Optical spin current injection in graphene

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Charge and spin current injection by optical methods is investigated in single-layer and bilayer graphene within the tight-binding model, including bias and interlayer coupling effects. Two-photon absorption in graphene presents a strong linear-circular dichroism that is frequency-independent as calculated from the Dirac Hamiltonian. This unusual nonlinear response is exploited in coherent two-color injection and control setups, resulting in a current response that is maximal for co-circularly polarized beams and vanishes for opposite-circularly polarized beams [1]. Further, the magnitude of the injected current is independent of the angle between polarization axes for linearly-polarized beams. This does no longer hold when we consider bilayer graphene. Interlayer coupling in bilayer graphene has a distinct qualitative effect on the polarization dependence of charge and spin current injection. This has recently been observed in the charge current injection into epitaxially-grown multilayer graphene [2]. In combination with interlayer coupling, which induces trigonal warping of the electronic bands, the bias voltage allows to control the warping at the Fermi surface. The resulting implications for the spin current injection are presented.

The excitation scheme employs interference between two-photon absorption at ω and one-photon absorption at 2ω. The one- and two-photon transition amplitudes are given by

$$\Omega_{cv}^{(1)}(\omega,\vec{k}) = \frac{ie}{\hbar\omega}\vec{v}_{cv}(\vec{k})\cdot\vec{E}(\omega)\,, \tag{1}$$

$$\Omega_{cv}^{(2)}(\omega,\vec{k}) = \frac{2e^2}{\hbar^2\omega^2}\sum_m \frac{\vec{v}_{cm}(\vec{k})\cdot\vec{E}(\omega)\,\vec{v}_{mv}(\vec{k})\cdot\vec{E}(\omega)}{\omega_{mc}(\vec{k})+\omega_{mv}(\vec{k})}\,, \tag{2}$$

where $\vec{v}_{mn}(\vec{k})$ indicate matrix elements of the velocity operator, $\vec{E}(\omega)$ is the electric field, $\hbar\omega_m(\vec{k})$ is the energy of band m, and $[\omega_{mc}(\vec{k})+\omega_{mv}(\vec{k})]/2 = \omega_m(\vec{k})-[\omega_v(\vec{k})+\omega]$ is the usual energy denominator appearing in second-order perturbation theory. The reciprocal space, the linear energy-crystal momentum dispersion of graphene near K, and a diagram of the two-color excitation scheme are shown in Figure 1a. The band dispersion of bilayer graphene and the breakdown of the transition amplitudes for two-photon absorption into contributions of different symmetry are shown in Figure 1b. Current injection using linearly-polarized ω and 2ω light in an isotropic medium can be characterized by the ratio $d = \eta_I^{xyyx}/\eta_I^{xxxx}$, where η_I is the current injection tensor. For linearly-polarized ω and 2ω beams forming an angle θ between their polarization axes, different values of d lead to injected currents with different magnitudes but also with vastly dissimilar angular dependencies:

$$\dot{\vec{J}} = 2\Im\left[\eta_I^{xxxx}\right] E_\omega^2 E_{2\omega}\sin(\Delta\varphi)\left[f(\theta,d)\,\hat{\vec{e}}_{2\omega} + g(\theta,d)\,\hat{\vec{e}}_{2\omega}^{\perp}\right], \tag{3}$$

where $f(\theta,d) = \cos^2\theta + d\,\sin^2\theta$ and $g(\theta,d) = \frac{1}{2}(1-d)\,\sin 2\theta$. Thus, the current component that is parallel to $\hat{\vec{e}}_{2\omega}$, the polarization of the 2ω field, has a nonseparable dependence on θ and d, whereas the perpendicular component always follows $\sin 2\theta$. Polar plots of $f(\theta,d)$ and $g(\theta,d)$, the angular distributions of the orthogonal projections of $\dot{\vec{J}}$, are shown in Figure 1c for various values of the parallel-perpendicular disparity parameter d. The dependence on d leads to different angular dependencies of the current in single- and bilayer graphene.

References

[1] J. Rioux et al., PRB **83**, 195406 (2011)

[2] D. Sun et al., Nano Lett. **10**, 1293 (2010)

