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Cyclotron effect on coherent spin precession of two-dimensional electrons

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Abstract.
High-mobility two-dimensional electron systems may be one of the bases of future spintronic devices, where the spin states of ballistic electrons could be manipulated via external gate voltages and the resulting spin-orbit fields. Therefore, the knowledge of spin dynamics in such systems is of technical interest and offers on the other side an exciting view on the underlying physics. Here, we present time-resolved Faraday rotation measurements in a high-mobility two-dimensional electron system in a GaAs/AlGaAs quantum well structure grown along the [001] direction. Even without applied external magnetic fields the optically generated spin ensemble shows a coherent precession about the effective spin-orbit field. If a nonquantizing magnetic field is applied normal to the sample plane, the effective spin-orbit fields are rotated by the cyclotron motion of the electrons. This rotation leads to fast oscillations in the spin polarization about a nonzero value and an strong increase of the spin dephasing times. The measurement data is in excellent agreement with a model based on a kinetic equation approach.

Keywords: Optical orientation, electron spin dynamics, GaAs heterostructures
PACS: 71.70.Ej, 73.20.-r, 85.75.-d

A key issue in semiconductor spintronics [1] is the dynamics of carriers in low-dimensional structures. Two-dimensional electron systems (2DESs) are a candidate for future spintronic devices, in which the spin states of ballistic electrons could be manipulated by the spin-orbit (SO) interaction. The development of GaAs/AlGaAs heterostructures led to very clean two-dimensional electron systems, where the carriers can move ballistically over distances of a few microns without being scattered. In such systems with momentum scattering times on the order of a few hundred ps, the weak scattering regime of the D'yakonov-Perel' (DP) spin-dephasing mechanism becomes accessible at low temperatures. In this regime, the electron spin can precess one or more full revolutions about the effective SO field $\boldsymbol{\Omega_k}$ before the electron is scattered. This leads in samples grown along the [001]-direction to the characteristic and well-known coherent precession of an optically excited spin ensemble even without an external magnetic field [2, 3].

In this work, the influence of an additional nonquantizing magnetic field normal to the sample plane is studied, which leads to a cyclotron motion of the electrons and rotates the SO field $\boldsymbol{\Omega_k}$ seen by the single electron. It was predicted [4], that even a small magnetic field should have a dramatic effect on the spin dynamics: Similar to the collision dominated motional narrowing regime of the DP mechanism, the averaging over the SO fields due to the cyclotron rotation leads to a drastic increase of the spin lifetime [5, 6]. A second effect is the appearence of a fast beating of the spin polarization about a nonzero value. In comparable (110)-grown high-mobility samples, these two effects are absent due to the different symmetry of the SO fields [7].

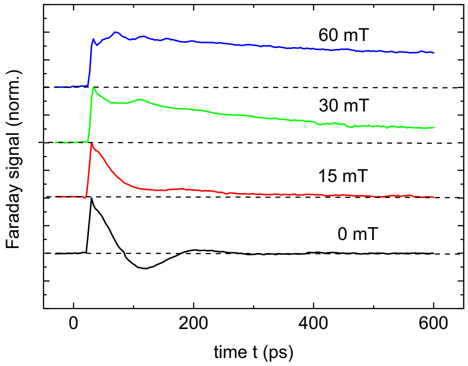

FIGURE 1. Experimental TRFR traces in various perpendicular magnetic fields measured at 400 mK .

In this study we used the all-optical time-resolved Faraday rotation (TRFR) technique to map the spin dynamics. The results shown here were determined on a symmetrically (001)-grown and doped 30 nm wide

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GaAs-Al$_{0.3}$Ga$_{0.7}$As single-quantum well (QW) with a electron density $n = 2.97 \cdot 10^{11}\,\mathrm{cm}^{-2}$ and a mobility $\mu_e = 14.8 \cdot 10^6\,\mathrm{cm}^2/\mathrm{Vs}$ at 1.3 K. To achieve the high mobility, a complex growth structure (similar to that used in Ref. [8]) was used. For measurements in transmission geometry, the samples were glued onto sapphire substrates, and the substrate and the buffer layers were removed by selective wet etching. The samples were mounted in an optical cryostat with a ^{3}He insert, which enables sample temperatures down to 400 mK and magnetic fields of up to 10 T normal to the sample plane. For the optical measurements, a Ti-Sapphire laser system was used, further details of the experiment and the samples are published elsewhere [9, 7].

