JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. 6 No 4, 04003(4pp) (2014)
ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том 6 № 4, 04003(4cc) (2014)

Effect of High-frequency Laser Radiation on the Graphene Current-voltage Characteristic

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(Received 26 May 2014; published online 29 November 2014)

The effective spectrum of electron states of graphene taking into account the action of high-frequency laser radiation with elliptical polarization was calculated. Band gap was shown to arise in the graphene spectrum in conditions of high-frequency electromagnetic wave. The current-voltage characteristic of the graphene exposed to such radiation was studied. Effect of high-frequency electric field on the electron magnetotransport in graphene was discussed.

Keywords: Graphene, Dirac equation, Current-voltage characteristic, Magnetoconductivity.

PACS numbers: 72.80.Vp, 72.15.Gd, 72.20.Ht

1. INTRODUCTION

The investigations of strong electromagnetic (EM) fields effect on the electron transport in graphene are very intensive last time [1, 2] and are due to unique properties of this material. Electric and optical properties of graphene-based structures are studied theoretically and experimentally in [3-17]. Graphene is also a perspective material for nanoelectronics applications [18-20]. Predicted nonlinear optical properties of the graphene-based structures give the new opportunities for building of the optoelectronic devices. In [5-8] the possible applica-tions of graphene for generation of terahertz radiation were discussed.

The influence of a high-frequency (HF) EM radiation on the electron transport in graphene-based structures was investigated in [21-35]. In [21-31, 33] the gap opening in the energy spectrum of originally gapless graphene was predicted for HF EM radiation of different polarizations. In [21-25, 30] gap opening in graphene was shown to have the nature of the parametric resonance. There is the set of qua-simomentum values near which the gaps arise in the en-ergy spectrum of originally gapless graphene. The explicit form of quasienergy spectrum near the one of such reso-nant values of quasimomentum was found in [22] by rotat-ing-wave approximation in the case of weak HF electric field.

Below we consider the graphene exposed to the EM radiation with elliptical polarization and calculate the qua-sienergy of electron in this case using the Dirac equation.

2. EFFECTIVE ELECTRON SPECTRUM OF GRAPHENE IN HF EM RADIATION

Let graphene is in the plane xy. EM radiation with frequency ω and with amplitude of electric field E_0 is propagating along the axis Oz. So the vector potential in the graphene plane xy is (c = 1):

$$\mathbf{A}(t) = -\frac{E_0}{\omega}\left\{\ \sin\omega t,\ \ \sin(\omega t+\phi)\ \right\}. \tag{1}$$

Thus spinor describing the electron dynamics in graphene in conditions of EM field satisfies the equation [1] $(\hbar = 1)$:

$$i\partial_t\psi = \upsilon_{\mathrm{F}}(\mathbf{p}+e\mathbf{A})\cdot\boldsymbol{\sigma}\psi\,. \tag{2}$$

Here σ is the Pauli matrixes, $\upsilon_{\mathrm{F}} = 10^8$ cm/s is the velocity on the Fermi surface. The solution of (2) satisfies the Floquet theorem [21-25, 27]:

$$\psi(t) = u(t)\exp(-i\varepsilon_{\mathrm{eff}}t)\,, \tag{3}$$

where $u(t)$ is the spinor with the terms $u_\uparrow(t)$ and $u_\downarrow(t)$ which are the periodic functions with the period $2\pi/\omega$, $\varepsilon_{\mathrm{eff}}$ is quasienergy [21, 27]. After substitution (3) into (2) we obtain:

$$-i\partial_t u + \upsilon_{\mathrm{F}}(\mathbf{p}+e\mathbf{A})\cdot\boldsymbol{\sigma}u = \varepsilon_{\mathrm{eff}}u\,. \tag{4}$$

The terms of spinor $u(t)$ are expanded in Fourier series: $u(t) = u_0 + u_1(t) + \ldots$. Here u_0 is the constant term of spinor $u(t)$. Further the frequency is proposed to satisfy the next condition: $\omega >> \sqrt{eE_0\upsilon_{\mathrm{F}}}$. It can be shown that $u_1 \sim 1/\omega^2$. Hence in the case of HF radiation we have: $|u_{0\uparrow}|^2 + |u_{0\downarrow}|^2 << \ |u_{1\uparrow}|^2 + |u_{1\downarrow}|^2 << \ldots$.

