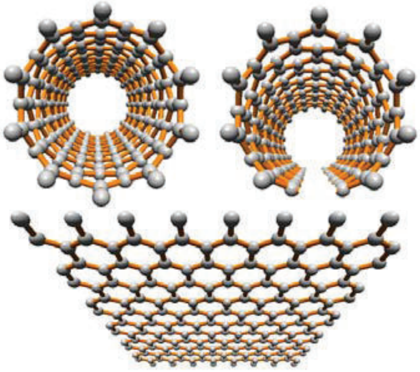

Fig. 1 The steps of unzipping the CNTs to form GNRs

Recently, the feasibility of using GNR as the channel material of FETs has been addressed [3]-[5]. A cross view of monolayer GNR FET with the definition of related geographic parameters is shown in Fig. 2. The major strength of adopting monolayer GNR as a channel material is due to its strong capability to control the electrostatics and hence expected to reduce the short channel effects that rely on the device electrostatics [6]-[9].

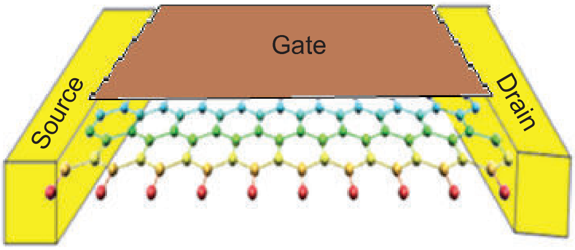

Fig. 2 A schematic of implemented FET with monolayer GNR as the channel material

Channel Length Modulation (CLM), which is defined as reduction of inverted channel region caused by large drain voltage is considered as one of the important short channel effects in FETs [10]. The output resistance decrement and current increment are two effects resulted by CLM in the FET which the latter is caused by the drain bias [10]. In this paper, an analytical model joint with numerical solution is proposed for CLM of monolayer GNR FET and its effects on drain current is studied. In Section II the proposed model for CLM is presented in detail, in Section III the simulated results are illustrated and discussed and finally Section IV concludes the study.

A. Proposed Model

The inversion charge density at the drain terminal will be reduced as the drain voltage of FET rises. This decrement starts since the voltage along the oxide is decreasing and finally reaches to zero at $V_{DS}(sat)=V_{GS}-V_T$ [10]. In addition, for drain-source voltages greater than saturation voltage, the inversion charge density is zero and the pinch-off point in the channel shifting from the drain to the source. In other words, depletion region extends laterally into the channel which makes the effective channel shorter than the physical gate length [11], [12]. This phenomenon is shown in Fig. 3. In addition, the effective channel length is assumed bias dependent and modulated by V_{DS}, since the width of depletion region is also bias dependent. In the presented model, the reduction of the effective channel is improved by employing a short-channel drain current model for GNR FET [13].

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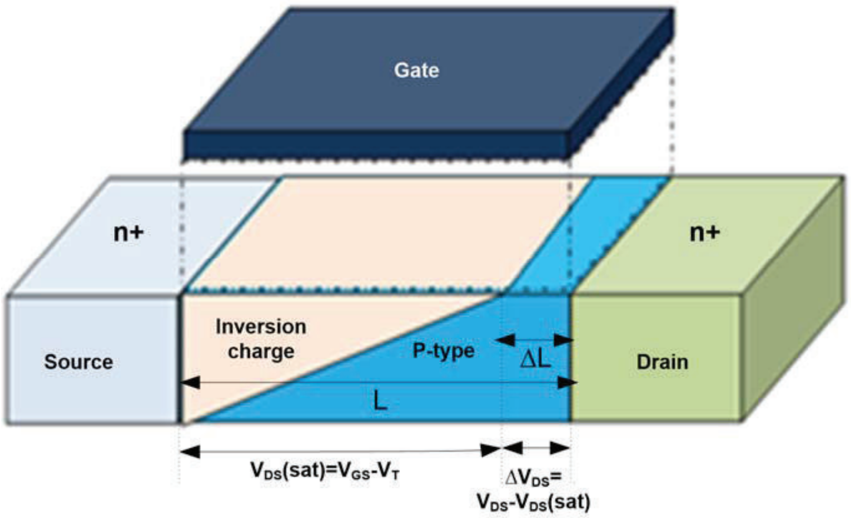

