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TEMPERATURE DEPENDENCE OF GRAPHENE ELECTRICAL CONDUCTIVITY

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INTRODUCTION

The exceptional transport characteristics, coupled with high thermal, mechanical and chemical stability, provide wide opportunities for practical application of graphene. Temperature dependence of graphene electrical conductivity is hereby analyzed in wide temperature range of 15-400 K, by solving semiclassical Boltzmann equation in the approximation of relaxation time. Basic relaxation mechanisms in graphene – electron scattering on impurities and electron-phonon interaction – are accounted with corresponding relaxation times introduced phenomenologically. The theoretical results are compared with experimentally observed.

GRAPHENE CRYSTAL STRUCTURE AND DISPERSION LAW OF QUASIPARTICLES

The graphene dispersion low, in case we take into account only area in the vicinity of Dirac points, can be significantly simplified:

$$E = \hbar v_F k.$$

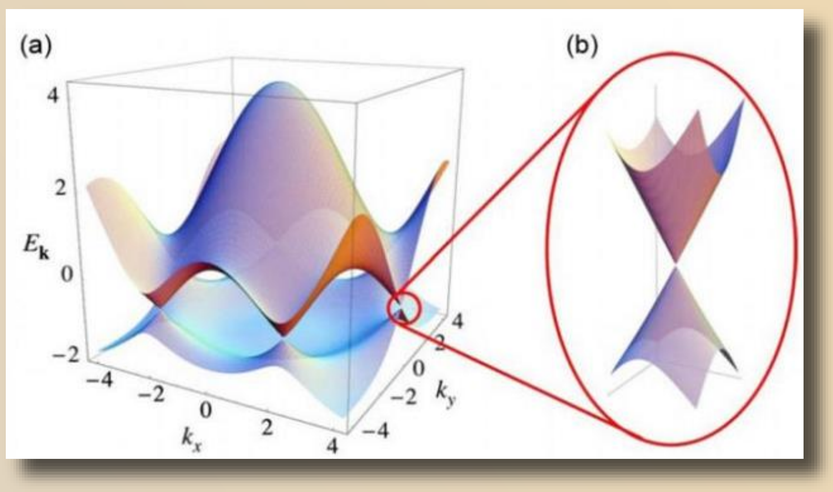

Figure 1. The graphene dispersion relation (a), and its view in the vicinity of Dirac point (b)

GRAPHENE ELECTRICAL CONDUCTIVITY

Further on, for finding graphene electrical conductivity we shall apply semiclassical Boltcmann transport equation in the approximation of relaxation time

$$\sigma = \frac{e^2}{2}\int_0^\infty \frac{g_s g_v}{2\pi(\hbar v_F)^2} v^2 \tau(\varepsilon)\left(-\frac{\partial f_0}{\partial \varepsilon}\right) = \frac{e^2}{2}\int_0^\infty D(\varepsilon) v^2 \tau(\varepsilon)\left(-\frac{\partial f_0}{\partial \varepsilon}\right).$$

To calculate total relaxation time we apply Matthiessen rule, in case of relaxation on charged impurities (long-range Coulomb interaction) and in case of relaxation on neutral impurities (short-range Coulomb interaction), respectively:

$$\frac{1}{\tau_{im}} = \begin{cases} \dfrac{u_0^2}{\hbar \varepsilon_F}; \\ \dfrac{n_d V_0^2}{\hbar}\dfrac{\varepsilon_F}{4(\hbar v_F)^2}. \end{cases}$$

In case of relaxation on phonons, we analyze the temperature ranges $T \geq T_{BG}$ and $T < T_{BG}$ (where T_{BG} is Bloch-Grüneisen temperature), respectively:

$$\frac{1}{\tau_{ph}(\varepsilon)} = \begin{cases} \dfrac{1}{\hbar^3}\dfrac{\varepsilon}{4v_F^2}\dfrac{D^2}{\rho_m v_{ph}^2} k_B T; \\ \dfrac{1}{\pi}\dfrac{1}{\varepsilon_F}\dfrac{1}{k_F}\dfrac{D^2}{2\rho_m v_{ph}}\dfrac{4!\zeta(4)}{(\hbar v_{ph})^4}(k_B T)^4. \end{cases}$$

