

Field-Effect in Multiple Graphene Layer Structures

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1. Introduction

The prospects of future applications of graphene in electron devices are primarily associated with single graphene layers (GLs) and graphene bilayers (GBLs). As demonstrated recently, multiple-graphene layer (MGL) structures with disoriented GLs fabricated using epitaxial processes can also exhibit very remarkable properties, in particular, very long electron momentum relaxation time (i.e., huge mobility) [1]. Such MGL structures can be rather effective in terahertz and mid-infrared devices, in particular, lasers and photodetectors (see, for instance, [2,3]), because of much stronger interband absorption of radiation. High quality MGL structures can also be used in devices akin to field-effect transistors. However, the efficiency of the voltage control of the electron density in gated MGL structures is affected by the screening of the electric field and, therefore, should be assessed. In this communication, we report the results of a theoretical investigation how the gate voltage affects the electron distribution over the GLs in gated MGL structures.

2. Device model

We consider MGL structures with the side Ohmic contacts (source and drain) to all GLs and the gate (isolated from MGL structure by the gate layer of thickness W_g) on the top of this structure. The positive gate voltage V_g is applied between the gate and the source contact. The applied voltage induces the two-dimensional electron systems of different electron density in each GL.

Since the side contacts are the Ohmic contacts, the electron Fermi energies in the k -th GL sufficiently far from the contacts (beneath the gate) are given by $\mu_k = -e\varphi_k$. Here e is the electron charge and $\varphi_k = \varphi|_{z=kd}$ is the potential of the k -th GL, $k = 1, 2, \dots, K$, where K is the number of GLs in the structure, d is the spacing between GLs, and the axis z is directed perpendicular to the GL plane with $z = 0$ corresponding to the topmost GL and $z = z_K = Kd$ - to the lowest one. The potential distribution along the z -direction and, consequently, the distributions of the Fermi energies and electron densities over the GLs are found using the Poisson equation for the self-consistent potential with the perti-

nent boundary conditions at the gate and far beneath it. Introducing the dimensionless potential $\psi = 2\varphi/V_g$ and taking into account the linear dispersion relations for electrons and holes in graphene, the problem is reduced to the following equations:

$$\frac{d^2\psi}{dz^2} = \frac{8\pi e}{\varepsilon V_g} \sum_{k=1}^K (\Sigma_k^- - \Sigma_k^+) \cdot \delta(z - kd + d), \quad (1)$$

$$\begin{aligned} \Sigma_k^\mp &= \frac{2}{\pi} \left(\frac{k_B T}{\hbar v_F} \right)^2 \int_0^\infty \frac{d\xi \xi}{1 + \exp(\xi \mp \mu_k/k_B T)} \\ &= \frac{12\Sigma_T}{\pi^2} \int_0^\infty \frac{d\xi \xi}{1 + \exp(\xi \mp \mu_k/k_B T)}, \end{aligned} \quad (2)$$

Here, ε is the dielectric constant, Σ_k^\mp are the equilibrium sheet densities in the k -th GL of electrons (“-”) and holes (“+”) expressed via their Fermi energies, $\delta(z)$ is the Dirac delta function, $\Sigma_T = (\pi/6)(k_B T/\hbar v_F)^2$ is the electron and hole density in the intrinsic graphene at the temperature T , $v_F \simeq 10^8$ cm/s is the characteristic velocity of electrons and holes in graphene, and \hbar and k_B are the Planck and Boltzmann constants, respectively. Here it is assumed that the electron (hole) energy spectrum is $\varepsilon = v_F p$, where p is the absolute value of the electron (or hole) momentum. The boundary conditions are assumed to be as follows:

$$\psi|_{z=-0} = 2 + W_g \frac{d\psi}{dz} \Big|_{z=-0}, \quad \frac{d\psi}{dz} \Big|_{z=kd+0} = 0. \quad (3)$$

3. Results

Equations (1) and (2) with boundary conditions (3) were solved numerically. The results of the calculations are shown in Figs. 1 - 4. We assumed that $\varepsilon = 4$, $d = 0.35$ nm, and $W_g = 10$ nm.