Fig. 3 The pinch-off phenomenon and shortening of the effective channel length resulted by high drain voltage

The derivative of the energy with respect to x is given by

$$\frac{dE}{dx} = \frac{N_d q + n_i q v L dt}{\varepsilon} \tag{1}$$

where N_d is the donor impurity doping concentration, q is the electron charge magnitude, n_i is the intrinsic carrier concentration, v is the drift velocity, L is the channel length and ε is the graphene permittivity constant. The second approximation is used to calculate the CLM and one dimensional (1D) Poisson equation is taken into account. The horizontal electric field, E_{sat}, is assumed to be at the pinch-off point for the inversion layer charge. Integrating over (1) specifies the electric field as

$$E(x) = \frac{N_d q x}{\varepsilon} + \frac{n_i q x^2 L}{2\varepsilon} + C_1 \tag{2}$$

where C_1 is the integral constant. Applying the boundary conditions of $E(x=0) = E_{sat}$, the electric field in the space charge region considering CLM effect is given by

$$E(x) = \frac{N_d q x}{\varepsilon} + \frac{n_i q x^2 L}{2\varepsilon} + E_{sat} \tag{3}$$

The potential can be calculated by integrating over the electric field in the space charge region as

$$\varphi(x) = \frac{N_d q x^2}{2\varepsilon} + \frac{n_i q x^3 L}{6\varepsilon} + xE_{sat} + C_2 \tag{4}$$

where C_2 is the integral constant. Based on the Fig. 3, the boundary condition $\varphi(x=0) = V_{sat}$ can be used to obtain the constant C_2.

$$\varphi(x) = \frac{n_i q L}{6\varepsilon} x^3 + \frac{N_d q}{2\varepsilon} x^2 + E_{sat} x + V_{sat} \tag{5}$$

The space charge region width, ΔL, reads

$$\left\{ \Delta L \to -\frac{b}{3a} - \frac{\left(2^{\frac{1}{3}}(-b^2+3ac)\right)}{\left(3aB^{\frac{1}{3}}\right)} + \frac{B^{\frac{1}{3}}}{32^{\frac{1}{3}}a} \right\} \tag{6}$$

where

$$B = \left(-2b^3 + 9abc + 27a^2vd - 27a^2vs + \sqrt{\begin{matrix} 4(-b^2+3ac)^3 + \\ (-2b^3 + 9abc + 27a^2vd - 27a^2vs)^2 \end{matrix}} \right)$$

In the proposed model of ΔL, the two dimensional effects as well as the negative charges resulted by drain current are neglected. For $x = \Delta L$, the potential $\varphi(x)$ will be equal to V_D which is given by

$$V_D = \frac{n_i q L}{6\varepsilon} x^3 + \frac{N_d q}{2\varepsilon} x^2 + E_{sat} x + V_{sat} \tag{7}$$

At the pinch of point, when the drain bias increases the effect of CLM which navigates a linear raise of the drain current, can be ignored by increasing threshold voltage [14]. The drain source current consists of diffusion and drift components. However, in the week inversion where the device is on the subthreshold region, the diffusion part is the dominant part of drain-source current which is proportional to carrier concentration in this region [14]. The previous 2D potential model can be used to derive the subthreshold drain-source current [15], [16]. On the other hand, the off-state current which is defined by the current at zero gate-source voltage, is highly affected by the band gap in the monolayer GNR FET.

II. RESULTS AND DISCUSSION

According to the relationship between the potential and drain current, the current-voltage characteristics of the modeled monolayer GNR FET is depicted in Fig. 4. It can be seen that as V_{DS} increases, the I_{DS} increases and there is a linear relation between them for small values of V_{DS}, while I_{DS} saturated for high values of V_{DS}.

