Optical pure spin current injection in graphene

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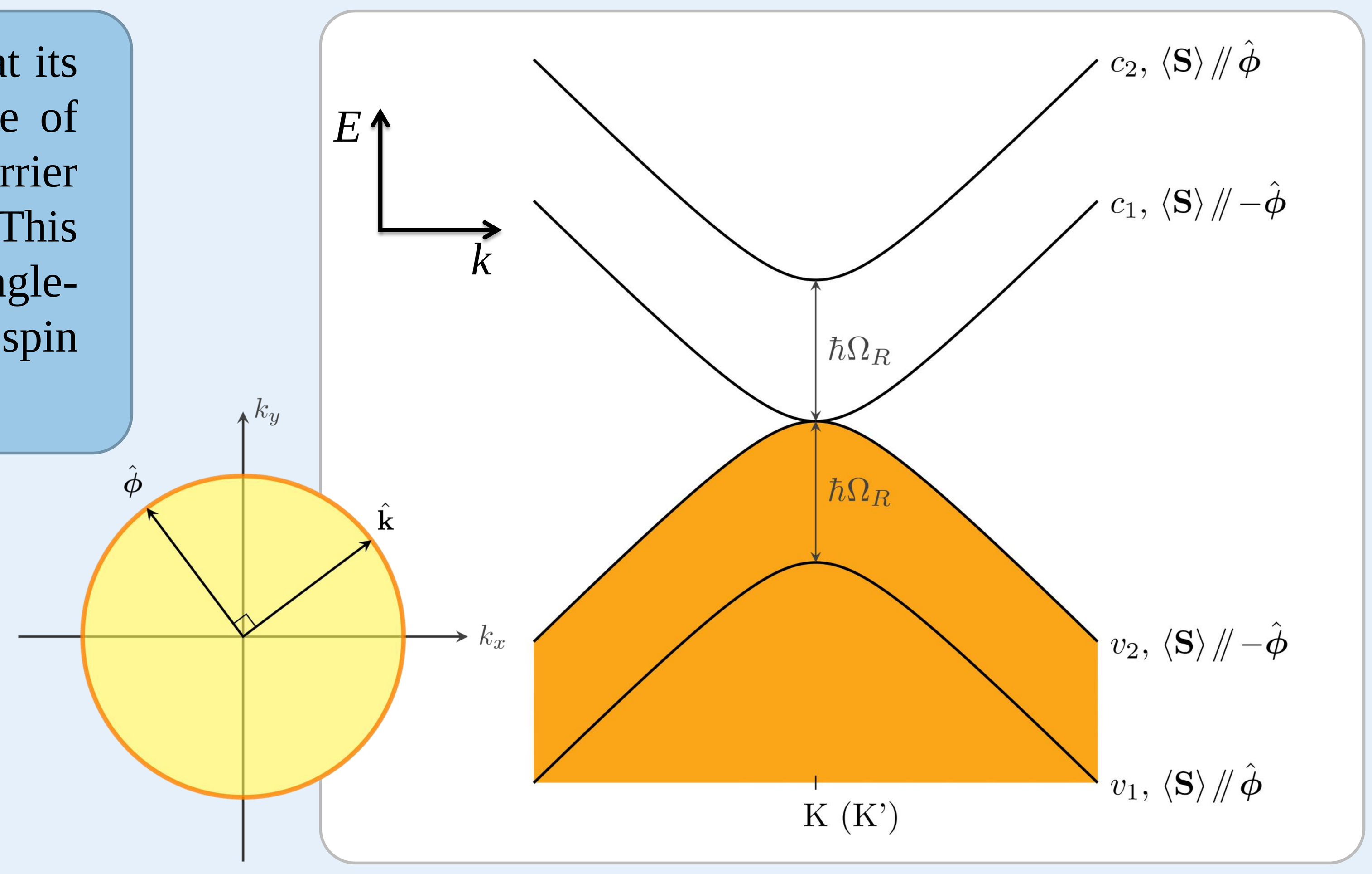
The unconventional optical properties of graphene were uncovered when it was discovered that its linear optical absorption coefficient approximates a fundamental constant over a wide range of frequencies (Nair 2008). Much earlier, Mele *et al.* have studied the coherent control of carrier distributions linearly-polarized light in graphene and carbon nanotubes (Mele 2000). This investigation is extended to charge and spin current injection using arbitrary polarizations in single-layer and bilayer graphene (Rioux 2011). With the additional Rashba spin-orbit coupling, pure spin current injection is possible using a single monochromatic beam.



