An analytical approach to calculate effective channel length in graphene nanoribbon field effect transistors

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A B S T R A C T

A compact analytical approach for calculation of effective channel length in graphene nanoribbon field effect transistor (GNRFET) is presented in this paper. The modelling is begun by applying Gauss’s law and solving Poisson’s equation. We include the effect of quantum capacitance and GNR's intrinsic carrier concentration in our model. Based on the model the effects of several parameters such as drain-source voltage, channel length, and oxide thickness are studied on the length of effective channel in GNRFETs. © 2012 Elsevier Ltd. All rights reserved.

1. Introduction

By using graphene nanoribbon it seems to be possible to make devices with channels that are extremely thin and will allow FETs to be scaled to shorter channel lengths and higher speeds without encountering the adverse short-channel effects restricting the performance of the existing devices. As a result, high performance logic circuits such as high speed full adders could be realized [1,2].

Recently, experimental and theoretical studies such as [3–6] have shown it is possible to fabricate GNR transistors. As a result, many researchers have been attracted to this field and provided several models for GNR's properties [7–12]. Nevertheless, there is lack of research in modelling the behaviour of GNRFET near the drain junction and the breakdown mechanism.

The effective channel length is one of the most important parameters of MOSFETs showing the portion of the channel contributing to the properties of MOSFETs such as I–V characteristic. In order to calculate the effective channel length, the width of the drain region, where impact ionization and carrier velocity saturation occurs, has to be computed. It controls the lateral drain breakdown [13,14], substrate current, hot-electron generation [15,16], and drain current at the drain region [17,18].

Although several models are available for saturation region of silicon-based MOSFETs such as [19,20,16,21,22], there is still plenty of room for research in modelling of this region for carbon-based FETs. In order to gain insights into reliability issues of these devices, close analysis of this region is necessary. In addition, these kinds of models open the way to explore the possibility of designing power transistors using carbon.

Since at the moment the fabrication technology is still at its very first steps, analytical modelling seems to be a useful tool in the case of examining saturation region. In this paper, simple and compact analytical models for surface potential, lateral electric field and effective channel length are proposed and the behaviour of a general top-gate GNRFET in the saturation region is studied.

2. Effective channel length model for GNRFET with top gate

A schematic cross-section of top-gated GNRFET is shown in Fig. 1, where ox is the oxide thickness of top gate with dielectric constant of εox; tg, W and L are the GNR’s thickness, width and the channel length respectively.

The channel is divided into two sections. Section 1 is defined between drain and saturation point and Section 2 between saturation point and source junction. We begin with applying Gauss’s law in the Section 1, shown in Fig. 1.

\[
-q \int_0^x \int_0^{r(x)(n+N)} dx \, dt = - \int_0^x \epsilon_{ox} \frac{\partial \phi}{\partial x} dx - \int_0^{t(x)} \epsilon_\phi \frac{\partial \phi}{\partial t} dt + \int_0^{t(x)} \epsilon_\phi \frac{\partial \phi}{\partial t} dt
\]

where q is the charge magnitude, εφ and εox are the graphene and oxide dielectric constants, n is the intrinsic carrier concentration,
\[ C_{tg} = \frac{(C_g + C_k)C_{ox}}{C_g + C_k + C_{ox}} \]  

(8)

It is found that

\[ \phi_{ch}(V_g) = V_g \left( 1 - \frac{(C_g + C_k)V_g}{C_g + C_k + C_{ox}} \right) + \phi_{ch}(0) \]  

(9)

where \( C_q \) is the quantum capacitance of the channel which is given by

\[ C_q = q^2 \frac{d\phi}{dE} \]  

(10)

where \( E \) is the energy. The \( \phi_{ch}(0) \) can be approximated to \( \phi(\frac{V_t}{2}) \) where \( \phi(x) \) is the surface potential at any point along the channel. This term will be addressed later in this paper. The two-dimensional carrier concentration \( n_{2D} \) is written as

\[ n_{2D} = \int_{E_0}^{\infty} \text{DOS}(E - E_{Fk}) - f(E - E_{Fk}) \ dE \]  

(11)

where for \( i = s, d \),

\[ f(E - E_{Fk}) = \frac{1}{1 + \exp \left( \frac{E - E_{Fk}}{\kappa T} \right)} \]  

(12)

We approximate \( E_{Fk} = E_{ks} \) and \( E_{Fd} = E_{kd} - qV_{ds} \) and the density of states \( \text{DOS}(E) \) is given by \[ \text{DOS} = \frac{2m_{c}}{\pi \hbar^2} \]  

