PHYSICAL REVIEW B **67**, 201302(R) (2003)

THz collective spin-flip excitation of a two-dimensional electron system

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(Received 24 March 2003; published 7 May 2003)

Resistively detected electron cyclotron resonance and spin-flip excitation are studied on a two-dimensional electron system of InAs. A THz spin-flip excitation is observed in the Faraday configuration and is found strongly damped around odd filling factors, indicating a distinct many-body effect in a two-dimensional electron system with a spin-orbit interaction.

DOI: 10.1103/PhysRevB.67.201302 PACS number(s): 73.20.Mf, 71.70.Ej, 73.21.−b, 78.30.−j

In the classical picture, conduction electrons of a semiconductor placed in a magnetic field **B** feel a Lorenz force that drives the electron moving in the cyclotron orbit, while the magnetic moment of the spin feels a torque that causes the spin to precess. These motions resonantly interact with the electromagnetic radiation, with cyclotron resonance (CR) frequency $\omega_c = eB/m^*$ and electron-spin-resonance (ESR) frequency $\omega_z = -\nu_0 \omega_c$ being typically in the THz and the GHz regime, respectively ($\nu_0 = gm^*/2m_e < 0$ for most semiconductors). They provide textbook examples of accurate determination of the electron effective mass m^* and the Landé g factor. In the quantum mechanical picture, CR is the inter-Landau-level electric dipole transition with $\triangle N = 1$ and $\triangle S = 0$, and ESR is the inter-Zeeman-level magnetic dipole transition with $\triangle N = 0$ and $\triangle S = -1$, where N and S are the Landau and spin quantum numbers, respectively.

These are simplified pictures that neglect the nonparabolicity in narrow gap semiconductors and spin-orbit interaction in semiconductors lacking an inversion center. In both cases, coupling between the orbital and the spin motion of the electrons breaks the simple selection rules described above. It results in a combined resonance (CBR) with both the Landau and spin quantum numbers changed, which can be excited by either the electric (**E**) or the magnetic (**H**) component of the radiation, typically with the THz frequency. Electric dipole excited CBR with $\triangle N = 1$ and $\triangle S = -1$ was first observed by McCombe *et al.*[1] in bulk InSb in 1967. It was ascribed to the nonparabolicity mechanism characterized by a longitudinal ($\mathbf{E} \parallel \mathbf{B}$) polarization. Theory predicts since then electric dipole excited CBR via the mechanism of the spin-orbit interaction, which is allowed for circular polarizations with $\mathbf{E} \perp \mathbf{B}$ (the Faraday configuration).[1] It is, however, up to today unobserved, possibly due to its rather small matrix element[2] that requires a highly sensitive THz spectroscopic experimental technique.

Recently, there is a growing interest in the spin-orbit interaction in the two-dimensional electron system (2DES). It has been found that in InGaAs/InAlAs heterojunctions, the structure inversion asymmetry dominates the spin-orbit interaction over the bulk inversion asymmetry, so that the spin-splitting energy is given by[3]

$$|\hbar\omega_s| = \{[\hbar(\omega_c + \omega_z)]^2 + (2\Delta_R)^2\}^{1/2} - \hbar\omega_c, \tag{1}$$

which approaches the Zeeman splitting energy $\hbar\omega_z$ only at high B fields when $\hbar\omega_c \gg 2|\Delta_R|/(1-\nu_0)$. Here the matrix element $\Delta_R = \alpha k_F$ depends on the spin-orbit parameter α and the Fermi wave vector k_F, which both can be controlled via a front gate.[4] The potential significance of manipulating spin via the gate is best illustrated in the classic paper of Datta and Das for a novel spintronic device.[5] Up to now, however, this highly interested subject has been only experimentally indirectly investigated using the magnetotransport technique,[4,6] and theoretically simply analyzed based on single-particle pictures. It is accompanied by huge controversy[6] troubling the exploding field of semiconductor spintronics.