Model

The tight-binding model of graphene is expanded in the usual way in the linear regime to yield the effective Hamiltonian

$$\mathcal{H}_1(\mathbf{K}^{(\prime)}+\mathbf{k}) \rightarrow \hbar v_F\,(\tau\sigma_x k_x + \sigma_y k_y)\,,$$

in the basis {A, B} of the triangular sublattices, where v_F is the Fermi velocity, $\boldsymbol{\sigma}$ are the Pauli matrices, and $\mathbf{k}$ is the in-plane crystal momentum in the plane of the crystal relative to the K point (τ = 1) or the K' point (τ = -1) (Geim 2007). For the bilayer, the Hamiltonian

$$\mathcal{H}_2(\mathbf{K}+\mathbf{k}) \rightarrow \begin{pmatrix} 0 & 0 & 0 & v_F\hbar k_- \\ 0 & 0 & v_F\hbar k_+ & 0 \\ 0 & v_F\hbar k_- & 0 & \gamma_1 \\ v_F\hbar k_+ & 0 & \gamma_1 & 0 \end{pmatrix}$$

is used, where γ_1 is the interlayer coupling strength. For the injection of spin-polarized currents the spin-orbit coupling must be taken into account. By breaking center-of-inversion symmetry we introduce an effective Rashba-Hamiltonian

$$\mathcal{H}_{S-O} \rightarrow \Omega_R\,(\tau\sigma_x S_y - \sigma_y S_x)\,,$$

where Ω_R is the Rashba frequency, $\boldsymbol{\sigma}$ acts on the basis {A, B} of the triangular sublattices, S is the electron spin, and $\tau = \pm 1$ determines the valley. The resulting energy dispersion relation for graphene has spin-split bands. In the two gapless bands, the electron spin is oriented (anti)parallel with $\hat{\phi} = \hat{\mathbf{z}} \times \hat{\mathbf{k}}$, while the electron spin is oriented opposite for the split-off bands. In all cases, the expectation value of spin has a magnitude

$$|\langle\mathbf{S}\rangle| = \frac{v_F\hbar k}{\sqrt{\Omega_R^2 + 4v_F^2 k^2}}\,.$$

Spin current injection: one-color

The excitation energy and the Fermi energy are chosen so that excitation occurs for one spin-split band but not the other. The coupling to the electromagnetic field is given by the velocity matrix element

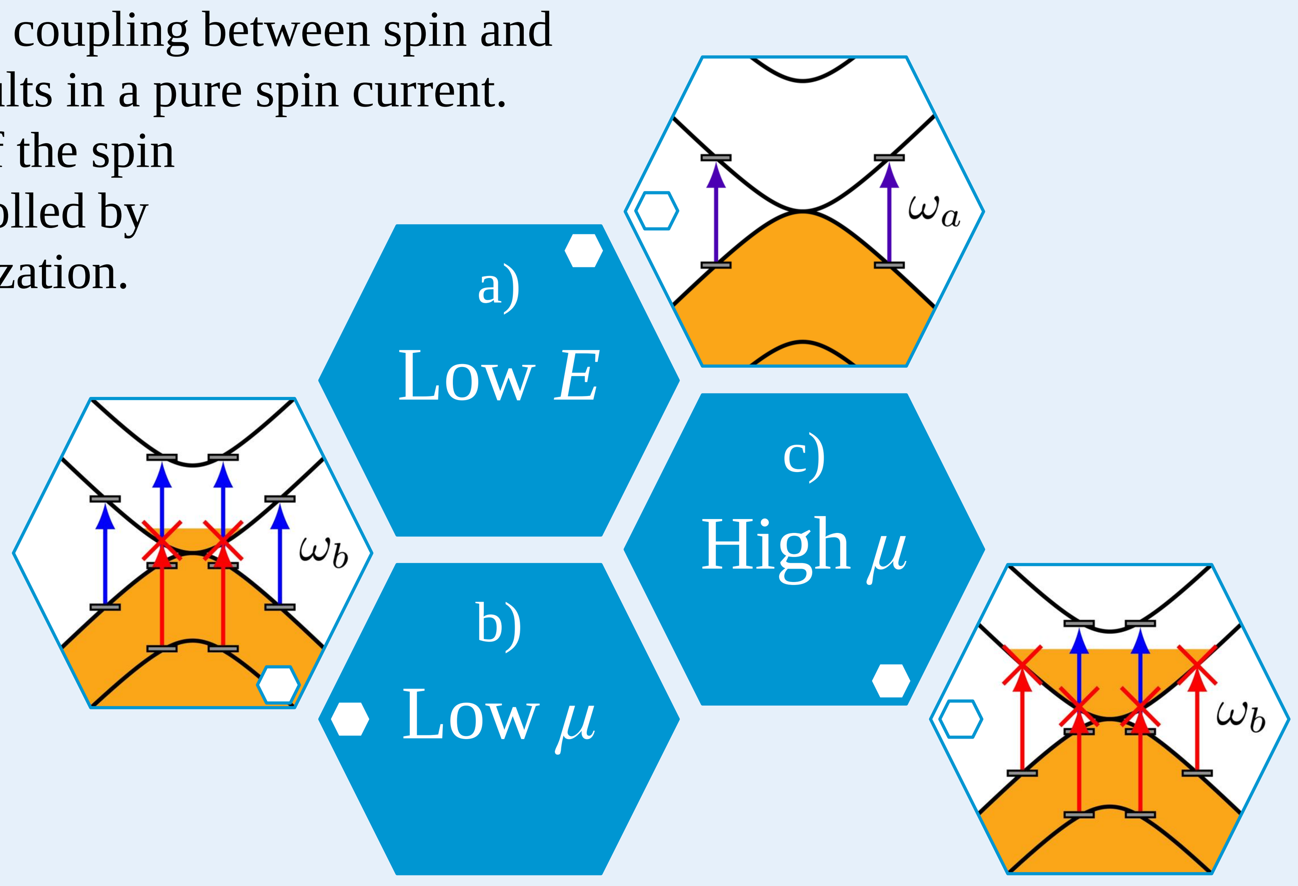
$$\mathbf{v} \rightarrow \frac{\Omega_R}{\sqrt{\Omega_R^2+4v_F^2k^2}} \begin{pmatrix} \frac{\hbar k}{m}A & v_F B \\ v_F B^\dagger & \frac{\hbar k}{m}A \end{pmatrix}$$