One can see Figs. (1) and (2) that the Fermi energy steeply decreases with increasing GL index. However, in GLs with not too large k , the Fermi energy is larger or about of the thermal energy. As one might expect, the electron Fermi energies in all GLs at $T = 77$ K are somewhat larger than at $T = 300$ K. The obtained values of the electron Fermi energies in topmost GLs are

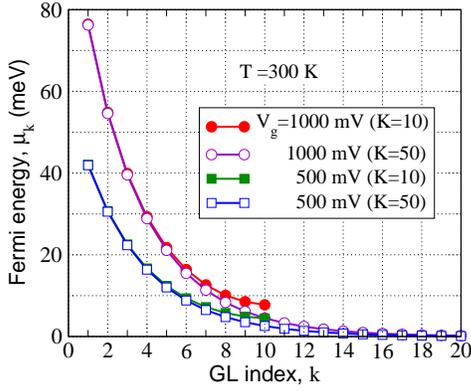


Figure 1: The electron Fermi energy μ_k in different GLs calculated for MGL structures with different number of GLs K for different gate voltages V_g ($T = 300$ K).

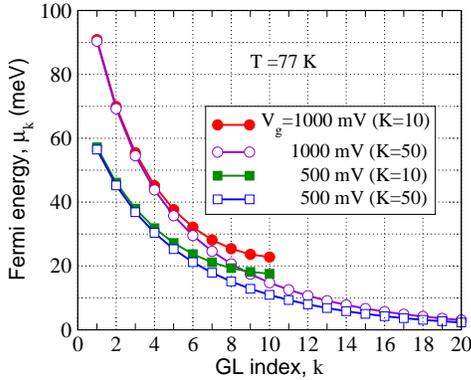


Figure 2: The same as in Fig. 1 but for $T = 77$ K.

$\mu_1 \simeq 92$ meV and $\mu_1 \simeq 77$ meV for $V_g = 1000$ mV at $T = 77$ K and $T = 300$ K, respectively. Figure 3 shows a marked increase in the electron Fermi energies in the topmost GL ($k = 1$) moderately depends on the number of GL K . in multiple-GL structure with ($K = 2$, $K = 10$, and $K = 50$), although these increase is rather weak for the 10-th GL. Figure 4 shows that the calculated electron densities in GLs with sufficiently large indices ($k > 15$ at $T = 77$ K and $T = 300$ K) approach to their values in the intrinsic graphene ($\Sigma_T = 0.59 \times 10^{10} \text{ cm}^{-2}$ and $8.97 \times 10^{10} \text{ cm}^{-2}$). The electron densities in GLs in the structures with different K are rather close to each other, particularly, in GLs with small and moderate indices.

4. Conclusions

We calculated the dependences of the electron Fermi energies and densities (and, hence, the heights of the barriers induced by the gate voltage) in different GLs of gated MGLs on the GL indices, gate voltage, temperature, and the structural parameters. It was demonstrated that the gate-voltage control can be rather effective in MGL structures with about ten or less GLs. The obtained results can be useful for creation of MGL-

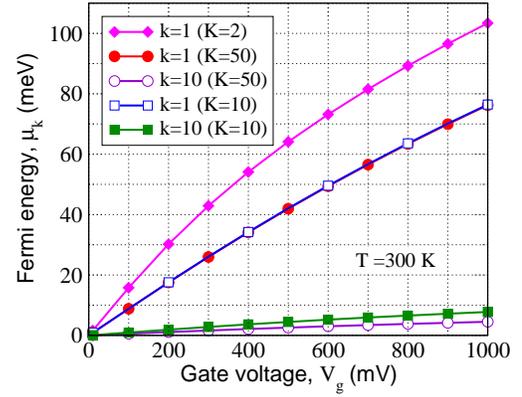


Figure 3: The electron Fermi energies vs gate voltage V_g in different GLs in MGL structure with different K .

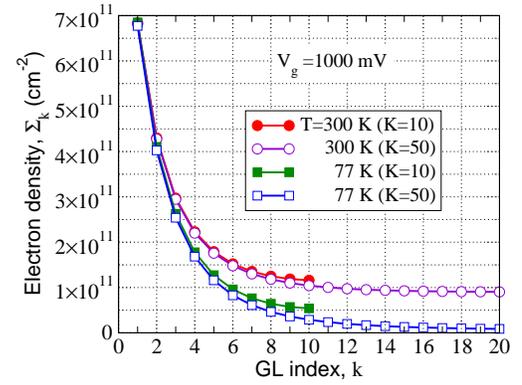


Figure 4: Electron density as a function of GL index in MGL-structures with $K = 10$ and $K = 50$ at different temperatures.

based field-effect transistors, as well as terahertz tunneling transit-time oscillators, lasers, and high performance interband photodetectors [2,3,4] with electrically induced n- and p-regions [5].

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