Of primary importance for a 2DES is the effect of the electron-electron interaction. In the presence of a strong B field normal to the 2DES layer, the Coulomb interaction gives rise to the fractional quantum Hall effect[7] and enhanced Zeeman splitting[8] observed in dc transport experiments. For dynamic excitations, assuming a parabolic band without the spin-orbit interaction, the single-particle transitions described above are replaced by collective excitations with the dispersion relations:[9]

$$E_{\triangle N,\triangle S}(\mathbf{q}) = \triangle N\omega_c - \triangle S\omega_z + \triangle E_{\triangle N,\triangle S}(q), \tag{2}$$

where the excited states are labeled by $\triangle N$, $\triangle S$, and wave vector $\mathbf{q}$. For the $q=0$ excitations using the THz or the GHz radiation, many-body corrections for CR and ESR are given by $\triangle E_{1,0}(0) = \triangle E_{0,-1}(0) = 0$, according to Kohn's theorem[10] and Larmor's theorem,[9] which apply to translationally and spin rotationally invariant systems, respectively. On the contrary, no simple symmetry argument exists for the many-body correction $\triangle E_{1,-1}(0)$ to the CBR at $q=0$. The shifted CBR is therefore labeled as the spin-flip excitation, which was first observed by Pinczuk *et al.*[11] using the inelastic light-scattering technique in a 2DES of GaAs where both the nonparabolicity and spin-orbit interaction are negligible. Via a spectroscopic experiment one can measure not only directly band splitting due to the spin-orbit interaction, but also get an easy access to many-body effects by analyzing oscillator strengths. It is therefore highly interesting to search for a possible THz spin-flip excitation in a 2DES with the spin-orbit interaction. The main challenge is to improve the spectroscopic sensitivity to detect the usually very weak spin excitations.

In this Rapid Communication, we report resistively detected CR and spin-flip excitation in a 2DES formed in an

InAs quantum well. Unlike conventional absorption experiment, this technique combines magneto transport with spectroscopy.[12] Its high sensitivity has been long demonstrated in the GHz ESR (Ref. 13) and THz CR (Ref. 14) experiments by using microwave generators and far-infrared lasers, respectively. We use in this work much weaker THz source of a mercury lamp, which makes the experiment more difficult but allows a better spectroscopic analysis due to its broad bandwidth. We find clearly that the THz excitations in an InAs 2DES are influenced by spin-orbit, electron-electron, and electron-phonon interactions.

Our sample is an inverted-doped InAs step quantum well with 40-nm $In_{0.75}Al_{0.25}As$ cap layer. The step quantum well is composed of 13.5-nm $In_{0.75}Ga_{0.25}As$, an inserted 4-nm InAs channel, and a 2.5-nm-thick $In_{0.75}Ga_{0.25}As$ layer. Underneath the quantum well is a 5-nm spacer layer of $In_{0.75}Al_{0.25}As$ on top of a 7-nm-wide Si-doped $In_{0.75}Al_{0.25}As$ layer. The sample is grown by molecular-beam epitaxy on a buffering multilayer accommodating the lattice mismatch to the semi-insulating GaAs substrate. A self-consistent Schrödinger-Poisson calculation shows that the 2DES is about 55 nm below the surface, mainly confined in the narrow InAs channel.[15] The carrier density N_s and mobility μ at 2.2 K were determined by Shubnikov–de Haas measurement to be 6.66×10^{11} cm^{-2} and 150 000 cm^2/Vs, respectively. An extremely long 2DES Hall bar with a channel width of $W=40$ μm and a total length L of about 10 cm was defined by chemical wet etching. The 2DES channel runs meandering in a square of 4×4 mm^2. The extremely large L/W ratio enhances the sensitivity of our measurement. Ohmic contacts were made by depositing AuGe alloy followed by annealing.

Our experiment was performed by applying a dc current of 4.5 μA to the Hall bar and measuring the changes of the voltage drop caused by the THz radiation. At fixed magnetic fields, the broadband THz radiation was modulated by the Michelson interferometer of a Fourier-transform spectrometer. Using the sample itself as the detector, the corresponding change in the voltage drop of the sample was ac coupled to a broadband preamplifier and recorded as an interferogram, which was Fourier transformed to get the photo conductivity spectrum. The sample was mounted in a He cryostat with a superconducting solenoid. A Si bolometer behind the sample allows us to measure the direct absorption and to monitor the phase correction factor sometimes needed if the signal was too weak. All data reported here were obtained at 2.2 K in the Faraday geometry.