(13)

Replacing \( \zeta = \frac{1}{\kappa T} \), \( n_{2D} \) is written as

\[ n_{2D} = \int_{E_0}^{\infty} \text{DOS}(\zeta - \zeta_k) \ dE \]  

(14)

finally, \( n = n_{2D} \frac{\pi \hbar^2}{2m_{c}} \), with \( t_{int} \) being the interlayer distance of graphene is written and limited as

\[ n = \int_{E_0}^{\infty} \text{DOS}(\zeta - \zeta_k) \ dE \]  

(15)

where \( \eta_i = \frac{\pi \hbar^2}{2m_{c} t_{int}} \). Finally, quantum capacitance is given as

\[ C_q = q^2 \frac{1}{\kappa T} \frac{2m_{c}}{\pi \hbar^2} (\zeta_{kd} - \zeta_k) \]  

(16)

Now we can proceed to calculate surface potential and lateral electric field analytically. Boundary conditions for \( \phi_1(x) \) are defined as \( \phi_1(0) = V_0 + V_{th} \), \( \phi_1(\Delta L) = V_{th} + V_{ds} \), \( \zeta_1(0) = \zeta_{th} \), where \( V_0, V_{th}, \Delta L, \) and \( \zeta_{th} \) are the saturation voltage at the onset of saturation region, drain voltage, length of saturation region and saturation surface electric field respectively. Solving the differential equation and taking

\[ A = \frac{Q}{t_{int} \varepsilon_{ox}} - \frac{V_x - V_{bi}}{\kappa T} \]  

(17)

yields

\[ \phi_1(x) = A^2 \left[ \frac{\sinh \left( \frac{x}{\kappa T} \right)}{\sinh \left( \frac{X}{\kappa T} \right)} - 1 \right] + (V_0 + V_{th}) \cosh \left( \frac{x}{\kappa T} \right) + \lambda \zeta_0 \times \sinh \left( \frac{x}{\kappa T} \right) \]  

(18)

Since \( \xi(x) = -\frac{\partial \phi(x)}{\partial x} \), surface electric field distribution \( \xi_1(x) \) is expressed as

\[ \xi_1(x) = -\left( A^2 \frac{V_0 + V_{th}}{\kappa T} \sinh \left( \frac{x}{\kappa T} \right) - \zeta_0 \cosh \left( \frac{x}{\kappa T} \right) \right) \]  

(19)

In order to model the surface potential \( \phi_2(x) \) between source and saturation point (Section 2), we apply Gauss’s law at the region 2 with boundary conditions of \( \xi_2(0) = \zeta_0 \) and \( \phi_2(0) = V_0 + V_{th} \).
Assuming that $\Delta L < L/2$, $\phi(L/2) = \phi(2L - \Delta L)$. As a result $\phi_{th}(0)$ is expressed as

$$\phi_{th}(0) = \cosh \left( \frac{L - 2\Delta L}{2\lambda} \right) \lambda^2 A_0 - \lambda^2 A_0 + (V_0 + V_{th}) \cosh \left( \frac{L - 2\Delta L}{2\lambda} \right)$$

(20)

where $A_0$ at $V_s = 0$ V is defined as

$$A_0 = \frac{Q}{\epsilon\tau x D} + \frac{V_{th}}{\lambda^2}$$

(21)

To calculate $\Delta L$, Eq. (18) can be numerically solved at $x = \Delta L$. As a result, the effective channel length $L_E = L - \Delta L$ is given as

$$L_E = L - \frac{\sinh \left( \frac{L}{2\lambda} \right) V_{th}}{V_{th} - \lambda^2 \left[ \cosh \left( \frac{L}{2\lambda} \right) - 1 \right] + (V_0 + V_{th}) \cosh \left( \frac{L}{2\lambda} \right)}$$

(22)

According to [24,22,13] the electric field at Section 2 can be assumed to be linear. As a result it is concluded that $\phi'(L_E)/\partial x = -\xi_0/L_E$. In addition, it is assumed that $\phi'(0) = V_0 + V_{th} = \xi_0 L_E + V_{th}$. Therefore using Poisson's equation again, $\xi_0$ is given as

$$\xi_0 = \frac{L_E \lambda^2}{L_E^2 - \lambda^2} \left( \frac{Q}{\epsilon\tau x D} + \frac{V_{th} - 2V_{th}}{\lambda^2} \right)$$

(23)

3. Simulation results and discussion

In this section, the results calculated from presented equation is presented. Table 1, shows the values employed in calculation. Fig. 3 shows the electric field distribution in the lateral direction with the different drain voltages. The values for $V_{th}$ have been chosen based on saturation voltage $V_0$, which has been almost 0.23 V in this simulation. This figure indicates that the potential distribution along the nanoribbon surface is similar to the profile of an abrupt junction at the edges of p-base/drift region and drain/drift region junctions [25]. In other word, it shows the electric field profile follows an exponential form depending on the distance from the source.