Moreover, these inequalities are performed the better, the higher the frequency of the radiation. The above allows leaving the first two terms of the Fourier series for the components of the spinor: $u(t) = u_0 + u_1(t)$. After substitution of the last equality into (4) and averaging over the small oscillations we derive:

$$\upsilon_{\mathrm{F}}\mathbf{p}\cdot\boldsymbol{\sigma}u_0 + \frac{\upsilon_{\mathrm{F}}^2 p_E^2\sin\phi}{\omega}\sigma_z u_0 = \varepsilon_{\mathrm{eff}}u\,. \tag{5}$$

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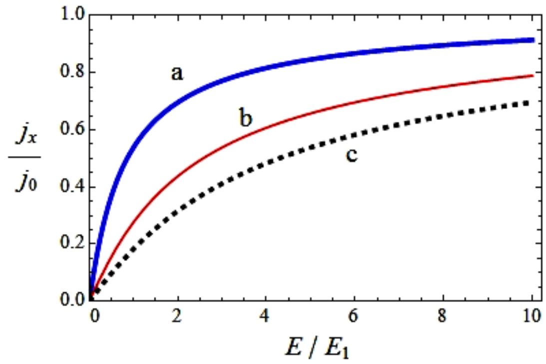

Fig. 1 – Current-voltage characteristic of graphene exposed to the HF laser radiation with circular polarization. a) $\Delta_{HF} = p_F\upsilon_F$, b) $\Delta_{HF} = 3p_F\upsilon_F$, c) $\Delta_{HF} = 5p_F\upsilon_F$

Here $p_E = eE_0/\omega$. From we find the quasienergy:

$$\varepsilon_{\text{eff}}(\mathbf{p}) = \pm\sqrt{\Delta_{\text{HF}}^2 + \upsilon_{\text{F}}^2 p^2}\,, \tag{6}$$

where $\Delta_{\text{HF}} = e^2E_0^2\upsilon_{\text{F}}^2 \sin\phi/\omega^3$ is the semiwidth of the gap, induced by the HF radiation [24,25]. The value of the gap is maximum for the circular EM radiation ($\phi = \pi/2$).

3. CURRENT-VOLTAGE CHARACTERISTIC OF GRAPHENE SUBJECTED TO HF EM RADIATION

Let the constant electric field with vector $\mathbf{E} = \{E, 0\}$ is applied along the axis Ox. The electric current density arising through the axis Ox in the constant relaxation time τ approximation is calculated with the following formula:

$$j_x = -e\int_0^\infty dz e^{-z}\sum_{\mathbf{p}} \upsilon_x(\mathbf{p} - e\tau\mathbf{E}z) f_0(\mathbf{p})\,, \tag{7}$$

where $f_0(\mathbf{p})$ is equilibrium state function, $\upsilon_x(\mathbf{p}) = \partial\varepsilon_{\text{eff}}/\partial p_x$ is electron velocity along the axis Ox.

The electron gas is nondegenerate when the next condition is performed for it:

$$\exp\left(\frac{\Delta_{\text{HF}} - \mu}{\theta}\right) >> 1\,, \tag{8}$$

where μ is the chemical potential, θ is the temperature of electron gas. For the nondegenerate electron gas at low temperatures $(\theta << \Delta_{\text{HF}})$ we obtain from (7):

$$j_x(E) = j_0 a(E)\int_0^\infty \frac{ze^{-z}dz}{\sqrt{1 + z^2a^2(E)}}\,. \tag{9}$$

In (9) we define: $j_0 = en_0\upsilon_{\text{F}}$, $a(E) = e\upsilon_{\text{F}}\tau E/\Delta_{\text{HF}}$, n_0 is the surface concentration of charge carriers of graphene. The dependence of current density on the intensity E is shown in figure 1 for different values of amplitude of HF electric field (here $E_1 = p_{\text{F}}/e\tau$, $p_{\text{F}} = 1/d_0$, $d_0 = 0.246$ nm is the lattice constant of graphene). Using

