Hydrodynamic Model for Double Injection of Electrons and Holes in Graphene p-i-n Structures

V. Ryzhii, I. Semenikhin*, M. Ryzhii †, A. Satou, D. Svintsov*, V. Vyurkov*, and T. Otsuji
Research Institute of Electrical Communication, Tohoku University, Katahira, Sendai 980-8577, Japan
* Institute of Physics and Technology, Russian Academy of Sciences, Moscow 117218, Russia
† Department of Computer Science and Engineering, University of Aizu, Aizu-Wakamatsu 965-8580, Japan
e-mail: v-ryzhii@riec.tohoku.ac.jp

INTRODUCTION

Unique properties of graphene-layer (GL) and multiple-graphene-layer (MGL) structures with both chemical doping (Fig. 1, upper panel) and "electrical" doping in the gated structures (Fig. 1, lower panel) are considered as novel building blocks for a variety of electron, terahertz, and optoelectronic devices.

In particular, these structures under the forward bias can be the basis of IR and THz lasers exploiting the interband population inversion due to the injection of electrons and holes from the n- and p-regions [1]. The spatial distribution of the potential can be rather nonuniform, particularly, near the edges of the i-region, i.e. near the p-i and i-n interfaces. Such an effect can markedly influence the conditions of the population inversion and the laser characteristics. The qualitative view of the p-i-n structure band diagrams at the applied voltages $V = 0$ and $V > 0$ (forward bias) are show in Figs. 2(a) and 2(b), respectively [2]. In this paper, we develop a hydrodynamic model for the GL/MGL forward biased p-i-n structures which accounts for the effects of strong nonuniformity and strong recombination [3]. The problem of the electron and hole injection (double injection) in GL/MGL p-i-n structures is complicated by the two-dimensional geometry of the device and the features of the carrier properties. This makes necessary to use two-dimensional Poisson equation for the self-consistent electric potential around the i-region and to invoke the hydrodynamic equations for carrier transport in GL and MGLs.

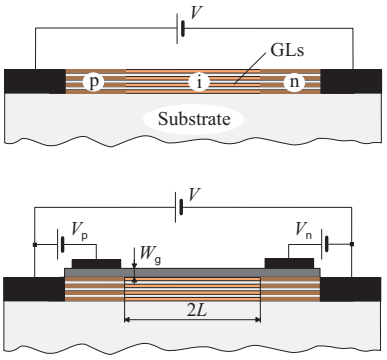

Fig. 1. Schematic views of GL/MGL p-i-n structures

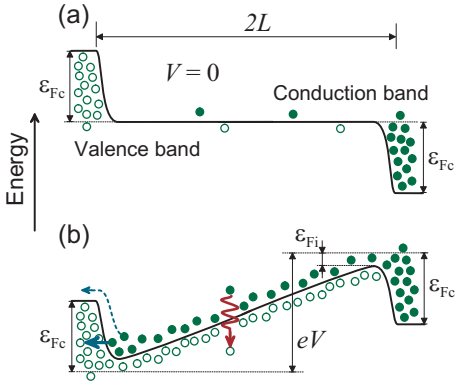

Fig. 2. Qualitative view of GL/MGL p-i-n structure band diagrams.

EQUATIONS OF THE MODEL

The equations of the model under consideration comprise the two-dimensional Poisson equation for the self-consistent electric potential. The Poisson equation for the two-dimensional electric potential $\psi = \psi(x, z)$ is presented as

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial z^2} = \frac{4\pi e}{\kappa}(\Sigma_e - \Sigma_d - \Sigma_h + \Sigma_a) \cdot \delta(z). \quad (1)$$

where $e = |e|$ is the electron charge, Σ_e and Σ_h are the net electron and hole sheet densities in the system (generally consisting of several GLs), $\Sigma_d = \Sigma_d(x)$ and $\Sigma_a = \Sigma_a(x)$ are the densities of donors and acceptors in the i-region (located primarily near the contact regions), and $\delta(z)$ is the delta function reflecting the fact that the GL/MGL system are located in a narrow layer near the

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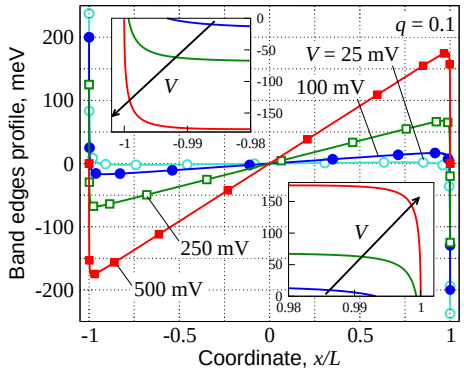

Fig. 3. Potential profiles of conduction band bottom (valence band top) calculated for different bias voltages V.

plane $z = 0$. The axis x is directed in the GL/MGL plane.

