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The Appearance of Transverse Current in the Graphene Superlattice under the Influence of Elliptically Polarized Wave

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It is explored the direct current which appears in superlattice on the base of graphene in transverse direction to the axis of this structure under the condition of constant electric field and elliptically polarized electromagnetic wave normally incident in the surface of the sample. The current dependence on constant electric field intensity has some peculiarities which has a nature closed to Stark resonance. The effect of direct current appearance is connected with energy spectrum non-additivity of graphene superlattice.

Keywords: Graphene superlattice, Transverse rectification, Stark Resonanse.

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1. INTRODUCTION

Graphene was experimentally obtained for the first time in 2004 [1] and now it is one of the most studied material in microelectronics. Recent time the researchers' attention is concerned in the study of superlattices on the base of this material (see [2] and cited literature). In [2] the model superlattice on the base of graphene placed on the substrate, consisted of periodically interchanged strips of different dielectrics, is presented. It is well-known that the forbidden zone in the graphene energy spectrum may be opened because of interaction of the graphene and the substrate. In the spectrum of graphene on silicon carbide substrate there is an energy gap about $2\Delta \approx 0.26eV$ [3]. But graphene, placed on the silicon dioxide template hasn't the band gap in its energy spectrum [1, 4]. The alternation of strips of gap and gapless modification of this material creates a set of potential barriers for charge carriers. This structure, on our opinion, is the most reasonable and simple model of the superlattice on the base of graphene. Investigation of electronic properties of superlattice on the base of graphene is interesting because of the possibility of new nonlinear effects appearance connected with the presence of additional periodical potential. Furthermore, the energy spectrum of graphene is non-additive [1, 4], which leads to mutual dependence of motions of charge carriers in transversal each other directions, so it is arising an additional ability to govern the current along the superlattice axis by transverse voltage in electronic devices. The mean free path of graphene charge carriers is much more than one in majority of bulk semiconductors [1], that's why the sizes of electronic devices can be increased which may simplify their fabrication.

2. PROBLEM STATEMENT

2.1 Model expression for energy spectrum of superlattice on the base of graphene.

In [2] the dispersion relation for superlattice on the base of graphene was obtained. By numerical solving of this relation one may obtain the dependence of energy on quasimomentum for each of miniband in which the energy spectrum is divided because of the influence of periodical potential. As it is followed from immediate calculations, in sufficiently great range of parameter values the miniband energy of electron is well-described by next expression:

$$\varepsilon(\mathbf{p}) = \Delta\left(f_1 + \sqrt{f_2^2 + f_3^2 q_y^2} + \frac{f_4(1-\cos q_x)}{\sqrt{f_2^2 + f_3^2 q_y^2}} \right). \qquad (1)$$

Here Δ is the forbidden band half-width of gap graphene modification, $q_{x,y} = p_{x,y}d/\hbar$ - components of dimensionless quasimomentum, d is superlattice period, and coefficients f_i are fitted numerically. In the case of parity of widths of the well and the barrier, at the absence of additional potential induced by mismatch of the middle of forbidden band of gap graphene modification and contact point of bands in gapless modification, in condition $B = (\hbar v_F)/(\Delta d) = 0.25$ (which is correspond to maximal width of bandgaps) the values of adjustable parameters are:

$$f_1 = -0.027,\ f_2 = 0.451,\ f_3 = 0.255,\ f_4 = 0.048\,. \qquad (2)$$

Spectrum in a form (1) describes the crucial peculiarities of superlattice on the base of graphene: in one hand, as it should be, it is periodical on the quasimomentum component p_x, and, in other hand, it is non-additive. The relative error which arises because of a change of energy values, derived from numerical solution of dispersion relation, by values, calculated according (1), is not more than 2 per cent. In Fig. 1 the graphics of energy dependence on quasimomentum components in first two minibands are presented.

The width of forbidden band between first and second miniband $\varepsilon_{1,2}^{g}$ is approximately equal 0.6Δ, width of first miniband $\Delta_1 \approx 0.2\Delta$, energy gap between the lowest electron miniband and highest hall miniband is $\varepsilon_{1,2}^{g} \approx 0.85\Delta$.

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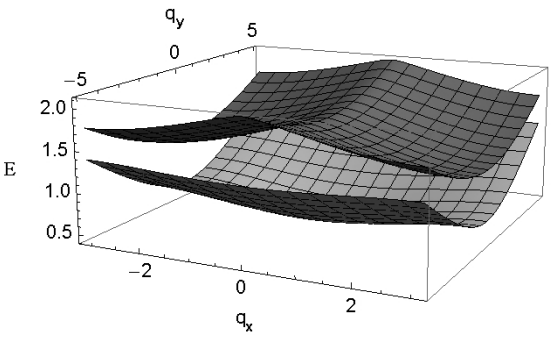