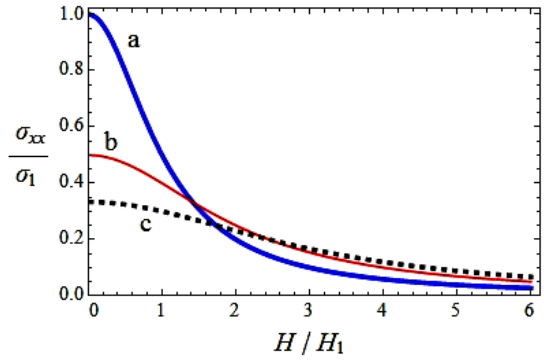

Fig. 2 – Dependence of diagonal conductivity σ_{xx} of graphene on the magnetic field intensity for different values of gap induced by HF laser radiation. a) $\Delta_{HF} = p_F\upsilon_F$, b) $\Delta_{HF} = 2p_F\upsilon_F$, c) $\Delta_{HF} = 3p_F\upsilon_F$

the normalization condition we find from the inequality (8) the next condition for the HF electric field amplitude:

$$E_0 >> \frac{\omega}{e}\sqrt{\frac{n_0\omega}{\theta}}\,. \tag{10}$$

For the following parameters values [6]: $n_0 = 10^{10}$ cm^{-2}, $\omega \sim 10^{13}$ s^{-1}, $\theta \sim 77.4$ K, inequality (10) gives for amplitude of HF electric field: $E_0 >> 500$ V × cm^{-1}.

4. MAGNETOCONDUCTIVITY OF GRAPHENE SUBJECTED TO HF EM RADIATION

Let the constant magnetic field is applied along the axis Oz. The modification of electron spectrum of graphene by the HF EM radiation leads to the change of the graphene magnetoconductivity and the cyclotron mass also. Therefore the measurements of graphene magnetoconductivity in the presence of HF field give the way to determine the energy gap changing. If there is a constant magnetic field additionally then the character of conductivity changing is defined by the relation between the amplitude E_0 of HF laser radiation and the magnetic field intensity H.

In this section we calculate the magnetoconductivity of graphene with an energy spectrum modified by the HF laser radiation (6). The magnetic field is assumed to be directed perpendicular to the graphene plane: $\mathbf{H} = (0, 0, H)$. Electric field is considered to be directed along the Ox axis: $\mathbf{E} = (E, 0, 0)$.

In the linear approximation in parameter E and in the approximation of relaxation time τ, the current density induced by the aforementioned field is

$$\begin{gathered} J = e^2\upsilon_{\text{F}}^2\tau E\sum_{\mathbf{p}} \frac{f_0(\mathbf{p})}{(1 - i\omega_{\text{c}}\tau)\varepsilon_{\text{eff}}(\mathbf{p})}\times \\ \times\left(1 - \frac{\upsilon_{\text{F}}^2p^2}{2\varepsilon_{\text{eff}}^2(\mathbf{p})}\frac{1}{1 - i\omega_{\text{c}}\tau}\right) \end{gathered}, \tag{11}$$

where $\omega_{\text{c}} = e\upsilon_{\text{F}}^2H/\varepsilon_{\text{eff}}$, $J = j_x + ij_y$.

Using (11) we find for diagonal conductivity the next formula:

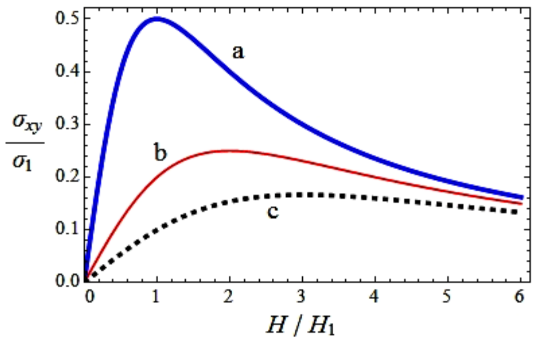

Fig. 3 – Dependence of Hall conductivity σ_{xy} of graphene on the magnetic field intensity for different values of gap induced by HF laser radiation. a) $\Delta_{HF} = p_F\upsilon_F$, b) $\Delta_{HF} = 2p_F\upsilon_F$, c) $\Delta_{HF} = 3p_F\upsilon_F$

$$\sigma_{xx} = e^2\upsilon_F^2\tau\sum_{\mathbf{p}}\frac{f_0(\mathbf{p})}{\left(1+\omega_c^2\tau^2\right)\varepsilon_{\mathrm{eff}}(\mathbf{p})}\times \left(1-\frac{\upsilon_F^2 p^2}{2\varepsilon_{\mathrm{eff}}^2(\mathbf{p})}\frac{1-\omega_c^2\tau^2}{1+\omega_c^2\tau^2}\right). \quad (12)$$