For numerical calculation of electrical conductivity, we shall adopt the following values of parameters:

$$D = 30{,}4\cdot 10^{-19}\,\mathrm{J};\quad \rho_m = 7{,}6\cdot 10^{-7}\,\frac{\mathrm{kg}}{\mathrm{m}^2};\quad v_{ph} = 2\cdot 10^4\,\frac{\mathrm{m}}{\mathrm{s}};\quad \varepsilon_F = 4{,}168\cdot 10^{-19}\,\mathrm{J};$$

$$v_F = 10^6\,\frac{\mathrm{m}}{\mathrm{s}};\quad k_F = 4{,}8\cdot 10^8\,\mathrm{m}^{-1};\quad n_i^C = 4\cdot 10^{15}\,\mathrm{m}^{-2};\quad Z = 1;\quad \tilde{\varepsilon}_r = 2{,}4;\quad \tilde{\gamma} = 4{,}2;$$

$$n_d = 0{,}4\cdot 10^{14}\,\mathrm{m}^{-2};\quad V_0 = 16\cdot 10^{-37}\,\mathrm{Jm}^2;\quad T_{BG} = 54\mathrm{K}.$$

For lower and for higher temperatures, expression for electrical conductivity is transformed, respectively:

$$\sigma = \frac{4\pi e^2}{h^2}\int_0^\infty dx\{k_B T\, x + \varepsilon_F[1 - \frac{\pi^2}{6}(\frac{k_B T}{\varepsilon_F})^2]\}\,\tau(x)\frac{e^x}{(e^x+1)^2};\quad x = \frac{\varepsilon-\mu}{k_B T};\quad \mu = \varepsilon_F - \frac{\pi^2}{6}\frac{(k_B T)^2}{\varepsilon_F};$$

$$\sigma = \frac{4\pi e^2}{h^2}\int_0^\infty dx\{k_B T\, x + \frac{1}{4\ln 2}\frac{\varepsilon_F^2}{k_B T}]\}\,\tau(x)\frac{e^x}{(e^x+1)^2};\quad x = \frac{\varepsilon-\mu}{k_B T};\quad \mu = \frac{1}{4\ln 2}\frac{\varepsilon_F^2}{k_B T}.$$

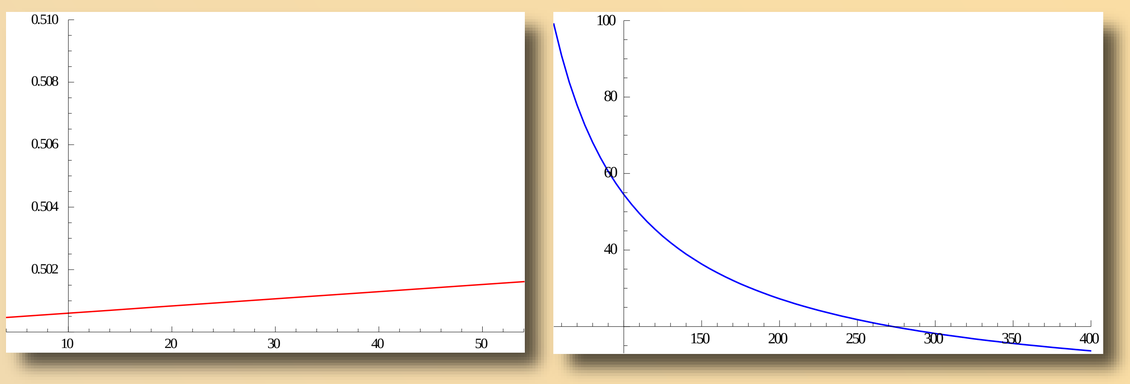

Figure 2. Temperature dependance of graphene electrical conductivity in case of relaxation on charged impurities, for temperature ranges $T<<T_{BG}$ (left) and $T>T_{BG}$ (right)