Fig. 1 – Graphics of charge carriers energy in graphene superlattice

2.2 Effect of transverse current generation

The energy spectrum non-additivity is the cause of mutual dependence of charge carrier motions on orthogonal directions which may lead to arising of so-called transverse rectification effects [5-7]. In [5] it was investigated the effect of appearance of the direct current component in direction perpendicular to the axis superlattice on the base of graphene under the influence of two normally incident in the surface of the sample electromagnetic waves with frequency relation equal 2 and transverse polarizations. Another effect connected with non-additivity of material energy spectrum, is the induction of direct current in graphene placed in the field of elliptically polarized electromagnetic wave, in perpendicular direction to the constant electric field [6, 7]. Periodical potential should lead to new non-linear effects, so some interest has a investigation of the problem, posed in [6, 7], in graphene superlattice. Problem geometry is shown in Fig. 2.

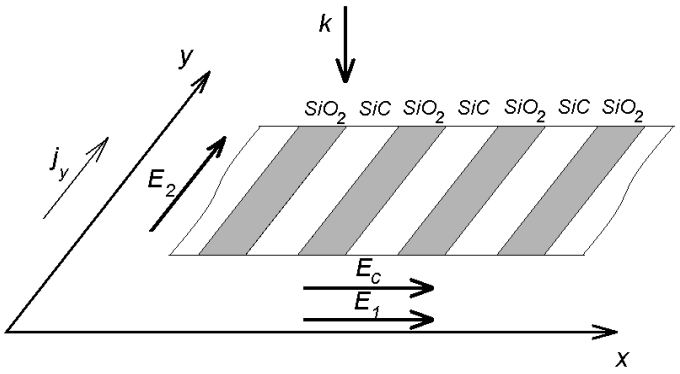

Fig. 2 – Problem geometry. E_c – constant electric field strength, $E_1 = E_{10}\cos(\omega t + \varphi)$ - strengths of electric field of elliptically polarized wave components

3. FINDING OF DIRECT CURRENT DENSITY

Let us derive a constant current component along the Y axis. Non-equilibrium distribution function $f(\mathbf{p}, t)$ satisfied to Boltzmann kinetic equation with collision term in a form of constant relaxation frequency:

$$\frac{\partial f(\mathbf{p},t)}{\partial t} + e\mathbf{E}\frac{\partial f(\mathbf{p},t)}{\partial \mathbf{p}} = -\nu\left(f(\mathbf{p},t) - f_0(\mathbf{p})\right), \qquad (3)$$

where $f_0(\mathbf{p})$ is equilibrium Boltzmann distribution function, $\mathbf{E} = \{E_c + E_1,\ E_2\}$ – result electric field strength vector. The solution of (3) takes a form

$$f(\mathbf{p},t) = \nu\int_{-\infty}^{t} dt' \exp\left(-\nu(t-t')\right) f_0\left(\mathbf{p}'(t';\mathbf{p},t)\right), \qquad (4)$$

here $\mathbf{p}'$ is a solution of semiclassical equation of motion $d\mathbf{p}'/dt = e\mathbf{E}(t')$ with initial condition: $\mathbf{p}' = \mathbf{p}$ at $t' = t$. Direct current density component along the Y axis is defined by:

$$j_y = \left\langle e\sum_{\mathbf{p}} \mathrm{v}_y f(\mathbf{p},t)\right\rangle_t, \qquad (5)$$

where $\langle\ \rangle_t$ means averaging in large in compare the periods of incident waves time interval, v_y is a component of charge carrier velocity along Oy axis. Finally one obtains:

$$j_y = en\frac{\Delta d}{\hbar} f_3^2 f_4 \frac{P_1}{P_0}\cos\varphi \cdot F_2 \cdot G_y(F_0, F_1, \gamma), \qquad (6)$$

where $\gamma = \nu/\omega$, $\mathrm{F}_0 = eE_c d/\hbar\omega$, $\mathrm{F}_{1,2} = eE_{10,20}d/\hbar\omega$, n - surface concentration of charge carriers,

$$P_0 = \int_{-\infty}^{\infty} dq_y I_0\left(\frac{\Delta}{T}\frac{f_4}{\sqrt{f_2^2 + f_3^2 q_y^2}}\right)\exp\left(-\frac{\Delta}{T}\frac{f_2^2 + f_3^2 q_y^2 + f_4}{\sqrt{f_2^2 + f_3^2 q_y^2}}\right)$$

$$P_1 = \int_{-\infty}^{\infty} dq_y \frac{2f_3^2 q_y^2 - f_2^2}{\left(f_2^2 + f_3^2 q_y^2\right)^{5/2}} I_1\left(\frac{\Delta}{T}\frac{f_4}{\sqrt{f_2^2 + f_3^2 q_y^2}}\right)\exp\left(-\frac{\Delta}{T}\frac{f_2^2 + f_3^2 q_y^2 + f_4}{\sqrt{f_2^2 + f_3^2 q_y^2}}\right)$$

$$G_y(F_0, F_1, \gamma) = \gamma F_0 \sum_{k=-\infty}^{\infty} J_k(F_1)\left(J_{k+1}(F_1) - J_{k-1}(F_1)\right)\frac{F_0^2 - k^2 + \gamma^2}{\left((F_0 - k)^2 + \gamma^2\right)\left((F_0 + k)^2 + \gamma^2\right)}$$

Graphics of dependence of j_y on dimensionless electric field strengths F_0, F_1 are shown in figure 3.