For Hall conductivity we obtain:

$$\sigma_{xy} = e^2\upsilon_F^2\tau\sum_{\mathbf{p}}\frac{\omega_c\tau}{1+\omega_c^2\tau^2}\frac{f_0(\mathbf{p})}{\varepsilon_{\mathrm{eff}}(\mathbf{p})}\times \left(1-\frac{\upsilon_F^2 p^2}{\varepsilon_{\mathrm{eff}}^2(\mathbf{p})}\frac{1}{1+\omega_c^2\tau^2}\right). \quad (13)$$

Note that in (12) and (13) ω_c is the function of quasimomentum $\mathbf{p}$ and amplitude of HF electric field E_0. Conductivities dependences on the magnetic field intensity are shown in Fig. 2 and Fig. 3 for different values of amplitude of HF electric field (here $H_1 = p_F/e\upsilon_F\tau$, $\sigma_1 = e^2 n_0\upsilon_F\tau/p_F$, $\phi = \pi/2$).

5. DISCUSSIONS

The HF EM radiation is shown above to increase the band gap in the quasienergy spectrum of graphene. The band gap semiwidth is seen from (5) can be regulated by changing of the HF field amplitude E_0. For the next values of the parameters: $\upsilon_F = 10^8$ cm × s^{-1}, $\omega = 10^{13}$ s^{-1}, $E_0 = 5\cdot 10^3$ V × cm^{-1}, $\phi = \pi/2$ we have $\Delta_{HF} = 0.4$ eV. The calculations show that gap appearing can be registered by measuring of graphene conductivity in HF electric field. For instance in the absence of the magnetic field the gap can be find as $\Delta_{HF} = e^2 n_0\upsilon_F^2\tau/\sigma_{xx}$, where conductivity σ_{xx} can be measured experimentally.

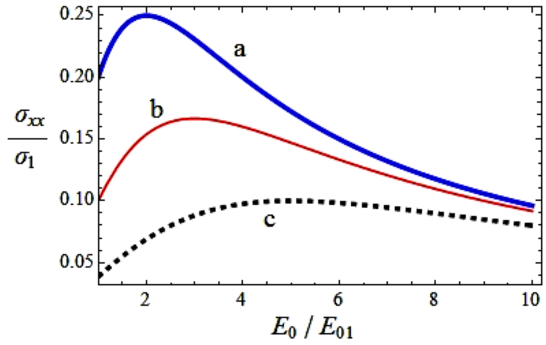

Fig. 4 – Dependence of diagonal conductivity on amplitude of HF electric field. a) $H = 2H_1$, b) $H = 3H_1$, c) $H = 5H_1$

Moreover the presence of the HF electric field gives the way of continuous change of graphene conductivity at fixed value of magnetic field intensity. Hall conductivity is seen from Fig. 2 to decrease if the amplitude of HF electric field increases. As for diagonal conductivity σ_{xx} it is seen from Fig. 2 to increase with increasing of amplitude of HF field if $\Delta_{HF} < He\upsilon_F^2\tau$ and to decrease with increasing of amplitude of HF field if $\Delta_{HF} > He\upsilon_F^2\tau$ (Fig. 4, here we define: $E_{01} = \sqrt{p_F\omega^3/e^2\upsilon_F}$).

ACKNOWLEDGEMENTS

The work was supported by the RFBR Project 13-02-97033 r–povolzhye–a and with the funding of the Ministry of Education and Science of the Russian Federation within the base part of the State task №2014/411 (Project Code: 522).

