Frequency limits for graphene conducting channel, imposed by quantum capacitance and kinetic inductance

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Dynamic conductance of quantum nano-scale conductors is an important problem of nanoelectronics theory [1]. Generally, electrostatic capacitance of the system “graphene strip – substrate – gate” plays a crucial role in grapheme physics, being responsible for the “gate doping” of graphene with electrons or holes [2]. However, later we examine the case of mono- and multilayer graphene dynamic conductivity in drain – source circuit, without gate doping, with gate not being included into such circuit. As it was demonstrated in [3], additional quantum capacitance and kinetic inductance arise for such a circuit a result of a correct solution of Boltzmann transport equation. Therefore equivalent circuit for the long strip of graphene can be presented as a combination of quantum capacitance *C*, and kinetic inductance *L* (see Fig.1).

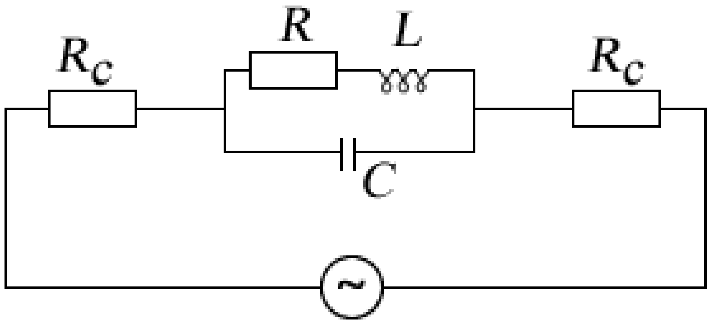

Fig.1. Equivalent circuit for a strip of graphene. *R* – graphene strip resistivity, R_C – contacts resistivity.

The quantum capacitance of the graphene strip can be presented [3] as:

$$C = e^2 \sum_{m,k} \left(-\frac{\partial f_o}{\partial E} \right) \tag{1}$$

Here e is a charge of electron, f_o is equilibrium distribution function, E is energy. Summation in (1) is carried over all the sub-bands m, and wave-vectors $\boldsymbol{k}$ in xy plane.

Kinetic inductance is introduced as:

$$\frac{1}{L} = \frac{e^2}{l^2} \sum_{m,k} v^2 \left(-\frac{\partial f_o}{\partial E} \right), \tag{2}$$

where l is a strip length between the contacts, v is electron speed in x direction between source and drain. With allowance for the linear band spectrum of graphene

$$E = \pm \hbar v_F k, \tag{3}$$

where $v_F = 10^6$ m/s, (1) and (2) can be rewritten approximately as:

$$C \approx \frac{2e^2Ml}{hv_F} \quad , \tag{4}$$

$$\frac{1}{L} \approx \frac{2e^2M}{hv_F l}\langle v^2 \rangle . \tag{5}$$

Here M is a total number of sub-bands, which is roughly equal to the number of electronic have-wavelengths which fit in the graphene strip cross-section in yz plane (across the current), <…> means average for electron drift in x direction (along the current).

The impedance of the circuit, presented in Fig.1, is given by:

$$Z = 2R_c + \frac{R(1-\varpi^2 LC)+\varpi^2 RLC}{(1-\varpi^2 LC)^2+(\varpi RC)^2} + i\frac{\varpi L(1-\varpi^2 LC)-\omega R^2 C}{(1-\varpi^2 LC)^2+(\varpi RC)^2} \tag{6}$$

For ω = 0 (6) obviously yields:

$$Z = 2R_c + R . \tag{7}$$

However, with the increase of the applied field frequency, the resonance occurs at ω_r frequency when the imaginary part in (6) is zero and the resistivity of the circuit reaches maximum:

$$\varpi_r = \varpi_o \sqrt{1-\frac{R^2C}{L}};\varpi_o = \frac{1}{\sqrt{LC}} \tag{8}$$

With allowance for (4), (5) one can see, that $\varpi_r \approx \varpi_c$ in the case, when $\langle v^2 \rangle / v_F^2 << 1$.

Now let us estimate the frequencies, predicted by (8). For the high quality graphene Landauer resistor [1], where electron passes from source to drain without scattering and where with allowance for (3) $\langle v^2 \rangle \approx v_F^2$, (8) yields:

$$\omega_o \sim \sqrt{\langle v^2 \rangle}/l = v_F / l . \tag{9}$$

This leads to the frequencies of GHz range for the submicron length of graphene strip between the contacts. However, in a long graphene strip of mm length order with a diffusive movement of electron from source to drain, where $\sqrt{\langle v^2 \rangle} \sim \mu \overline{E}_{sd}$, μ is electron mobility, $\overline{E}_{sd}$ is average in time electric field in source-drain circuit, one can get for $\overline{E}_{sd} \sim 10^3$ V/m and $\mu \sim 1$ m^2/Vs (which is a typical value for CVD graphene) the frequency of MHz order. Therefore, by varying CVD graphene strip length (in hundreds μm – mm range) and mobility (in 0.1 – 1 m^2/Vs range), we can fabricate filters for tens KHz – MHz range.

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