Fig. 4 depicts the effect of the drain voltage and channel length on the length of saturation region. The higher the drain voltage and longer channel are, the longer the $\Delta L$ is. In addition, the figure shows that the ratio of $\Delta L/L$ increases as $L$ decreases. In Fig. 5 it is shown that increasing oxide thickness causes decrease in $L_E$. In addition, the term $d(L_E)/d(V_{th})$ increases as $t_{ox}$ increases.

To put in nutshell, using empirical equation extracted from presented charts and equations, the dependence of effective channel length on controllable parameters can be simply given as

$$L_E \propto \frac{L N_s C_q + C_{ph}}{V_{th} t_{ox} L_d}$$

(24)

4. Conclusion

A simple model for the effective channel length of graphene nanoribbon FET is presented in this paper. The model is developed by solving Poisson's equation in two different sections of the channel. Quantum capacitance and intrinsic carrier concentration were modelled for the studied device and included in the surface potential model. Using the proposed models, we plotted the profile of quantum capacitance, lateral electric field, effective channel length, and length of velocity saturation $l_v$ region. In addition, the effects of device parameters such as drain-source voltage, channel length, and oxide thickness were examined on the length of effective channel. We showed that in the presented GNRFET, the effective channel can occupy up to half of the channel and decreases as $V_{th}$ and $t_{ox}$ increases.

Appendix A

Typical simulation parameters used in this paper is given in Table 1.

![Fig. 3. Lateral electric field at different drain voltages.](image)

![Fig. 4. The length of velocity saturation region (LVSR) with different channel lengths and drain voltages.](image)

![Fig. 5. The effective channel length vs. oxide thickness variations at different drain voltages.](image)
and GNR’s width may treat as variable.

Typical value for parameters used in simulation. Some values such as channel length and Fermi velocity

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Symbol and value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doping concentration</td>
<td></td>
</tr>
<tr>
<td>Fermi velocity</td>
<td>$v_F = 10^6$ m/s</td>
</tr>
<tr>
<td>Carbon–carbon distance</td>
<td>$d = 0.14 \times 10^{-9}$ m</td>
</tr>
<tr>
<td>Graphene layer’s interlayer distance</td>
<td>$t_{	ext{int}} = 5$ nm</td>
</tr>
<tr>
<td>GNR’s thickness</td>
<td>$t_g = 0.14$ nm</td>
</tr>
<tr>
<td>GNR width</td>
<td>$W = 5$ nm</td>
</tr>
<tr>
<td>GNR dielectric constant</td>
<td>$\varepsilon_{GNR} = 3.3 \times 10^{-15}$ F/m</td>
</tr>
<tr>
<td>Charge magnitude</td>
<td>$q = 1.6 \times 10^{-19}$ C</td>
</tr>
<tr>
<td>Temperature</td>
<td>$T = 300$ K</td>
</tr>
<tr>
<td>Bolzman’s constant</td>
<td>$\alpha = 1.38 \times 10^{-21}$ J/K</td>
</tr>
<tr>
<td>Planck’s constant</td>
<td>$h = 6.6 \times 10^{-24}$ J s</td>
</tr>
<tr>
<td>Thermal voltage</td>
<td>$V_t = k_B T / q$ V</td>
</tr>
<tr>
<td>SiO$_2$ dielectric constant</td>
<td>$\varepsilon_{SiO_2} = 3.9 \times 10^{-14}$ F/m</td>
</tr>
<tr>
<td>Vacuum permittivity</td>
<td>$\varepsilon_0 = 8.85 \times 10^{-12}$ F/m</td>
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<tr>
<td>Oxide thickness</td>
<td>$t_{ox} = 2$ nm</td>
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<tr>
<td>Channel length</td>
<td>$L = 20$ nm</td>
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<tr>
<td>Gate voltage</td>
<td>$V_g = 0.1$ V</td>
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References