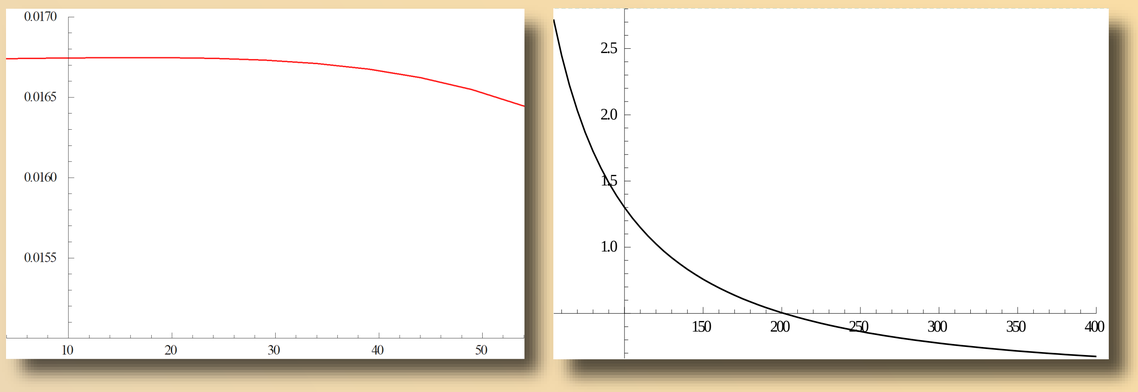

Figure 3. Temperature dependance of graphene electrical conductivity in case of relaxation on neutral impurities, for temperature ranges $T << T_{BG}$ (left) and $T > T_{BG}$ (right)

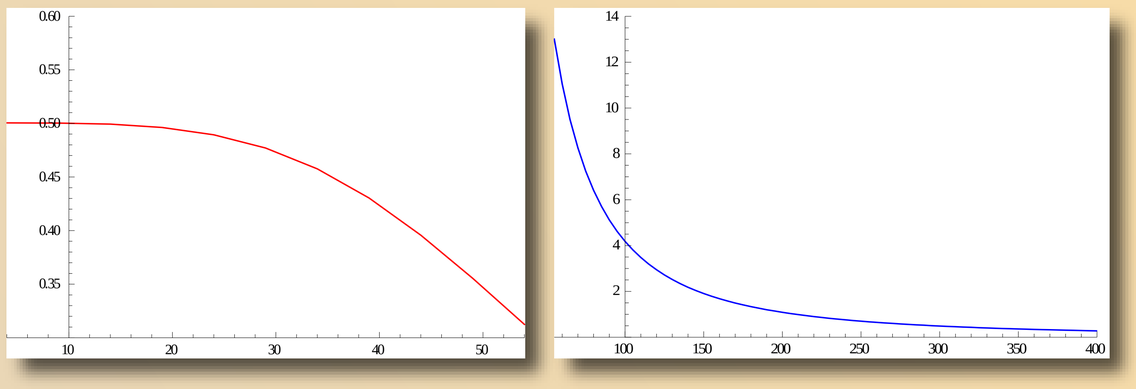

Figure 4.Temperature dependance of graphene electrical conductivity in case of relaxation on both charged impurities and phonons, for temperature ranges $T << T_{BG}$ (left) and $T > T_{BG}$ (right)

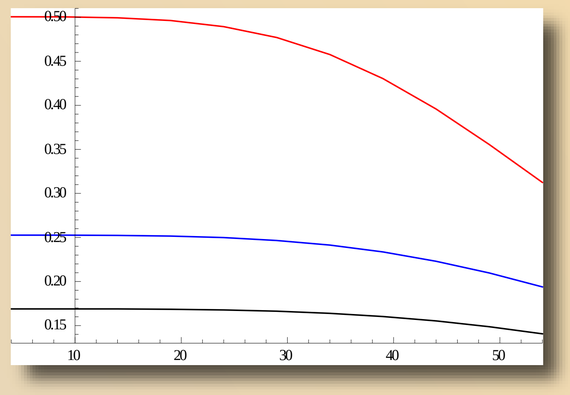

Figure 5. Low-temperature dependance of graphene electrical conductivity (for $T << T_{BG}$) in case of relaxation on both charged impurities and phonons, for several concentrations of impurities as parameters

CONCLUSION

It is obtained that graphene electrical conductivity decreases with temperature for all relaxation mechanisms. Numerical calculations and graphs are presented separately in low-temperature and high-temperature regions, due to different temperature dependences of chemical potentials and relaxation times in these regiouns.

For relaxation on neutral impurities, graphene electrical conductivity is almost temperature independent till 300 K (cf. Fig. 3), which is in excellent agreement with experimental data.

For relaxation on phonons, electrical conductivity is analyzed until T_{BG} temperature with degenerate phonons and above T_{BG} temperature with non-degenerate phonons. It is found that low-temperature electrical conductivity is lower than high-temperature one.

It is also obtained that graphene electrical conductivity decreases with increase of impurity concentration.