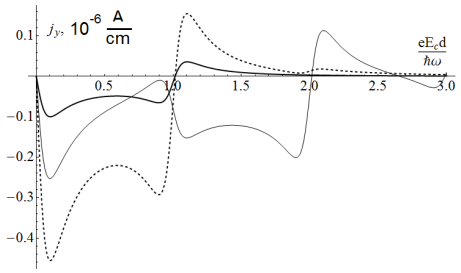

Fig. 3 – The dependence of transverse current density on the strength of constant electric field, directed along the superlattice axis. Thick line corresponds to $F_1 = 0.1$, dashed line – to $F_1 = 0.5$, thin line – to $F_1 = 2$ (graphics are plotted at $F_2 = 0.1$)

At temperature $T \sim 70\ K$, $\gamma \sim 0.1$, $\omega \sim 10^{12}\ c^{-1}$, $d \sim 10^{-6}$ cm, E_c, $E_1 \sim 1$SGS units, $E_2 \sim 0.1$ SGS units, $n \sim 10^{10}\ \text{cm}^{-2}$ a current density is about $j_y \sim 10^{-7}$ A/cm. Near the integer values of F_0 some peculiarities in transverse current take place. Their nature is similar to the nature of Stark resonance in quantum semiconductor superlattices [8]. But in considered problem a presence of resonant conditions for longitudional field leads to peculiarities in transverse current. Similar resonant singularities should be arisen in the axial current so. Really, let us to calculate a direct current density along the axis of graphene superlattice under the conditions of constant electric field E_c and high-frequency E_1 field:

$$j_x = j_0 f_4 P_2 / P_0 \cdot G_x(F_0, F_1, \gamma), \tag{7}$$

$$G_x(F_0, F_1, \gamma) = \gamma F_0 \sum_{k=-\infty}^{\infty} J_k^2(F_1) \frac{F_0^2 - k^2 + \gamma^2}{\left((F_0 - k)^2 + \gamma^2\right)\left((F_0 + k)^2 + \gamma^2\right)} \tag{8}$$

$$P_2 = \int_{-\infty}^{\infty} \frac{dq_y}{\sqrt{f_2^2 + f_3^2 q_y^2}} I_1\left(\frac{\Delta}{T}\frac{f_4}{\sqrt{f_2^2 + f_3^2 q_y^2}}\right) \exp\left(-\frac{\Delta}{T}\frac{f_2^2 + f_3^2 q_y^2 + f_4}{\sqrt{f_2^2 + f_3^2 q_y^2}}\right)$$

From (6) and (7) one can see that behavior of functions G_x and G_y is similar near integer values of F_0, corresponded to values of Stark frequency $\Omega_{St} = eE_c d/\hbar$ which is multiple to the frequency of incident wave: $\Omega_{St} = k\omega$, $k = 1, 2, 3$. Because of non-additivity of energy spectrum of graphene superlattice electrons are in some complicated motion under the influence of applied fields, so in conditions related to Stark resonance a transverse current has a unvarying character. At $F_1 = 0$ in a sum (8) only one term remains ($k = 0$):

$$G_x(F_0, 0, \gamma) = \frac{\gamma F_0}{F_0^2 + \gamma^2} = \frac{\nu \Omega_{St}}{\nu^2 + \Omega_{St}^2} \tag{9}$$

The dependence of direct current density along the superlattice axis on the strength of constant electric field is analogous of the same in semiconductor superlattice [8]. Since the collision frequency in graphene is much less than that in semiconductor superlatticies ($\nu \sim 10^{10} - 10^{11}\ \text{s}^{-1}$ [1, 4] in graphene and $\nu \sim 10^{12}\ \text{s}^{-1}$ in a semiconductor superlattice), in graphene superlatticies negative differential conductivity and other non-smoothnesses in behavior of electric current should be appeared in much less magnitudes of electric field strengths.

4. CONCLUSIONS

Model expression (1) for energy spectrum of superlattice on the base of graphene allows one to investigate of electronic properties of same structures almost analytically. The dependence of miniband width of superlattice, created along one direction, on the value of the quasi-momentum in transverse direction takes in account energy spectrum non-additivity of this structure. The non-additivity of energy spectrum of superlattice on the base of graphene leads to mutual dependence of charge carrier motions in perpendicular each other directions. This dependence is, particulary, the cause of arising in this structure the effect of current rectification in direction perpendicular to constant electric field under the influence of elliptically polarized electromagnetic wave, incident in the plane of the sample.

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