Figures

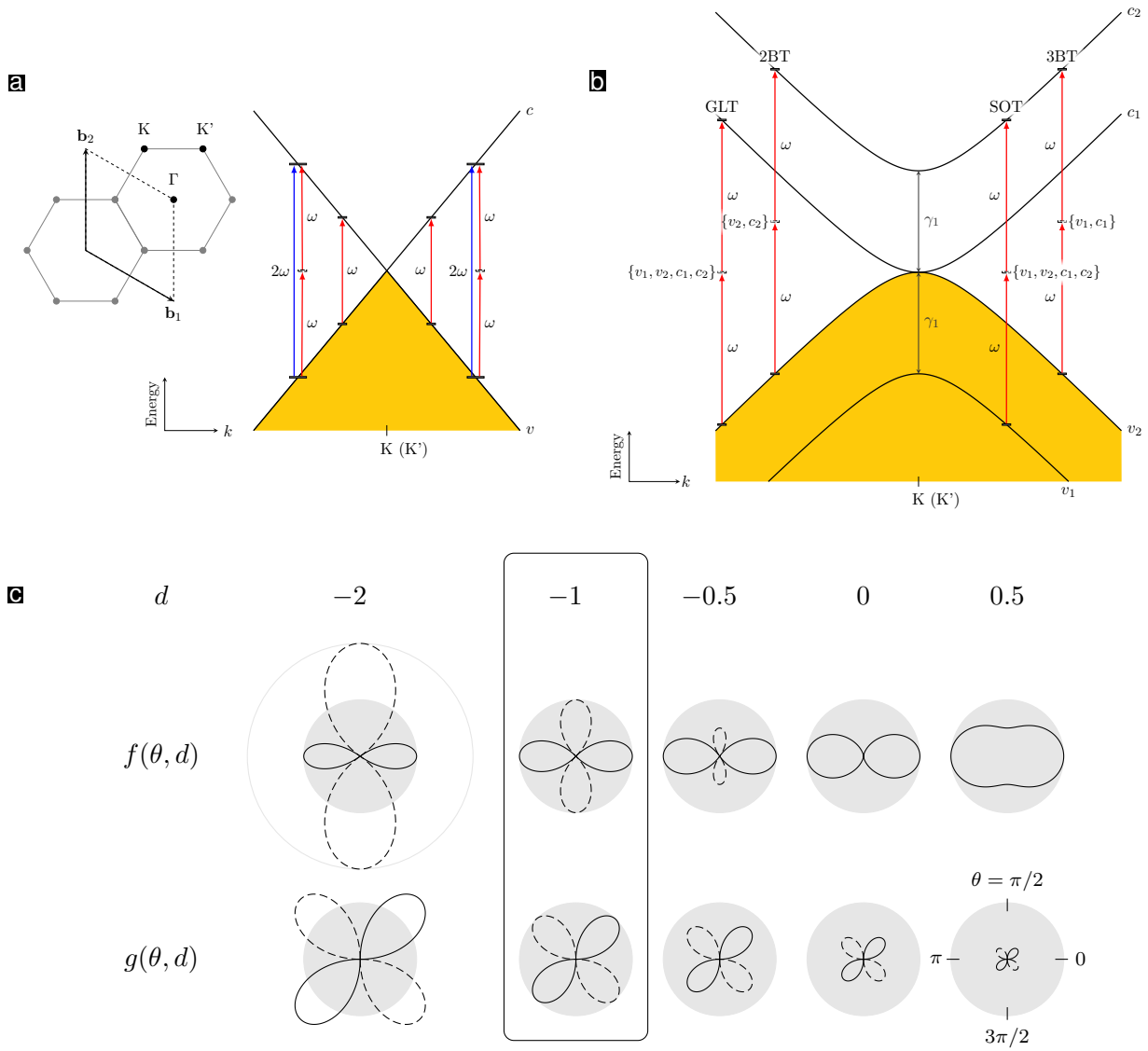

Figure 1: The excitation scheme employs interference between two-photon absorption at ω (red arrows) and one-photon absorption at 2ω (blue arrows), leading to generation of charge and current. **a** The reciprocal space and linear energy-crystal momentum dispersion of graphene near K. The basis vectors $\vec{b}_1$ and $\vec{b}_2$ form the reciprocal unit cell, enclosing one K and one K' valley. The dispersion shows the initially empty conduction band c and occupied valence band v touching at the K point. **b** The band dispersion of bilayer graphene and the breakdown of the transition amplitudes for two-photon absorption into contributions of different symmetry. Bands v_1 and v_2 are valence bands and initially filled, c_1 and c_2 are initially empty conduction bands. Bands v_2 and c_1 form a gapless doublet touching at the K point; c_2 and v_1 are split-off bands shifted by an energy γ_1 above and below the gapless doublet, respectively. All bands are quadratic near K and linear at larger k. Transition amplitudes appear in four variants: i) the gapless term (GLT) between bands v_2 and c_1, ii) two- and iii) three-band terms involving exactly one split-off band (2BT and 3BT, respectively), and iv) the split-off term (SOT) between bands v_1 and c_2. The notation $\{...\}$ next to a virtual state indicates that the sum in equation (2) is restricted to $m \in \{...\}$. Not shown are the 2BT and 3BT between bands v_1 and c_1. **c** Current injection using linearly-polarized ω and 2ω light in an isotropic medium. Polar plots of $f(\theta, d)$ and $g(\theta, d)$, the angular distributions of the projections of $\dot{\vec{J}}$ parallel and perpendicular to $\hat{\vec{e}}_{2\omega}$, as a function of the angle θ between the polarization vectors, for $d = -2$, -1, -0.5, 0, and 0.5. The shaded circles represent unit amplitude and dashed lines represent negative projections. The graphene prediction, $d = -1$, is highlighted.