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Analytical model for threshold voltage of double gate bilayer graphene field effect transistors

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ABSTRACT

A new model for threshold voltage of double-gate Bilayer Graphene Field Effect Transistors (BLG-FETs) is presented in this paper. The modeling starts with deriving surface potential and the threshold voltage was modeled by calculating the minimum surface potential along the channel. The effect of quantum capacitance was taken into account in the potential distribution model. For the purpose of verification, FlexPDE 3D Poisson solver was employed. Comparison of theoretical and simulation results shows a good agreement. Using the proposed model, the effect of several structural parameters i.e. oxide thickness, quantum capacitance, drain voltage, channel length and doping concentration on the threshold voltage and surface potential was comprehensively studied.

1. Introduction

As predicted by Moore, the semiconductor industry has been facing an exponential growth of the number of transistors per chip during the last three decades. It is also predicted by ITRS (International Technology Roadmap for Semiconductors) that the gate length would scale down to 4.5 nm by 2023 [1]. However, maintaining this trend is a major challenge for both the industry and scientific community due to arising short channel effects. As a result new device structures including FinFETs, nanowire FETs, and recently carbon nanotube field-effect transistors (CNTFETs) and graphene nanoribbon FETs have been proposed. Among them graphene based devices (either single layer graphene or bilayer graphene) have attracted the attention of scientific community due to their fascinating electronic properties such as quantum hall effect, high carrier mobility and their ability to be scaled down [2–5].

On the other hand, the gapless nature of single layer graphene which is considered as the main obstacle on its application in graphene based electronics [6], causes the gate voltage to lose its control on switching off the device [7]. To overcome this drawback, bilayer graphene can be used where the band-gap is induced by introducing a potential difference between two layers as a result of an external perpendicular electric field [8,9]. Moreover, the potential difference can be realized with an applied gate field which means the band-gap can be controlled by gate bias [10]. Recently, the feasibility of using bilayer graphene as channel material is addressed in some analytical device models [11–14].

The surface potential is a fundamental variable in the derivation of various short channel effects. Thus, it is highly desirable for bilayer graphene to model the surface potential analytically with the detailed device physics for developing the threshold voltage model.

The paper is organized as follows. In Section 2 the potential distribution along the channel is modeled for the proposed structure, the quantum capacitance is also modeled and subsequently included in the potential model. In Section 3 the threshold voltage is modeled based on the potential model. Section 4 deals with the analysis of obtained results and illustrations. In Section 5 the main conclusions are drawn.

2. Theoretical model for potential distribution

A schematic cross section of a double gate BLGFET with the definition of the geometrical characteristics are shown in Fig. 1 where t_{ch}, t_g, t_{ox} are bilayer graphene, single layer graphene and oxide thicknesses respectively and L is the channel length. The first and second graphene layers are arranged in AB-stacking [15] as shown in Fig. 2.

Using the common Poisson's equation the potential distribution, $\Phi(x,y)$, for any point (x,y) of BLG channel is given by [16]:

$$\frac{\partial^2\Phi(x,y)}{\partial x^2}+\frac{\partial^2\Phi(x,y)}{\partial y^2}=\frac{q(N_D+n_i)}{\varepsilon_g} \quad (1)$$
$$0\leqslant x\leqslant t_{ch}, 0\leqslant y\leqslant L$$

where ε_g is the dielectric constant of graphene; q is the electron charge; N_D [in cm^{-3}] is the doping concentration and $n_i=\lfloor n/t_{ch}\rfloor$ [in cm^{-3}] is the intrinsic carrier concentration where n is the two

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dimensional carrier concentration of bilayer graphene which is given by [17]:

$$n = \int_0^{\infty} DOS(E)[f(E - E_{FS}) + f(E - E_{FD})]dE \tag{2}$$

where $f(E - E_{Fi}) = 1/(1 + e^{(E-E_{Fi})/K_BT})$, $E_{Fs}(E_{Fd})$ is the Fermi energy of source (drain) and DOS is the density of state

$$DOS(E) = \frac{m^*}{2\pi\hbar^2}\left[1 + \frac{\hbar k_g}{[2m^*(E - E_c)]^{1/2}}\right] \tag{3}$$

where E_c is the conduction band edge, m^* and E are effective mass and energy of electron in BLG respectively, $\hbar$ is the reduced Planck's constant, $t_\perp = 0.35$ eV is the interlayer hopping parameter and k_g is the wave vector in which the smallest gap is observed which is given by [18]

$$k_g = \frac{V}{2\upsilon_F\hbar}\sqrt{\frac{V^2 + 2t_\perp^2}{V^2 + t_\perp^2}} \tag{4}$$

where $V = V_1 - V_2$ is interlayer potential, $\upsilon_F \approx 1 \times 10^6$ m s^{-1} is Fermi Velocity [10].