The transport of electrons and holes along the i-region in GL/MGLs is governed by the system of hydrodynamic adjusted to the features of the GL/MGL energy spectra, scattering of electrons and holes with each other and with impurities and acoustic phonons, and recombination primarily due to the emission of optical phonons [1], [2]. The boundary conditions account for the injection of electrons and holes from the n- and p-regions and their reflection and tunneling recombination at the opposite edges.

RESULTS

The equations of the model in question were solved numerically and analyzed analytically (in some cases). Figures 3 - 6 demonstrate the examples of the obtained dependences. In particular, it was found that the spatial distributions of the potential and carrier densities and hydrodynamic velocities are very sharp near the edges of the i-region, while they are very smooth in the main portion of this region (see Figs. 3 - 5). This is due to the smallness (several orders of magnitude) of the

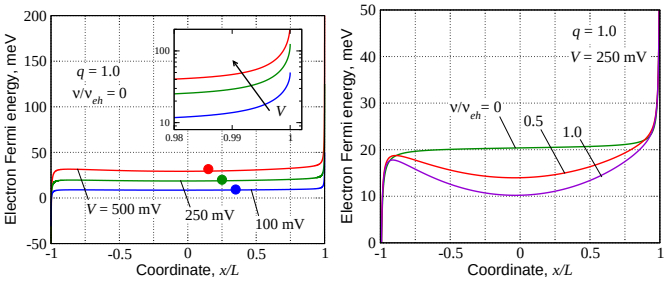

Fig. 4. Spatial dependence of electron Fermi energy at different bias voltages and $\nu/\nu_{eh} = 0$ (left panel) and for different values of ν/ν_{eh} (right panel).

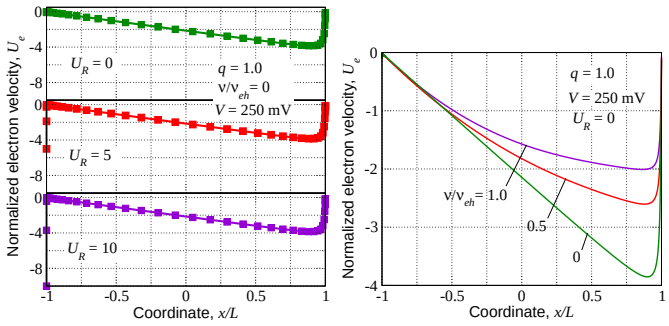

Fig. 5. Spatial dependences of normalized hydrodynamic electron velocity for different values of edge recombination probability U_R (left panel) and different ratios ν/ν_{eh} (right panel).

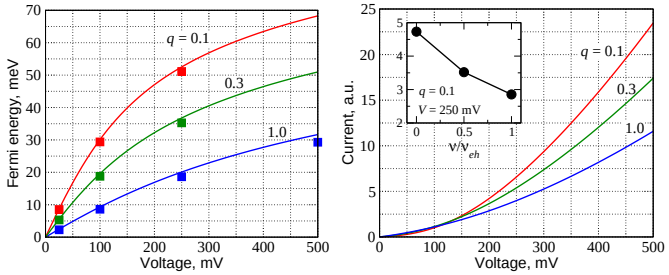

Fig. 6. Voltage dependences of Fermi energy (left panel) and recombination current (right panel). for different parameters q

screening length in the p- and n-region in comparison with the i-region length $2L$. It was also shown that the electron and hole quasi-Fermi energies are fairly slow (sub-linear) functions of the bias voltage in contrast to idealized models [1]. The latter leads to super-linear (non-exponential) recombination current-voltage characteristics (see Fig. 6). The shape of the dependences is determined mainly by the parameters $q = (L/L_D)^2$ and ν/ν_{eh}, here L_D is the characteristic length of the bipolar diffusion, ν_{eh} and ν are the collision frequencies electrons with holes and with impurities and phonons.

The obtained results might be useful for GL/MGL-based IR and THz lasers optimization. The developed model can also be applied to the injection phenomena in double-GL tunneling structures [4]–[6].

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