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Photocurrent in a two-dimensional ribbon with the conic electron spectrum

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The strips of graphene or 2D HgTe with the conic electron spectrum illuminated by interband radiation are studied in the assumption of classical carriers motion. Linearly polarized radiation produces optical orientation of electron momenta. The asymmetry of edges together with the radiation polarization leads to electric current along the strip. The cases of narrow and wide strip with respect to the mean free path are considered. Besides, the edge photocurrent is investigated in a wide strip, one of edge of which is illuminated. We show that interelectron collisions play an important role by violating $e-h$ symmetry that provides the overall current.

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Introduction. Besides the bulk photogalvanic effects (PGE), caused by the intrinsic material asymmetry there exists a group of effects originated from the surface asymmetry, namely the film and the surface PGE. They appear due to even asymmetry of excitation by polarized light together with film surfaces nonequivalence. The last may originate from the difference of surface scattering [1, 2], or the difference of light intensity caused by local light absorption in a film [3–5].

The specificity of graphene is a conic spectrum with near-ideal rotational symmetry. In that case electrons excited by monochromatic light have the same energy. This leads to the amplification of the photon drag effect converting it to the resonance effect [6]. Graphene has the inversion center; hence, the overall photogalvanic effect vanishes, while the currents in individual valleys exist if one takes into account the trigonal warping corrections [7]. This warping manifests itself in the valley currents via a very unusual character of electron-electron collisions, existing only for collinear motion of impacting and scattered particles and in some $\pi/3$-sectors of the electron momentum space [7].

The purpose of the present paper is the theoretical study of the optical orientation of electron momentum in graphene and resulting currents in a graphene ribbon. The conic 2D spectrum is also realized in the CdTe/HgTe/CdTe system with critical 6.3 nm width of HgTe layer [8–13]. Unlike graphene, it has the only conic point. All results of this paper is applicable to this system, too. The consideration is based on the classical kinetic equation approach taking into account electron-impurities and electron-electron collisions.

The τ-approximation. We shall consider a graphene ribbon $|y| < d/2$ in (x, y) plane illuminated by linearly-polarized light with in-plane electric field $\mathbf{E}_0 \cos(\omega t)$. The polarization of light is tilted towards the x-axis. Edges $\pm d/2$ have different electron specularities $P_\pm$.

Starting from the graphene Hamiltonian in the conic approximation

$$H = v_0 \begin{pmatrix} 0 & \pi_- \\ \pi_+ & 0 \end{pmatrix}, \tag{1}$$

$$\pi_\pm = p_x \pm i p_y - e[A_x(t) \pm i A_y(t)]/c, \tag{2}$$

where v_0 is the electron velocity, e is the electron charge, $\mathbf{p}$ is the 2D momentum, $\mathbf{A}(t)$ is the vector-potential of electromagnetic field, c is the light velocity, we obtain the optical interband transition probability

$$g = g_0 \sin^2(\alpha - \beta);$$
$$g_0 = \frac{4\pi^2 e^2 v_0^2 I t_0^2}{\omega^2 c} \theta(\omega - 2\varepsilon_\mathrm{F}) \delta(\omega - 2v_0 p), \tag{3}$$

where $I = cE_0^2/8\pi$ is the electromagnetic field intensity, $t_0 = 2/(n+1)$, n is the substrate refractive index, α and β are the polar angles of $\mathbf{E}_0$ and electron momentum $\mathbf{p}$ (angles are counted from axis x).

In accordance with Eq. (3) the excitation probability essentially depends on the angle $\alpha - \beta$ between the momentum and the polarization. This dependence is even and does not produce the current (see Fig. 1). The ex-

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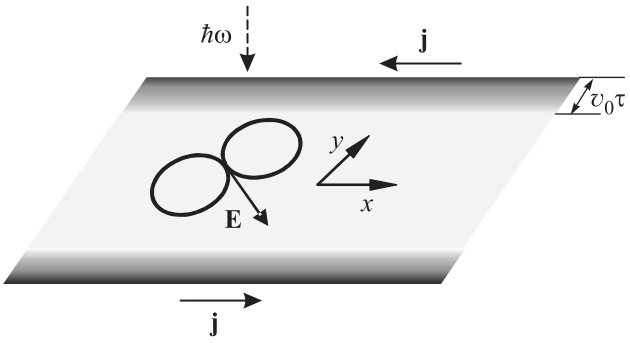

Fig. 1. Sketch of the effect. The graphene ribbon is illuminated by light with the polarization tilted towards the ribbon edges. The excitation directional diagram (tilted symbol "8") has maxima orthogonal to the light polarization. Electrons moving towards the edge are scattered, while electrons with the opposite direction are not and they move over a longer distance. This gives rise to the residual current, if the edge specularities differ. The photocurrent is concentrated near edges within the strips of width $v_0\tau$

citation maxima in Fig. 1 correspond to $v_x > 0$, $v_y > 0$ and $v_x < 0$, $v_y < 0$. However, interaction with nonequivalent edges leads to non-equal electron relaxation for these maxima. This results in the appearance of the overall current in x-direction.

