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Dynamic Characteristics of Graphene Nanoribbon Field-Effect Transistors

Maxim Ryzhii[1,3], Akira Satou[1,3], Taiichi Otsuji[2,3], and Victor Ryzhii[1,3]

[1]Computational Nanoelectronics Laboratory, University of Aizu, Aizu-Wakamatsu, 965-8580, Japan
[2] Research Institute for Electrical Communication, Tohoku University, Sendai, 980-8577, Japan
[3]Japan Science and Technology Agency, CREST, Tokyo 107-0075, Japan
Phone: +81-242-372566; E-mail: m-ryzhii@u-aizu.ac.jp

1. Introduction

The utilization of the patterned graphene which constitutes an array of sufficiently narrow graphene nanoribbons as the basis for field-effect transistors (GNR-FETs) opens up wide opportunities for the energy band engineering promoting the achievement of the optimal device parameters. By properly choosing the width of the nanoribbons, one can fabricate the graphene structures with relatively wide band gap but rather high electron (hole) mobility [1, 2] (see also, for instance, refs. [3, 4, 5]). In this paper, we present a device model for GNR-FETs and obtain the device characteristics.

2. Model

We consider GNR-FETs with the structure shown in Fig. 1(b). Under the back and top gate bias voltages, V_b and V_g, the device band diagram corresponds to that shown in Fig. 1(b) The electron transport in the section

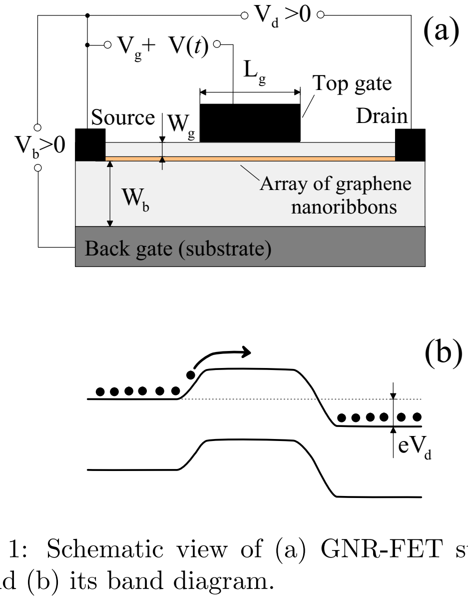

Figure 1: Schematic view of (a) GNR-FET structure side and (b) its band diagram.

of the electron channel beneath the top gate (the gated section), in which the electron density is small, is governed by the following kinetic equation for the electron distribution function $f_p(x,t)$:

$$\frac{\partial f_p}{\partial t} + v_p \frac{\partial f_p}{d x} = -\nu_p (f_p - f_{-p}). \tag{1}$$

Here $v_p = d\varepsilon_p/dp = p/(m^* \sqrt{1 + 2p^2/\Delta m^*})$. is the electron velocity with the momentum p, m^* is the electron effective mass for given value of the GNR energy gap Δ, ν_p is the collision frequency of electrons associated with the disorder (including edge roughnesses) and acoustic phonons. We disregard the inelasticity of the scattering on acoustic phonons, so that all the scattering mechanisms under consideration result in the change of the electron momentum from p to $-p$. Taking into account collisional broadening, we approximate the dependence in question as $\nu_p = \nu\sqrt{\gamma^2+1}/\sqrt{\gamma^2 + (p/p_T)^2}$, where ν is the value of the collisional frequency of thermal electrons, γ characterizes the collision broadening, $p_T = \sqrt{2k_B T m^*}$, k_B is the Boltzmann constant, and T is the temperature.

Taking into account small variations of the top gate voltage $\delta V(t) \propto \delta V_\omega \exp(-i\omega t)$, where δV_ω and ω are the amplitude of the ac signal and its frequency, solving eq. (1) the terminal source-drain ac current δJ_ω can be presented as

$$\delta J_\omega = J_0^B \frac{W_b}{(W_b + W_g)} \frac{e\delta V_\omega}{k_B T} G_\omega D_\omega. \tag{2}$$

Here J_0^B is the dc source-drain current under the ballistic electron transport conditions [5], W_b and W_g are the thicknesses of the gate layers (see Fig. 1(a)), and G_ω and D_ω are the frequency-dependent factors associated with the transit-time effects under the top gate and in the region between the top gate and the drain. As shown,

$$\frac{G_\omega}{4} = \int_0^\infty \frac{d\xi\, \exp(-\xi)\,\omega\,\tilde{\omega}}{(\tilde{\omega}+\omega)^2 \exp\left(-\frac{i\tilde{\omega}\tau}{\sqrt{\xi}}\right) - (\tilde{\omega}-\omega)^2 \exp\left(\frac{i\tilde{\omega}\tau}{\sqrt{\xi}}\right)}, \tag{3}$$

where $\tilde{\omega} = \sqrt{\omega(\omega + i2\nu\sqrt{\gamma^2+1}/\sqrt{\gamma^2+\xi})}$ and $\tau = L_g\sqrt{m^*/2k_B T}$ is the characteristic electron transit