In nanoscale devices where t_{ox} is small, quantum capacitance which is connected in series with oxide capacitance, should be taken into account in overall gate capacitance [19]. To include the effect of quantum capacitance into the potential distribution of Eq. (1), the surface charge density is used

$$Q = \int_0^L \int_0^{t_{ch}} q(N_D + n_i)dxdy \tag{5}$$

As a result, $q(N_D + n_i) = Q/(L\ t_{ch})$. In addition, the surface charge density using the Gauss theorem can be written as

$$Q = t_{ch}\left[C_{fg}(\Phi_{ch,f} + V_{fb} - V_{fg}) + C_{bg}(\Phi_{ch,b} + V_{fb} - V_{bg})\right] \tag{6}$$

where $C_{fg}(C_{bg})$ is the front (back) gate oxide capacitance, $\Phi_{ch,f}(\Phi_{ch,b})$ is the self consistent potential in the central region of the front (back) channel and V_{fb} is the flat band voltage, the voltage at which there is no band bending in the semiconductor, and is given by [20,21]:

$$V_{fb} = \phi_m - \left[\frac{\chi_g}{q} + \frac{E_g}{2} + \frac{K_BT}{q}\ln\left(\frac{N_D}{n_i}\right)\right] \tag{7}$$

where ϕ_m is the metal work function, χ_g is the electron affinity, T is the temperature and K_B is the Boltzmann constant. For symmetric structures it is assumed that $C_g = C_{fg} = C_{bg} = \varepsilon_{ox}/t_{ox}$, $\Phi_{ch} = \Phi_{ch,f} = \Phi_{ch,b}$ where ε_{ox} is the oxide dielectric. To gain a better insight in device capacitances, the electrostatics of device is shown in Fig. 3

from which the differential capacitance seen by each gate is given by

$$C_{d,i} = C_g\left(1 - \frac{\partial\Phi_{ch,i}}{V_{ig}}\right) \tag{8}$$

where $(i = f, b)$ indicates front and back gates. According to Fig. 3 one can rewrite $C_{d,i}$ as

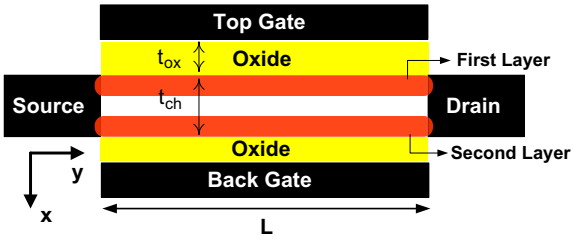

Fig. 1. Cross view of bilayer graphene double gate transistor.

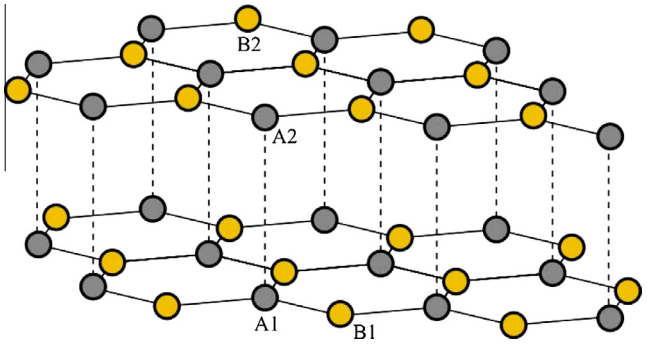

Fig. 2. A typical AB-stacked bilayer graphene [4].

$$C_{d,i} = \frac{C_g(C_g + C_q)}{2C_g + C_q} \tag{9}$$

from Eqs. (8) and (9) we have

$$\Phi_{ch,i} = \frac{C_gV_{ig}}{2C_g + C_q} \tag{10}$$

consequently Eq. (6) can be obtained as

$$Q = t_{ch}C_g\left[\left(\frac{C_g}{2C_g + C_q} - 1\right)(V_{fg} + V_{bg}) + 2V_{fb}\right] \tag{11}$$

In addition, the quantum capacitance is given by

$$C_q = q^2\frac{\partial n_i}{\partial E} \tag{12}$$

where E is energy. Substituting n_i in Eq. (12), the quantum capacitance is written as

$$C_q = \frac{m^*}{2\pi\hbar^2 t_{ch}}D(E)\sum_{i=S,D} f(E - E_{Fi}) \tag{13}$$

where $D(E) = \left[1 + \frac{\hbar k_g}{[2m^*(E-E_c)]^{1/2}}\right]$. The Mexican-hat structure of the band in BLG provides a large DOS and makes quantum capacitance comparable to C_g. Now the effect of quantum capacitance can be included into the potential distribution of Eq. (1)

$$\frac{\partial^2\Phi(x,y)}{\partial x^2} + \frac{\partial^2\Phi(x,y)}{\partial y^2} = \frac{1}{\varepsilon_g}\left(\frac{Q}{Lt_g}\right) \tag{14}$$

Inasmuch as in the strong inversion region the charge controls the channel potential along the y-direction [23,22], Eq. (1) is valid for weak inversion region where the potential can be approximated by a simple parabolic function along the (x) [24,25]:

$$\Phi(x,y) = P_0(y) + P_1(y)x + P_2(y)x^2 \tag{15}$$

where coefficients P_0, P_1 and P_2 are functions of y only and are solved with the boundary conditions of:

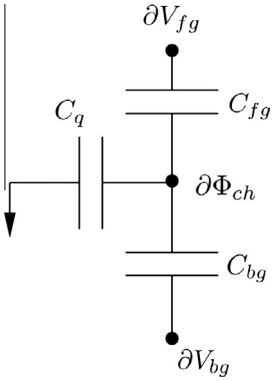

Fig. 3. Equivalent circuit of device electrostatics.