We utilize the classical kinetic equation for the distribution functions f_ν of electrons ($\nu = 1$) and holes ($\nu = -1$)

$$v_y \partial_y f_\nu + \frac{\phi_\nu}{\tau_\nu} = g(\mathbf{p}). \tag{4}$$

Here $\phi_\nu = f_\nu - \langle f_\nu \rangle$, $\langle f_\nu \rangle$ is the angular average.

It is evident, that isotropic generation does not give any x-current. The term $\propto \langle f \rangle$ can be treated in this equation as isotropic generation; hence, we can omit this term and arrive at

$$v_0 \sin\beta \; \partial_y \phi + \frac{\phi}{\tau} = g(\beta, p). \tag{5}$$

Here and below the subscript ν is omitted, for short. We will search the solution of Eq. (5) with boundary conditions $\phi(\pm\beta) = P_\mp \phi(\mp\beta)$ at $y = \mp d/2$, $0 < \beta < \pi$, where $P_\pm$ are reflectivity coefficients of edges $y = \pm d/2$. The solution of Eq. (5) is

$$\phi(y, \beta) = \tau g(\beta) + C(\beta) e^{-y/(l \sin\beta)}, \tag{6}$$

where $l = v_0\tau$.

Using the boundary conditions, we find for function $C(\beta)$:

$$C(\pm\beta) = \\ = \tau e^{-u/(2l\sin\beta)} \Big\{ g(\mp\beta) P_\mp - g(\pm\beta) + e^{-u/\sin\beta} \times \\ \times [g(\pm\beta) P_\pm - g(\mp\beta)] P_\mp \Big\} \Big(1 - P e^{-2u/\sin\beta} \Big)^{-1}, \\ 0 < \beta < \pi. \tag{7}$$

Here $u = d/l$, τ is the relaxation time at the energy equal to $\omega/2$, $P = P_+ P_-$.

The current x-component is found with the use of (7):

$$j_x = e\mu \frac{v_0^2 I \eta t_0^2}{2\pi\omega} \sum_\nu \nu\tau^2 (P_+ - P_-) \sin(2\alpha) F(u, P),$$

$$F(u, P) = \int_0^{\pi/2} \sin^2(2\beta) \frac{e^{u/\sin\beta} + e^{-u/\sin\beta} - 2}{e^{u/\sin\beta} - P e^{-u/\sin\beta}} d\beta. \tag{8}$$

Here μ is the number of valleys ($\mu = 2$ for graphene and $\mu = 1$ for critical HgTe). The sum runs electrons and holes, numerated by $\nu = \pm 1$, respectively; we mean that parameters τ and $P_\pm$ depend on the carriers type. Function $F(u, P)$ has asymptotics

$$F(u, P) \approx \pi/4 \;\; \text{at } u \to \infty,$$

$$F(u, P) \approx 4u/3 \;\; \text{at } u \to 0, \;\; P \to 1, \;\; u \gg 1 - P, \tag{9}$$

$$F(u, P) \approx \pi u^2/(1 - P) - 4u^3 \ln(1/u) \frac{1 + P}{(1 - P)^2}$$

$$\text{at } u \to 0, \;\; u \ll 1 - P. \tag{10}$$

We kept the second term in the last formula because the first one can cancel due to $e-h$ symmetry.

Dependence $F(u, P)$ on the parameter u for different P is demonstrated in Fig. 2. In almost all the range

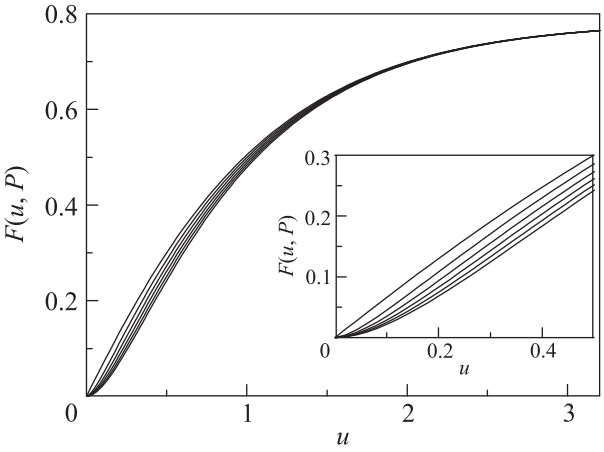

Fig. 2. Function $F(u, P)$ at $P = 0, 0.2, 0.4, 0.6, 0.8, 1$ (upward)

of u except for small values of u curves fuse together.