Figure 1 shows typical THz photoconductivity spectra (thick lines) measured at two B fields of 3.5 and 6.5 T. A weak resonance is observed at the high-energy side of the dominant peak. For comparison, conventional absorption spectra measured using the Si bolometer under the same experimental conditions are plotted as thin lines. The absorptional spectroscopy probes the high-frequency conductivity of the 2DES so that the resonance intensity is limited by the transition matrix element and the electron density. On the contrary, photoconductivity of the 2DES is caused by the bolometric effect where photoexcitation of electrons effectively heats the 2DES, which changes its resistance.[16] Its resonance intensity depends on the absorbed power of the radiation, the energy relaxation time of the photoexcited nonequilibrium electrons and the heat capacity of the 2DES. Therefore, its sensitivity can be enhanced by carefully choosing the experimental condition and the sample design. The weak resonance, whose intensity is only about 0.8% of that of the strong one, is only resolved in our highly sensitive photoconductivity spectrum.

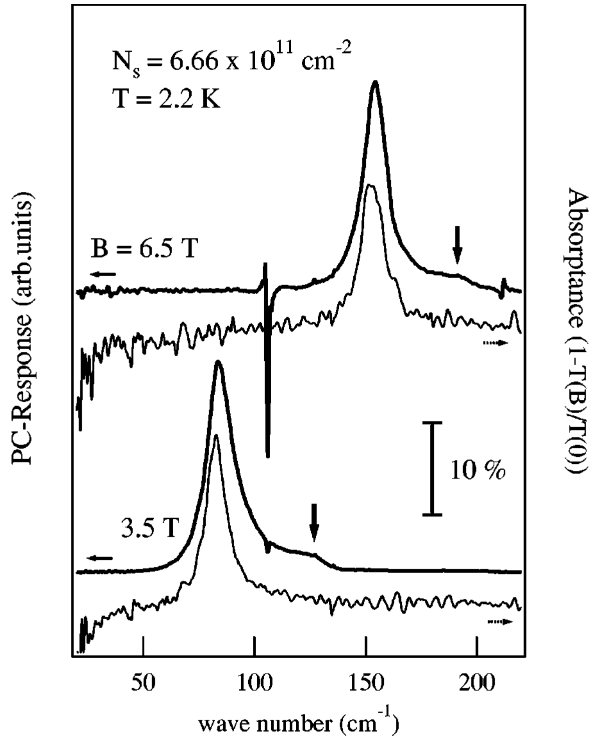

FIG. 1. THz photoconductivity spectra (thick lines) measured at two magnetic fields in comparison with conventional absorption spectra (thin lines) under the same experimental conditions using a Si bolometer. In addition to the CR, thick arrows indicate the weak spin-flip excitations which are only observable using the high sensitive photoconductivity technique.

In Fig. 2(a) we plot the B-field dispersion of both resonances. Also shown is the magnetoresistance R_{xx} measured without the THz radiation with the same excitation current of 4.5 μA. The open circles determined from the strong peaks are easily identified as the CR with $\omega_c = eB/m^*$ that can be described (dashed line) using $m^* = 0.039 m_e$. The solid circles for the weak resonances are fit (dashed curve) to $\omega_c + \omega_s$ using Eq. (1) with two fitting parameters $\Delta_R = 38$ cm^{-1} and $g = -8.7$. The fairly good fit using a reasonable g factor for InAs encourages us to attribute it for the time being to the longly expected CBR. Later we will see that its behavior is more complicated. Observing the THz dipole-excited CBR in the Faraday configuration requires the spin-orbit interaction, in accordance with the obtained zero-field spin splitting $2\Delta_R = 76$ cm^{-1}, which gives a spin-orbit parameter $\alpha = 2.38\times 10^{-11}$ eV m that is comparable to that measured early in similar samples using transport technique.[4] Using these parameters, we calculate the Landau levels[3] and plot them in Fig. 2(b) together with the dotted lines showing the Fermi level. The thin and thick arrows illustrate the CR