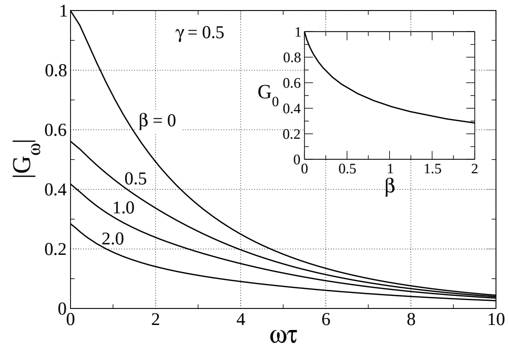

Figure 2: Frequency dependences of the GNR-FET transconductance modulus for different ballistic parameter β. Inset shows G_0 as a function of this parameter.

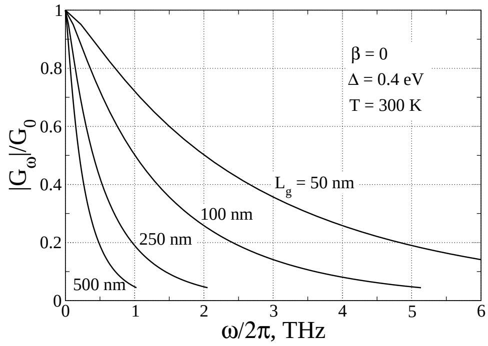

Figure 4: Normalized transconductance vs signal frequency $f = \omega/2\pi$ calculated for different top gate lengths L_g.

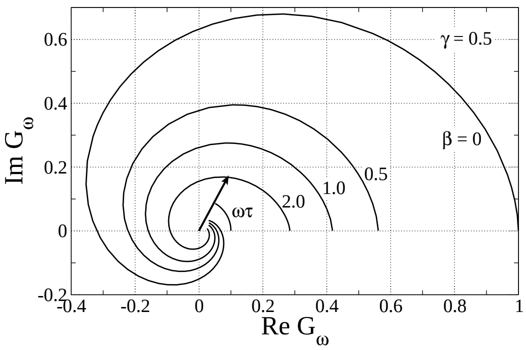

Figure 3: The amplitude-phase diagram of GNR-FETs with different parameter β.

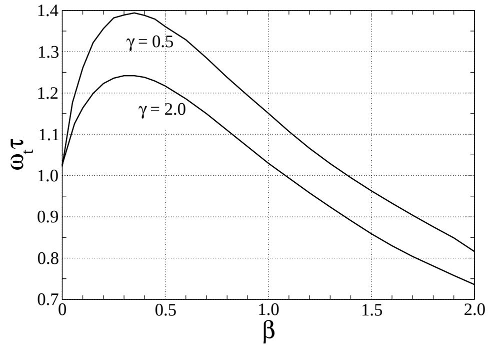

Figure 5: Normalized threshold frequency $\omega_t\tau$ vs ballistic parameter β.

time beneath the top gate . In the most realistic situations the electron transit time across the gate-drain region, τ_d, can be short, and $D_\omega \simeq 1$.

3. Results

The results of calculations using the above formulas are shown in Figs. 2 - 5. Here we use the parameter $\beta = \nu\, L_g\sqrt{m^*/2k_BT}$, where L_g is the top gate lengths, which can be called the ballistic parameter.

Figure 2 shows the frequency dependences of the GNR-FET transconductance modulus $|\mathcal{G}_\omega| = |G_\omega D_\omega| \simeq |G_\omega|$ calculated for different values of the ballistic parameter β. It was assumed that $\gamma = 0.5$. The inset shows G_0 as a function of β. In this and the following figures, we set $\Delta = 0.4$ eV and $T = 300$ K. Figure 3 demonstrates the amplitude-phase diagram calculated for the same parameters as in Fig. 2. The normalized transconductance $|G_\omega|/G_0$ as a function of the signal frequency $f = \omega/2\pi$ calculated for GNR-FETs with different top gate lengths is show in Fig. 4. Figure 5 shows the dependence of the normalized threshold frequency $\omega_t\tau$ at which $|G_\omega|/G_0 = 1/\sqrt{2}$. It is instructive that the obtained dependences exhibit maxima at certain values of the ballistic parameter β (not at $\beta = 0$ as one might expect).

4. Conclusions

(1) We proposed a device model for GNR-FETs

(2) Using this model, we derived explicit analytical formulas for the GNR-FET transconductance as a function of the signal frequency in wide ranges of the collision frequency of electrons and the top gate length.

(3) The variation of the GNR-FET high-frequency characteristics due to the transition from the ballistic and to strongly collisional electron transport was traced.

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