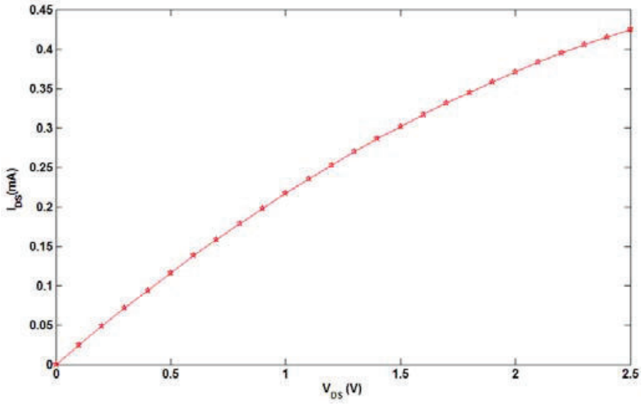

Fig. 4 I_{DS} -V_{DS} characteristic of monolayer GNRFET

As the channel length and drain current have a reverse relation, one can write

$$I'_D = (\frac{L}{L-\Delta L})I_D \tag{8}$$

The I-V characteristic of monolayer GNR FET for different values of V_{gs} is plotted in Fig. 5. It can be seen that as V_{gs} increases the I_{DS} also increases, in addition the effect of CLM is taken into account.

Fig. 6 indicates comparison between the current-voltage characteristic of analytical GNRFET model and experimental data. According to Figs. 5 and 6, the I_{DS} -V_{DS} characteristic of analytical model considering channel length modulation effect is nearer to experimental data.

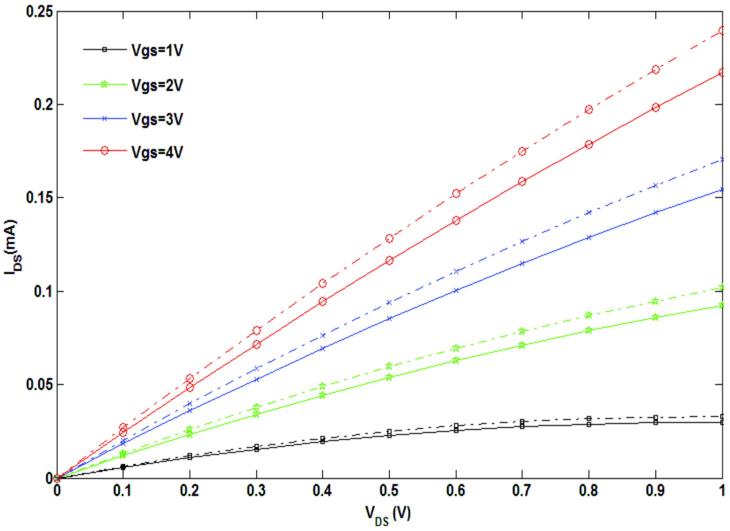

Fig. 5 Current-Voltage characteristic of GNRFET for different values of V_{gs} with (dashed lines) and without (solid lines) channel length modulation effect

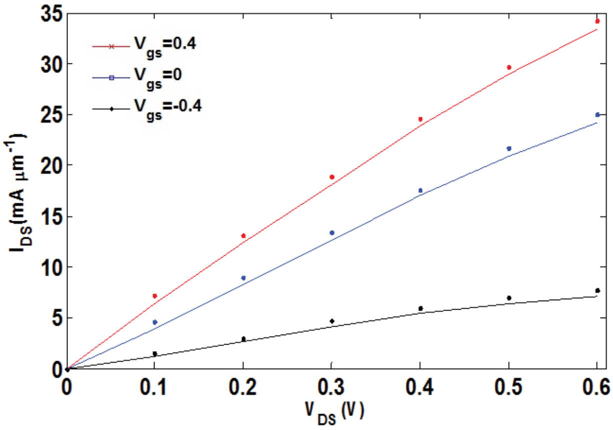

Fig. 6 Comparison between the I_{DS} -V_{DS} characteristic of analytical model considering channel length modulation effect (solid lines) and experimental data extracted from [] (symbols).

III. CONCLUSION

In this paper, the effect of channel length modulation on monolayer GNR FETs is analytically studied. To this end, a model is developed for current-voltage, and the obtained results of analytical model are compared against the experimental data of published works. Accordingly, the comparison between analytical results of the model and experimental data indicates that taking into account CLM effect is more accurate to study the bahavior of GNR FETs.

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