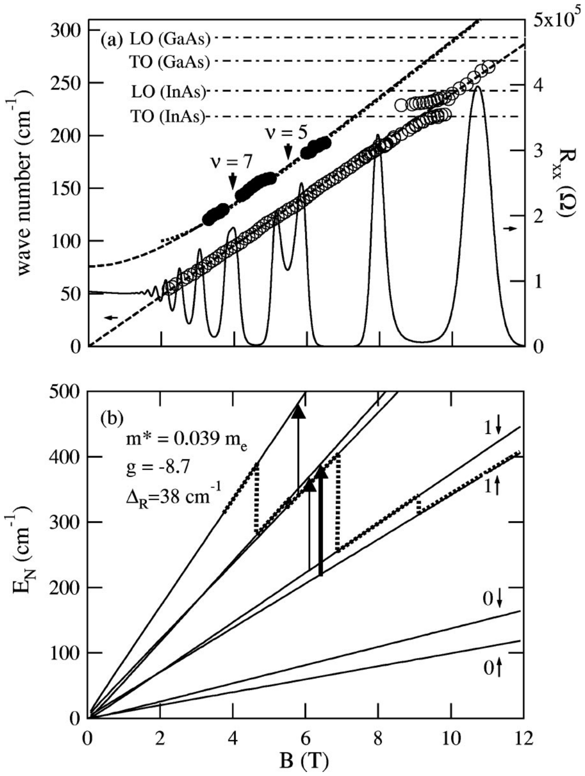

FIG. 2. (a) Resonance dispersions determined from the photoconductivity spectra and magnetoresistance R_{xx} measured without the THz radiation. The dashed line and curve are fits for the CR and CBR using a constant effective mass and Eq. (1), respectively. The dotted line is for CBR using Eq. (2) and assuming $\triangle E_{1,-1} \propto \nu$. Dash-dotted lines indicate the optical-phonon energies of InAs and GaAs. (b) Landau levels calculated using the band parameters obtained from the fit in (a). Dotted lines indicate the Fermi energy. The thin and thick arrows illustrate the CR and CBR, respectively.

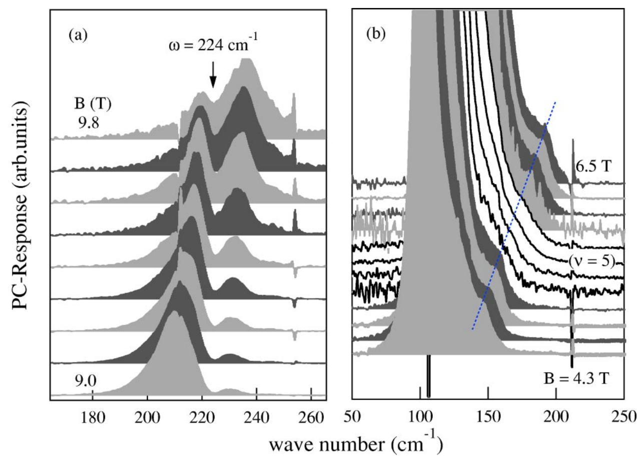

FIG. 3. (a)Photoconductivity spectra measured between 9 and 9.8 T showing the splitting of CR due to the influence of optical phonons. (b) Normalized photoconductivity spectra measured between 4.3 and 6.5 T displaying damping of the collective spin-flip excitation around $\nu=5$. The dotted line is guide to eyes.

and CBR, respectively. Note that the crossover of the Landau levels with opposite spin at small B-field regime is the characteristic of the spin-orbit interaction. It should give rise to a beating pattern in the R_{xx} curve[4] in a single-particle picture but is not observed in our sample. This phenomenon has been pointed out in a previous study[6] and is now the major mystery questioning the strength of the spin-orbit interaction. Our results shed light on the mystery indicating clearly that missing a beating pattern does not simply mean that the spin-orbit interaction vanishes.

Up to now, we have discussed our data in a single-particle picture. Many-body effects, however, play an essential role in both the CR and R_{xx}. As illustrated in Fig. 2(b), the Zeeman gaps at odd filling factors are much smaller than their neighboring Landau gaps at even filling factors. The clear minima observed in R_{xx} in Fig. 2(a) around odd filling factors are well understood as enhanced spin splitting due to exchange interaction between electrons.[8] Besides, CR between different pairs of Landau levels should have different transition energies due to the band nonparabolicity.[17] Observed is only a single CR, indicating a strong coupling due to electron-electron interaction which hybridizes individual CR transitions, so that only their in-phase oscillation was observed.[18] It is therefore appealing to ask the question how many-body effect influences the CBR we observed.

