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Theory of magneto-spin resonances in a degenerate two-dimensional electron gas

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Abstract

Based on the magnetic-field analogy for the Rashba spin–orbit coupling, we identify a resonance in the magnetic susceptibility of a two-dimensional electron gas, which is excited by an oscillating perpendicular magnetic field.

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1. Introduction

The emerging field of spintronics [1] has stimulated the study of spin–orbit interactions in low-dimensional semiconductor heterostructures. For device applications, an effective spin-injection mechanism into the semiconducting material is necessary. For this purpose, the Rashba spin–orbit coupling in a two-dimensional electron gas (2DEG) represents a promising candidate [2]. However, this coupling also provides the dominant spin-relaxation mechanism. In a quasi-classical picture, the Rashba term has the form of a momentum-dependent magnetic field, which induces a spin precession of moving carriers. The application of a perpendicular magnetic field quantizes the energy spectrum of the 2DEG and leads to a number of additional spin-dependent effects. Due to the competition between the Rashba spin–orbit coupling and the Zeeman splitting, a resonant spin-Hall conductance has been predicted [3]. Another effect originating from the magnetic-field dependence of the scattering time gives rise to magneto-quantum oscillations of the spin relaxation rate [4]. In addition, when the Landau-level separation becomes comparable with the level broadening, a beating pattern occurs in the conductivity plot as a function of

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the magnetic field [5]. In this Letter, we study a 2DEG with Rashba spin–orbit coupling and focus on resonances, which result from a time-dependent perpendicular magnetic field.

2. Magnetic susceptibility

We consider electrons with charge e and effective mass m^* moving in a two-dimensional x–y plane of a semiconductor quantum well. The carriers are subject to a Rashba spin–orbit interaction and to an oscillating perpendicular magnetic field $\mathbf{H}(t)$ expressed by the vector potential $\mathbf{A}(t)$ [$\mathbf{H}(t) = \nabla \times \mathbf{A}(t)$]. In the quasi-momentum representation, the Hamiltonian is given by

$$H_0 = \sum_{\mathbf{k},\nu} a^+_{\mathbf{k}\nu}\big[\varepsilon\big(\mathbf{k} - \mathbf{A}(i\nabla_{\mathbf{k}})\big) - \varepsilon_F\big]a_{\mathbf{k}\nu} - \sum_{\mathbf{k},\nu,\nu'} \big(\mathbf{T}(\mathbf{k}) \cdot \vec{\sigma}_{\nu\nu'}\big) a^+_{\mathbf{k}\nu} a_{\mathbf{k}\nu'}, \tag{1}$$

where $\varepsilon(\mathbf{k}) = \hbar^2\mathbf{k}^2/(2m^*)$, ε_F, and $\vec{\sigma}$ denote the energy of free electrons, the Fermi energy, and the Pauli matrices, respectively. The Zeeman contribution and the Rashba spin–orbit coupling are described by the vector field

$$\mathbf{T}(\mathbf{k}) = \mu_B\mathbf{H}(t) + \frac{\hbar^2}{m^*}[\mathbf{K} \times \mathbf{k}] = \mu_B\mathbf{H}(t) + \mathbf{T}_0(\mathbf{k}), \quad \mathbf{K} = \frac{m^*\alpha}{\hbar^2}\mathbf{e}_z, \tag{2}$$

with α being the Rashba coupling constant and $\mu_B = |e|\hbar/(2m^*c)$ the Bohr magneton. The vector potential is calculated in the symmetric gauge

$$\mathbf{A}(\mathbf{r}) = \frac{eH(t)}{2\hbar c}(-y\mathbf{e}_x + x\mathbf{e}_y). \tag{3}$$

We shall treat the effect of a weak oscillating magnetic field and omit in Eq. (1) the magnetic-field dependence of the Rashba coupling, which is due to the kinetic momentum. This contribution is proportional to the spin–orbit coupling constant and the weak magnetic field and is, therefore, neglected. The kinetic equation for the density matrix

$$f_{\nu\nu'}(\mathbf{k} \mid t) = \langle a^+_{\mathbf{k}\nu} a_{\mathbf{k}\nu'}\rangle_t, \tag{4}$$

is derived for the vector field $\mathbf{f} = (f_x, f_y, f_z)$, the components of which are given by

$$f_x = f_{\uparrow\downarrow} + f_{\downarrow\uparrow}, \qquad f_y = i(f_{\downarrow\uparrow} - f_{\uparrow\downarrow}), \qquad f_z = f_{\uparrow\uparrow} - f_{\downarrow\downarrow}. \tag{5}$$

For simplicity and to demonstrate qualitative features of the model by an analytical solution, we restrict the consideration to elastic scattering within the relaxation-time approximation. A more realistic treatment of scattering goes beyond the scope of the present Letter. By making use of the kinetic equation for the density matrix, we obtain the following quasi-classical Boltzmann equation

$$\frac{\partial\mathbf{f}(\mathbf{k} \mid t)}{\partial t} + \frac{2}{\hbar}\big[\mathbf{T}(\mathbf{k}) \times \mathbf{f}(\mathbf{k} \mid t)\big] - \frac{e}{m^*c}\big[\mathbf{H}(t) \cdot (\mathbf{k} \times \nabla_{\mathbf{k}})\big]\mathbf{f}(\mathbf{k} \mid t) = \frac{1}{\tau}\big[\langle\mathbf{f}(\mathbf{k} \mid t)\rangle - \mathbf{f}(\mathbf{k} \mid t)\big], \tag{6}$$

in which the following average over the angle α (given by $k_x = k\cos(\alpha)$, $k_y = k\sin(\alpha)$)

$$\langle\mathbf{f}(\mathbf{k} \mid t)\rangle = \frac{1}{2\pi}\int_0^{2\pi} d\alpha\, \mathbf{f}(k, \alpha \mid t) \tag{7}$$

appears. In Eq. (6), τ denotes an effective scattering time. For a perpendicular time-dependent magnetic field $\mathbf{H}(t) = \mathbf{H}\exp(-i\Omega t)$, which oscillates with frequency Ω, the distribution function contains two parts. The first one, $\mathbf{f}_0(\mathbf{k})$, is calculated for a 2DEG at zero magnetic field. Results are presented in Appendix A. The second