The current changes the sign with the sign of $P_+ - P_-$ and the turn of polarization $\alpha \to \pi/2 - \alpha$. Besides,

the current disappears for non-polarized or circular-polarized light. In a symmetric ribbon, when $P_+ = P_-$, the photocurrent vanishes. Another reason for the current vanishing is e–h symmetry manifesting itself in equality of the electron and hole relaxation times and the reflectivities.

In fact, in the conic approximation electrons and holes have the same initial energies $\omega/2$. Hence, their scattering rates on the pure Coulomb impurity potential are equal. Also, the scattering rate does not depend on the carrier sign in the Born approximation. So, the difference of electron and hole relaxation times needs an account for the non-Born corrections to the Coulomb scattering due to the core impurity potential. Unless these fine factors are taken into account, the impurity scattering rate does not depend on the carrier sign.

It should be emphasized that abovementioned arguments are valid in the conic approximation, when carriers energies are small as compared with the bandwidths. These arguments fail in a system far from the neutrality point where e–e scattering leads to different relaxation of electrons.

An additional factor that could lead to the e–h asymmetry is the difference of electron and hole reflectivities. Quantities $P_\pm$ are formed by the graphene border structure. However, if the border is considered as a geometrical object on which the envelope wave function satisfies some boundary condition, the symmetry of these conditions for electrons and holes is dictated by the Schrödinger equation itself. This leads to the charge symmetry of the kinetic equation boundary conditions.

The microscopic boundary conditions can result in the appearance of electron edge states [14] with no charge symmetry, see Fig. 3. They exist in conduction or valence bands, but not in both simultaneously.

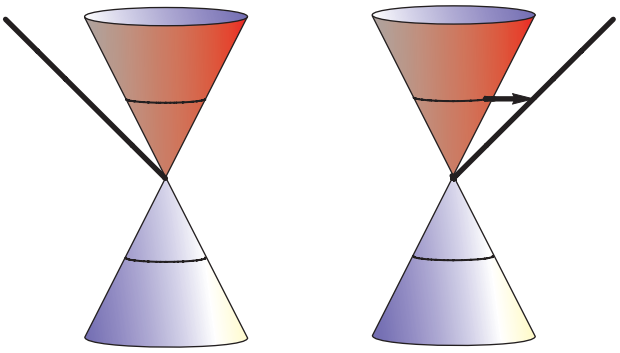

Fig. 3. (Color online) The 2D graphene spectrum (cones) with edge states (thick lines). Elastic scattering of 2D electrons (indicated by arrow) decreases their reflectivity due to transitions to the edge states

The elastic scattering of 2D electrons on such edges leads to the exchange of electrons between 2D states and edge states. The kinetic equation should be supplemented by the connected equation describing the edge electrons. However, when the edge electron relaxation is strong enough, the edge electrons can be treated as immobile and the transitions of 2D electrons to the edge states will decrease the reflectivity. The presence of the edge states, for one type of carriers only, will essentially decrease the reflectivity for these carriers. That gives rise to the needed e–h asymmetry of the reflectivity. We leave the accurate consideration of this question to the future publications.

Case $u \gg 1$ corresponds to a wide ribbon. In this case the edges have independent currents which add together to the total current. If only one edge is illuminated the current exists only on this edge. Besides, it is possible to contact only one edge. In this case we have the edge current (near $y = d/2$)

$$(j_x)_{\rm edge} = e\mu \frac{v_0^2 I \eta t_0^2}{8\omega} \sum_\nu \nu\tau^2 (P_+ - 1)\sin(2\alpha). \qquad (11)$$

Let us estimate the edge current in, to be certain, n-type graphene. If electrons are excited near the Fermi level, their mean free time can be treated as that of thermal electrons, while the hole mean free time is much shorter. Hence, we can neglect the hole contribution. At $E = 1\,\mathrm{V/cm}$, $v_0 = 10^8\,\mathrm{cm/s}$, $\tau = 10^{-10}\,\mathrm{s}$, $t_0 = 1$ (free suspended graphene), $\hbar\omega \approx 2\varepsilon_{\rm F} = 0.1\,\mathrm{eV}$, and absolutely diffusive edge ($P_+ = 0$) we have $(j_x)_{\rm edge} = 8\,\mathrm{pA}$. This value seems quite measurable.

A more accurate approach that requires consideration of e–e scattering see below.

The role of interelectron scattering. The other factors affecting the e–h asymmetry are interelectron and electron-phonon scattering. These kinds of scattering essentially depend on the distance of the non-equilibrium particle energy to the Fermi energy. If graphene is not in the neutrality point, just after excitation, electron and hole have different distances between their energies and the Fermi level of $|\omega/2 \mp \varepsilon_{\rm F}|$ for $\varepsilon_{\rm F} \neq 0$.