Let us examine our data more carefully, in particular, let us study why CBR is only observed in certain B-field regimes. At high B fields where the CR and CBR lie above 200 cm^{-1}, spectra are influenced by the reststrahlen bands of our sample. In addition to the bulk phonon frequency of GaAs and InAs indicated in Fig. 2(a), there are two phonon bands for both $In_{0.75}Ga_{0.25}As$ and $In_{0.75}Al_{0.25}As$ layers, not shown for brevity. The spectra are complicated due to both resonant polaron effect[19] and an optical effect.[20] As examples, we plot in Fig. 3(a) CR measured between 9 and 9.8 T that show splitting and subside structures. Although the combined nature of the optical effect, band nonparabolicity, electron-electron and electron-phonon interaction is interesting for itself,[21] we would focus in this paper on CBR below 200 cm^{-1} where it is unambiguously observed free from any influence of optical phonons.

The most intriguing part of the data is that at intermediate B-field regime between 3 and 7 T. As shown in Fig. 2(a), we can not determine CBR energies around filling factor $\nu=5$ and 7. For a better analysis, we plot in Fig. 3(b) the blown-up spectra measured between 4.3 and 6.5 T around $\nu=5$. All spectra are normalized using their CR so that we can directly compare the intensity of the CBR without worrying about the change of the photoconductivity sensitivities at different B fields. We find clearly that the CBR disappears around $\nu=5$. The same behavior is observed around $\nu=7$. It provides us with the strongest evidence that what we observe is the collective-shifted combined resonance, i.e., the collective spin-flip excitation, since theory[22] has long predicted that at odd filling factors where the ground state of the 2DES is spin polarized, the collective spin-flip excitation decays into a magnetoplasmon and a spin wave that conserve spin, momentum, and energy. Our previous analysis using the single-particle picture coined in Eq. (1) is certainly oversimplified. In detail, there are two difficulties to use the many-body picture described in Eq. (2) to analyze our data. First, the spin-orbit interaction is not included, and second, even for the simplest case of parabolic band, no precise relation of $\triangle E_{1,-1}$ with B field is available. To bypass the first difficulty, let us assume that the spin-orbit interaction is only important for data at low B fields. For the second, we note that in a recent inelastic light-scattering experiment[23] on the 2DES of GaAs, Kulik *et al.* found that $\triangle E_{1,-1} \propto \nu$ for $\nu < 1$. Assuming $\triangle E_{1,-1} = a\nu$ holds also for higher filling factors, we are able to fit our data [dotted line in Fig. 2(a)] using the parameters $g = -8.7$ and $a = 3.2\ \mathrm{cm}^{-1}$. Very likely, these parameters do not really describe our sample well as it looks like in the fit, however, it emphasizes the fact that to accurately determine the g factor and spin-orbit parameter α, the electron-electron and spin-orbit interactions should be both taken into account.

In the many-body picture, magnetotransport measures the collective excitation of the 2DES at $q \to \infty$, it is very tempting to connect the mystery of the absence of low-field beating pattern in R_{xx} with the fact that the THz spin-flip excitation disappears also in our photoconductivity measurement at low B field. However, we would leave this subject to further experimental study to check whether strong spin-orbit interaction damps collective spin excitations.

We summarize our paper by pointing out experimental arguments pro and con the single-particle picture of Eq. (1) and the many-body picture of Eq. (2). Although both give rise to satisfactory numerical fits to the observed dispersion, the single-particle picture based on the spin-orbit interaction explains why a combined resonance is electric dipole active in the Faraday configuration, but cannot explain why it disappears around odd filling factors; on the other side, the many-body picture neglecting the spin-orbit interaction explains why the spin-flip excitation is damped around odd filling factors, but cannot explain why it is active in the THz regime. To understand the spin effects in the 2DES of InAs therefore calls for a unified picture including both interactions.

This work was supported by the NEDO international joint program for spintronics, the BMBF through Project No. 01BM905 and the DFG through Grant No. SFB 508.

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