REFERENCES

1. N.M.R. Peres, *J. Phys: Cond. Mat.* **21**, 323201 (2009).
2. D.S.L. Abergel, V. Apalkov, J. Berashevich, K. Ziegler, T. Chakraborty, *Adv. Phys.* **59**, 261 (2010).
3. R.R. Nair, P. Blake, A.N. Grigorenko, K.S. Novoselov, T.J. Booth, T. Stauber, N.M.R. Peres, A.K. Geim, *Science* **320**, 1308 (2008).
4. V.P. Gusynin, S.G. Sharapov, J.P. Carbotte, *J. Phys: Cond. Mat.* **19**, 026222 (2007).
5. M.L. Sadowski, G. Martinez, M. Potemski, C. Berger, W.A. de Heer, *Phys. Rev. Lett.* **97**, 266405 (2006).
6. L.A. Falkovsky, *Phys. Usp.* **51**, 887 (2008).
7. S.A. Mikhailov, *Physica E* **40**, 2626 (2008).
8. S.A. Mikhailov, K. Ziegler, *J. Phys. Cond. Mat.* **20**, 384204 (2008).
9. X.-F. Wang, T. Chakraborty, *Phys. Rev. B* **75**, 033408 (2007).
10. J. Berashevich, T. Chakraborty, *Phys. Rev. B* **80**, 115430 (2009).
11. D. Bolmatov, C.-Y. Mou, *Physica B* **405**, 2896 (2010).
12. D. Bolmatov, C.-Y. Mou, *J. Exp. Theor. Phys.* **110**, 612 (2010).
13. D. Bolmatov, C.-Y. Mou, *J.Exp. Theor. Phys* **112**, 102 (2011).
14. V.M. Apalkov, T. Chakraborty, *Phys. Rev. B* **86**, 035401 (2012).
15. V.P. Gusynin, S.G. Sharapov, J.P. Carbotte, *Phys. Rev. Lett.* **96**, 256802 (2006).
16. D. Bolmatov, D.V. Zavialov, *J. Appl. Phys.* **112**, 103703 (2012).
17. Neetu Agrawal (Garg), S. Ghosh, M. Sharma, *Int. J. Mod. Phys. B* **27**, 1341003 (2013).
18. D. Popa, Z. Sun, F. Torrisi, T. Hasan, F. Wang, A.C. Ferrari, *Appl. Phys. Lett.* **97**, 203106 (2010).
19. G. Konstantatos, M. Badioli, L. Gaudreau, J. Osmond, M. Bernechea, F.P. Garcia de Arquer, F. Gatti, F.H.L. Koppens, *Nature Nanotech.* **7**, 363 (2012).

20. S. Thongrattanasiri, F.H.L. Koppens, F.J. Garcia de Abajo, *Phys. Rev. Lett.* **108**, 047401 (2012).
21. M.V. Fistul, K.B. Efetov, *Phys. Rev. Lett.* **98**, 256803 (2007).
22. S.V. Syzranov, M.V. Fistul, K.B. Efetov, *Phys. Rev. B* **78**, 045407 (2008).
23. F.J. Lopez-Rodriguez, G.G. Naumis, *Phys. Rev. B* **78**, 201406(R) (2008).
24. T. Oka, H. Aoki, *Phys. Rev. B* **79**, 081406(R) (2009).
25. H.L. Calvo, H.M. Pastawski, S. Roche, L.E.F. Foa Torres, *Appl. Phys. Lett.* **98**, 232103 (2011).
26. D.S.L. Abergel, T. Chakraborty, *Nanotechnology* **22**, 015203 (2011).
27. Z. Gu, H.A. Fertig, D.P. Arovas, A. Auerbach, *Phys. Rev. Lett.* **107**, 216601 (2011).
28. M. Busl, G. Platero, A.-P. Jauho, *Phys. Rev. B* **85**, 155449 (2012).
29. S.V. Kryuchkov, E.I. Kukhar', D.V. Zav'yalov, *Laser Phys.* **23**, 065902 (2013).
30. S.V. Kryuchkov, E.I. Kukhar', O.S. Nikitina, *J. Nano-Elect. Phys.* **5**, 03005 (2013).
31. S.V. Syzranov, Ya.I. Rodionov, K.I. Kugel, F. Nori, *Phys. Rev. B* **88**, 241112 (2013).
32. S.V. Kryuchkov, E.I. Kukhar', O.S. Nikitina, *Superlattice. Microst.* **60**, 524 (2013).
33. S.V. Kryuchkov, E.I. Kukhar', O.S. Nikitina, *Phys. Wave Phenomena* **22**, 25 (2014).
34. S.V. Kryuchkov, E.I. Kukhar', *Superlattice. Microst.* **70**, 70 (2014).
35. S.V. Kryuchkov, E.I. Kukhar', *Physica B* **445**, 93 (2014).