The account for e–e scattering includes the consideration of the momentum redistribution within the electronic subsystem. Strictly speaking, this means that the τ-approximation fails and one should solve the integral kinetic equation.

For large excitation energy in clean samples the e–e scattering becomes a prevailing relaxation process. In unlimited graphene, e–e scattering controls the second angular harmonic of the distribution function and does not affect the first angular harmonic which determines

the current. What occurs in the ribbon? If the excitation energy is large the $e-e$ scattering rapidly suppresses the second angular harmonic in $g(\mathbf{p})$ before carriers reach the edge and contribute to the current after the edge scattering. Thus, if both electrons and holes are excited far from the Fermi energy, the current strongly drops.

But the situation changes when $|\omega-2|\varepsilon_{\rm F}|| \ll |\varepsilon_{\rm F}|$. In this case one quasiparticle is excited far from the Fermi level and the other near the Fermi level. The current is contributed by excitations in the vicinity of the Fermi energy (at zero temperature electrons over the Fermi level in n-type and holes below the Fermi level in p-type). As a result, the sign of current is determined by the main carriers.

The $e-e$ scattering is unusual in graphene. Near the neutrality point due to linear spectrum the $e-e$ scattering is strongly conditioned by the presence of trigonal warping and the interaction corrections to the spectrum [7]. However, this is the case in the neutrality point or when the excitation energy is essentially larger than the Fermi energy. To be more precise, the kinematic analysis shows that this occurs when $\omega > 4|\varepsilon_{\rm F}|$.

The estimation for the $e-e$ induced second harmonic relaxation time in unconfined graphene yields

$$1/\tau_2 \sim \frac{e^4}{\kappa^2 v_0^2}\varepsilon_{\rm F}\frac{|\epsilon-\varepsilon_{\rm F}|^2}{\varepsilon_{\rm F}^2}.$$

Here ϵ is the quasiparticle energy.

Let us estimate the current in the presence of $e-e$ scattering. In unconfined graphene the second angular harmonic of the distribution function is $f_2 = -\tau_2 g_0 \cos[2(\alpha-\beta)]/2$. The nonequilibrium (over angles) electrons come to the edge and scatter, loosing the tangential momentum, and, as a result, produce a tangential force applied to a unit length of the total electron subsystem

$$\mathcal{F} = -(1-P_+)\frac{\mu}{\pi^2}\int_{p_{\rm F}}^{\infty} pdp \int_0^{\pi} d\beta (p\cos\beta)(v_0\sin\beta) f_2.$$

If electrons move without acceleration this force is compensated by a friction force applied to all electrons $-(p_{\rm F}/v_0)unS/\tau_i$, where S is the system area, u is the mean x-component of the electron velocity, n is the electron concentration. With the use of equation $(j_x)_{\rm edge} = enud$ we have

$$(j_x)_{\rm edge} = e\frac{\mu v_0^2 I\eta t_0^2}{8\omega}\tau_i\tau_2(P_+-1)\sin(2\alpha). \qquad (12)$$

Eq. (12) is similar to Eq. (11) with replacement $\tau^2 \to \tau_2\tau_i$, where τ_2 is taken at the initial electron energy and τ_i is the impurity transport relaxation time taken for cold electrons. In accordance with Eq. (12), the current is large when $|\omega - 2\varepsilon_{\rm F}| \ll \varepsilon_{\rm F}$ and drops when $|\omega - 2\varepsilon_{\rm F}| \sim \varepsilon_{\rm F}$. If $\omega \to 2\varepsilon_{\rm F}$, the initial electron energy should be replaced by the temperature. This consideration is valid for n-type graphene; the p-type differs from the n-type by a reversed current sign.

Note that the current caused by phonon scattering has the similar behavior. The consideration of this mechanism goes beyond the scope of the present paper.

Conclusions. Thus, we have calculated the photoinduced current under interband transitions in the graphene ribbon. The photocurrent is connected with the light polarization and the non-equivalence of ribbon edges. The effect needs the $e-h$ asymmetry provided by the $e-e$ scattering in biased graphene. The photocurrent is large near the absorption threshold in biased graphene, changes its sign with the type of conductivity and disappears in the neutral point. Alternatively, the $e-h$ asymmetry can be caused by the elastic scattering into the edge states.

Unlike the photon drag [6], the considered here current does not need momentum transmission from the photons. Unlike the valley current [7], the current is total. Unlike the surface or film photocurrent [1–4], this current appears in a strict 2D system and under in-plane polarized light.

The edge photocurrent value has its essential dependence on different electron relaxation processes, and that gives the possibility to measure and separate them.

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