Anisotropic photoconductivity in graphene.
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We investigate the photoconductivity of graphene within the relaxation time approximation. In presence of the inter-band transitions induced by the linearly polarized light the photoconductivity turns out to be highly anisotropic due to the pseudospin selection rule for Dirac-like carriers. The effect can be observed in clean undoped graphene samples and be utilized for light polarization detection.

I. INTRODUCTION

Graphene membranes are optically transparent as well as highly conductive even at room temperatures. These two properties being incompatible with each other in conventional materials occur in carbon monolayers quite naturally and make them very promising for optoelectronic applications. There is, however, another unusual property of carriers in graphene which makes this material even more interesting for optoelectronics. The carriers in graphene display an additional degree of freedom which is often dubbed the pseudospin but, in fact, is connected to the sublattice index and has nothing to do with the real spin. We show, that the pseudospin manifests itself in the inter-band optical absorption making the transition probability sensitive to the pseudospin orientations in the initial and final states in a way similar to the real spin selective rules for the inter-band optical transitions in III-V semiconductors. Since the pseudospin is textured in the momentum space, as shown in Fig. 1 graphene’s photoconductivity turns out to be anisotropic in the case of the linearly polarized light. The effect seems to be strong enough to find some applications in graphene optoelectronics.

The model described below involves the optical excitation of the valence electrons to the conduction band of intrinsic (i.e. undoped) graphene. The idea is that the effective Hamiltonian describing the interaction between the electromagnetic wave and carriers in graphene inherits the pseudospin-momentum entangled structure from the low energy kinetic term derived within the tight-binding approach. Assuming normal incidence of a linear polarized electromagnetic wave one deduces an electron generation rate which strongly depends on the relative orientation between the electron momentum and the linear polarization plane, see Fig. 1. As consequence, the photoconductivity is predicted to be anisotropic resulting in a high on/off ratio as a function of the linear polarization angle. We note that the photoconductivity in graphene has been also theoretically investigated in recent works, not analyzing its anisotropy. Moreover, the photoconductivity studied in this work should not be confused with the photocurrents recently measured in graphene. The photocurrent can be generated without bias voltage applied, whereas the bias is necessary for the photoconductivity measurements.

II. PRELIMINARIES

The two-band effective Hamiltonian for $\pi$-system of graphene near half filling is $H_0 = \hbar v_F (\sigma_x k_x + \sigma_y k_y)$, where $v_F \approx 10^6 \text{ms}^{-1}$, $k$ is the electron momentum, and $\sigma_x, \sigma_y$ are the Pauli matrices. The Pauli operator $\sigma$ rep-
The energy spectrum of the charge carriers is described by the Hamiltonian
\[ H_0 = \frac{e v_F}{c} \begin{pmatrix} 1 & A \cr A_x + i A_y & 0 \end{pmatrix}, \]
and resembles the pseudospin structure. Assuming the initial state is the equilibrium one described by the Fermi-Dirac distribution function \( f_{\pm k}^{(0)} \). There is no electrical current in the steady state described by the distribution function \( f_{\pm k}^{(0)} \).

The momentum relaxation is assumed to be due to the elastic scattering of carriers on impurities. The average momentum \( \hbar \Delta k \) which the electrons gain due to the external electric field \( E \) can be estimated as \( \hbar \Delta k = e E \tau_e \), where \( \tau_e \) is the elastic momentum relaxation time. For small electric field (linear response) the non-equilibrium term \( f_{\pm k}^{(2)} \) can be obtained by expanding the steady-state function \( f_{\pm k}^{(1)} \) with respect to small \( \Delta k \) in up to linear order in \( E \). Recalling \( \hbar = -\partial_{\Delta k} E_\pm (k - \Delta k) |_{\Delta k = 0} \), the non-equilibrium distribution function for photo-excited electrons \( f_{\pm k}^{(2)} \) can be written as
\[
 f_{\pm k}^{(2)} = -e E \tau_e \frac{\partial f_{\pm k}^{(1)}}{\partial E_\pm} \quad \text{and} \quad \vec{v} = v_F \left( \frac{\cos \theta}{\sin \theta} \right).
\]
First of all, the chemical potential $\mu$ in graphene should be smaller than one-half of the excitation energy $\hbar \omega / 2$ enabling direct excitations from the valence band. Assuming THz radiation, as used in the work by Karch et al., we arrive at the maximum $\mu$ less than 10 meV. Thus, the unintentional doping in graphene samples used before should be reduced by almost of two orders of magnitude.

The temperature can also affect the effect even if the sample is perfectly neutral by reducing the photoconductivity by a factor of the order of $\hbar \omega / 2T$ at zero chemical potential. Thus, room temperature $T = 25$ meV seems to be somewhat too high for observing a sufficient signal at a radiation frequency of 1 THz. Moreover, the relaxation times $\tau_c$ and $\tau_i$ assumed to be constant so far, will in fact also be temperature-dependent. However, one can facilitate the measurement by increasing the overall multiplier proportional to the radiation power, possibly by means of a high power pulsed NH$_3$ laser.

In contrast to the photocurrents due to photon drag, the above effect is due to the pseudospin-selective inter-band transitions. The momentum transfer from photons to carriers is not important, and the effect should be observable even at normal incidence of light. The predicted anisotropy is strongest for linearly polarized light source, whereas for circular polarization the transition probability does not depend on the direction of carrier motion, and the photoconductivity anisotropy does not occur. An elliptically polarized light source interpolates between these extreme cases. Moreover, the vanishing anisotropy in the case of circular polarization can be used to separate the effect in question from the other photocurrent contributions.

As already stated, the eigenvalues of the photoconductivity tensor are predicted to differ by a factor of 3 in order to estimate the overall magnitude of the photocurrent contributions. The latter can be estimated as $n_{ph} = n_i/(L^2 \tau_{ph})$ where $\tau_{ph}$ relates to the total photoexcitation rate as $1/\tau_{ph} = \int 2 \pi d^2k l^2 I_{ph}$. On the other hand $\hbar \omega/\tau_{ph}$ can also be seen as the radiation energy absorption rate which is nothing else than the absorbed radiation power $W_a$. Note, that $W_a$ relates to the incident radiation power $W_i$ as $W_a/W_i = 0.023$ for a single layer graphene membrane.

To be specific we assume that the photoconductivity is generated by a CH$_3$OH laser with wavelength 118 μm (i.e. $\hbar \omega = 10.5$ meV) and $W_i \sim 20$ mW, and the sample itself is a suspended graphene membrane of the macroscopic size larger than the laser spot diameter of about 1 mm. Assuming $\tau_i \sim 1$ ps we arrive at $n_{ph} \sim 2 \times 10^7$ cm$^{-2}$ for $L^2 \sim 1$ mm$^2$. This values are comparable to the residual carrier concentration for suspended samples, thus, the conductivity change in the irradiated graphene should be observable.

The effect proposed above relies on the pseudospin texture shown in Fig. 1. This texture remains stable as long as the low energy one-particle Hamiltonian $H_0$ holds. At least from a theoretical point of view, the pseudospin texture can be altered by electron-electron interactions which may be important in extremely clean samples. This is the only fundamental obstacle for the photoconductivity anisotropy observation which we can see so far.

To conclude, we predict strong anisotropy of the photoconductivity in graphene is presence of the linearly polarized light. To observe the effect, we suggest to use undoped suspended graphene samples which allow the laser beam to excite the substantial number of photocarriers from the valence band. The cleaner samples are expected to demonstrate the better results. They can be used as transparent detectors for the polarization of the light passing through.

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