In figure 1 TRFR traces for different values of the B-field normal to the sample plane are shown. The coherent oscillation of the spin ensemble in zero field is clearly visible, the damping of the beats occurs on the timescale of the single electron momentum scattering time τ^*, which is mainly limited by electron-electron scattering processes [7]. With increasing field, both, the frequency of the spin beats and the lifetime of the long living tail of the spin polarization increase. Calculations based on a kinetic equation approach [4] reproduce the experimental findings and are shown in Ref. [7]. The solution of the kinetic equation for the spin distribution function in an external magnetic field normal to the sample plane leading to a cyclotron motion of the electrons with the cyclotron frequency $\omega_c = eB/mc$ is

$$s_{z,k_\mathrm{F}}(t) = \mathscr{A}\mathrm{e}^{-t/\tau_s} + \mathscr{B}\mathrm{e}^{-t/\tau_b}\cos\left(\Omega_\mathrm{eff} t\right), \qquad (1)$$

where $\Omega_\mathrm{eff} = \sqrt{\omega_c^2 + \Omega_{k_\mathrm{F}}^2}$, $\mathscr{A} = \omega_c^2/\Omega_\mathrm{eff}^2$, $\mathscr{B} = \Omega_{k_\mathrm{F}}^2/\Omega_\mathrm{eff}^2$, $\tau_s^{-1} = \mathscr{B}/\tau^*$, $\tau_b{}^{-1} = (1+\mathscr{A})/(2\tau^*)$. Figure 2 (a) shows a single TRFR trace in a 36 mT perpendicular magnetic field, which has all features expected from eq. (1): After the initialization of the spin ensemble rapid oscillations appear, which are damped out relatively fast on the timescale τ_b which is on the order of the electron-electron scattering time of about 80 ps under excitation conditions. The remaining part of the spin polarization has a long-living tail decaying with the decay time τ_s which increases quadratically with the magnetic field, as predicted [5, 6]. By fitting the data for different values of the perpendicular magnetic field, the dependences of the oscillation frequency of the spin beats as well as the spin lifetime of the tail, could be determined, this is shown in figure 2 (b)-(c). The effective oscillation frequency Ω_eff, being the geometric sum of ω_c and Ω_{k_F}, increases with B due to the cyclotron rotation of the k vectors, which leads to a modulation of the SO field. The amplitude of the fast spin beats decreases with increasing magnetic field, as can be seen from the TRFR traces in figure 1. Due to the fast cyclotron rotation of the SO field spin precession about Ω_{k_F} is suppressed. For cyclotron frequencies $\omega_c \gg \Omega_{k_\mathrm{F}}$, the system crosses over to a regime similar to the motional narrowing regime: the variation of the SO field due to the cyclotron rotation is much faster than the spin precession in the SO-field Ω_{k_F}. This leads to the observed increase of the spin lifetime of the long-living tail with increasing B field.

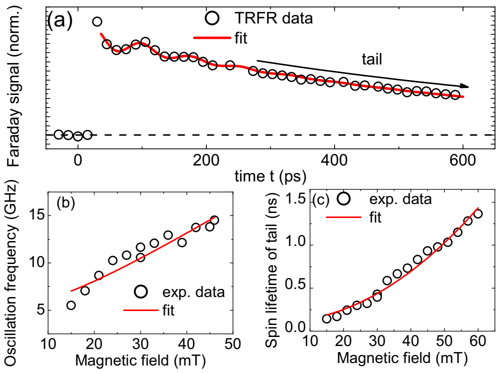

FIGURE 2. (a) TRFR measured at 400 mK in a 36 mT perpendicular magnetic field and corresponding fit. (b)-(c) Oscillation frequency of the spin beats and lifetime of the 'tail' of the spin-polarization decay as a function of magnetic field. The solid line is a fit to the experimental data.

In conclusion, we have investigated spin dynamics of electrons in a high-mobility 2DES. We observe the combined effect of the internal SO fields and weak external magnetic fields on electron spin precession and dephasing. The results are in good agreement with a calculation based on a kinetic equation approach.

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