where

$$A \equiv \begin{pmatrix} \hat{\mathbf{k}} & i\hat{\phi} \\ -i\hat{\phi} & -\hat{\mathbf{k}} \end{pmatrix}, \qquad B \equiv \begin{pmatrix} -i\hat{\phi} & -\hat{\mathbf{k}} \\ \hat{\mathbf{k}} & i\hat{\phi} \end{pmatrix},$$

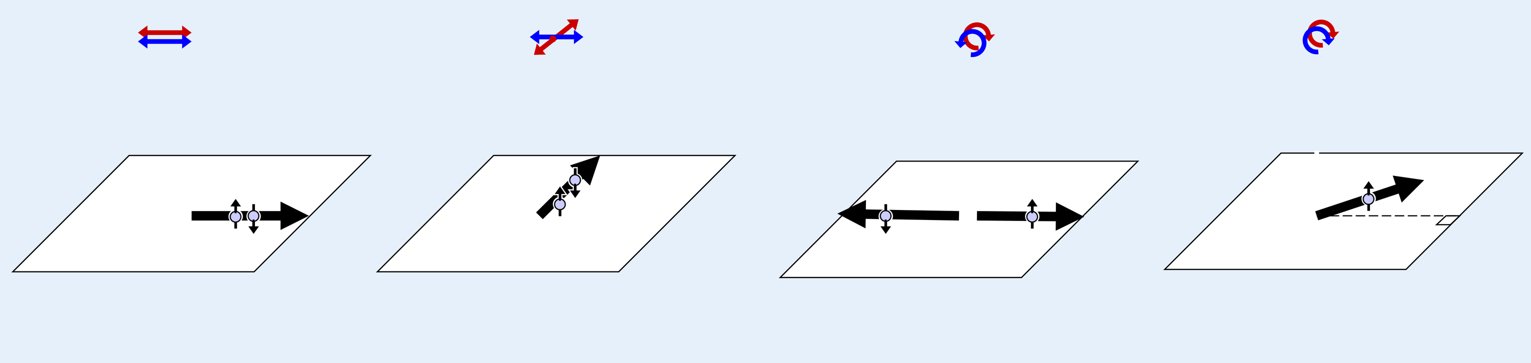
and m is the effective mass describing the $k \rightarrow 0$ dispersion.

For linearly polarized light, the injected carrier density in k-space varies as $\mathbf{k}\cdot\hat{\mathbf{e}}$ or $\boldsymbol{\phi}\cdot\hat{\mathbf{e}}$ where $\hat{\mathbf{e}}$ is the polarization vector. The resulting optical excitation induces a spin-polarized carrier density. Although the net spin and current both average to zero, coupling between spin and momentum results in a pure spin current. The direction of the spin current is controlled by the beam polarization.



Current injection: two-color

For linear absorption the resulting excited carrier distribution is symmetric at k and $-k$ and does not result in a charge current. Current injection instead relies on a two-color (fundamental and second harmonic) excitation scheme, with quantum interference between two-photon absorption at ω (red arrows) and one-photon absorption at 2ω (blue arrows) resulting in an injection term for the current density that is controllable through the polarization and relative phase of the two beams.



For isotropic band models the current density has an injection term characterized by the ratio $d = \eta_I^{\,xyyx} / \eta_I^{\,xxxx}$, where η_I is the current injection tensor (Atanasov 1996). 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. The calculated ratio d is exactly -1 when calculated for a single layer of graphene, but varies as a function of frequency for the bilayer. This has been reported has a signature for the detection of interlayer coupling effects in multilayer epitaxial graphene (Sun 2010).

Summary

The present work investigated charge and spin current injection by optical methods in single-layer and bilayer graphene using one-color or coherent two-color injection and control. Features of the current in single-layer graphene are:

- Large photocurrent due to large carrier velocities and long relaxation times.
- Maximal current response for co-circularly polarized beams, vanishing for opposite-circularly polarized beams.
- Possibility to independently control the current direction and strength.
- Turning on/off the effect with bias voltage.

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