Magnetic-field-induced dispersion anisotropy of intersubband excitations in an asymmetrical quasi-two-dimensional electron system

L. V. Kulik, I. V. Kukushkin, and V. E. Kirpichev
Max-Planck-Institut für Festkörperforschung, Heisenbergstr. 1, 70569 Stuttgart, Germany
and Institute of Solid State Physics, Russian Academy of Sciences, 142432 Chernogolovka, Russia

K. v. Klitzing and K. Eberl
Max-Planck-Institut für Festkörperforschung, Heisenbergstr. 1, 70569 Stuttgart, Germany
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In a quasi-two-dimensional (2D) electron system under an in-plane magnetic field, we have observed extrema in characteristics of intersubband excitations when a certain resonance condition is imposed on the magnetic field and momentum of the excitations. By changing the mutual alignment of the magnetic field and momentum, we have shown that the dispersion of the intersubband excitations in the in-plane magnetic field has a strong rotational anisotropy. The anisotropic contribution to the energy due to the quasi-2D electron system asymmetry is found to be a *linear* function of the magnetic field and in-plane momentum and can be used as an efficient tool in measuring the asymmetry of the 2D confining potential.

The spectrum of a quasi-two-dimensional (2D) electron system (2DES) with a finite dimension in the direction perpendicular to the 2D plane (along the z axis) has the form of a sequence of quantum subbands.[1] Within each subband, excitations in the electron system are essentially two-dimensional and little affected by the confining potential of the quasi-2DES. On the contrary, excitations that are due to transitions between different quantum subbands are strongly affected by the shape of the confining potential, and these transitions are usually investigated with a view to characterizing the confining potential.

The intersubband resonance in semiconductor quantum wells (QW's) has been employed in determining intersubband energies controlled by the QW potential.[2] Nonetheless, even though intersubband energies are known, one still cannot accurately determine the shape of the QW confining potential, which is derived mostly from theoretical calculations.[1] Attempts have been made to obtain more detailed knowledge about the confining potential using the intersubband resonance in an in-plane magnetic field ($B_\parallel$),[3] which modifies the intersubband spectrum, but has a weaker effect on the two-dimensional features of quasi-2DES. A limitation is imposed on $B_\parallel$ in this case: the magnetic length should be much shorter than the electric length determined by the gradient of the confining potential.[4] In practice, this condition is rarely satisfied since the energy of the intersubband resonance depends on $B_\parallel$ diamagnetically, therefore relatively strong-magnetic fields are needed to observe a modification in the intersubband spectrum.[5] Moreover, the energy of the intersubband resonance is invariant under the z-axis inversion, but the confining potential, unless it has a specific configuration, is not symmetrical with respect to the z-axis inversion. As a result, the intersubband resonance can hardly be used in determining experimentally the direction of the confining potential gradient.

Most of the previous studies of the intersubband resonance under an in-plane magnetic field focused on the infrared absorption at an in-plane momentum of the exciting photon close to zero. In this letter, we demonstrate remarkable features of the intersubband resonance excited by a photon with a *nonzero* in-plane momentum (indirect transition). The indirect intersubband resonance allows one to establish easily whether the confining potential is symmetrical with respect to the z-axis inversion. If the potential is asymmetrical, the resonance energy demonstrates a rotational anisotropy, which can be used in measuring the degree of the confining potential asymmetry. The anisotropic energy is a *linear* function of the magnetic field, therefore measurements can be performed under fairly low-magnetic fields. We have also shown that, in an asymmetrical quasi-2D electron system, an in-plane magnetic field generates a dispersion anisotropy of collective intersubband excitations and have found a simple expression for the energy of these excitations in terms of the effective mass approximation. The experimental results have been compared to calculations by the time-dependent local-density approximation (TDLDA),[6] and good agreement between the theory and experiment has been observed.

In the reported study, we have used a high-quality asymmetrically doped $Al_{0.3}Ga_{0.7}As\backslash GaAs$ single QW heterostructure with a QW width of 250 Å, a mobility of 1.5×10^6 cm^2/(V s), and an electron concentration $n_s=3.5\times10^{11}$ cm^{-2}. We have also studied a heterostructure with the same quantum well width of 250 Å, a close electron mobility of 1.5×10^6 m^2/(V s), but with a different electron concentration of 6.8×10^{11} cm^{-2}. The measurements of both samples have yielded fully consistent results, therefore we will discuss in what follows only the sample with the electron concentration of 3.5×10^{11} cm^{-2}. A spacer of 400 Å separated a δ-layer of Si donors from the QW. Ionized remote donors generated an electric field aligned with the z axis, which induced an asymmetry of the QW potential. The QW sample was mounted in an optical cryostat with a horizontal split-coil superconducting solenoid operating in a magnetic field range of 0 to 7 T at a base temperature of 1.5 K.

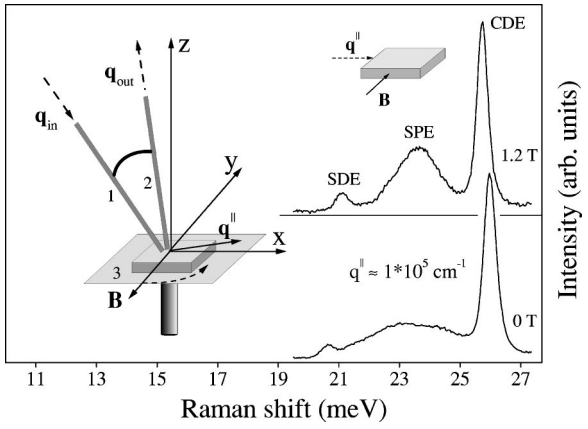

FIG. 1. On the left is a diagram of resonant inelastic light-scattering configuration: (1) fiber-conducting laser beam to the sample; (2) fiber collecting scattered light; (3) sample holder with the sample. The sample holder and fibers can be rotated around the z axis in a constant magnetic field. On the right are spectra of inelastic light scattering from a sample with a QW width of 250 Å and $n_s = 3.5\times10^{11}$ cm^{-2} measured at $B_{||}=0$ and 1.2 T, $q^{||}=1.0\times10^5$ cm^{-1}, and a laser excitation energy of 1.574 eV. The directions of $\vec{q}^{||}$ and $\vec{B}$ are shown in the top diagram.

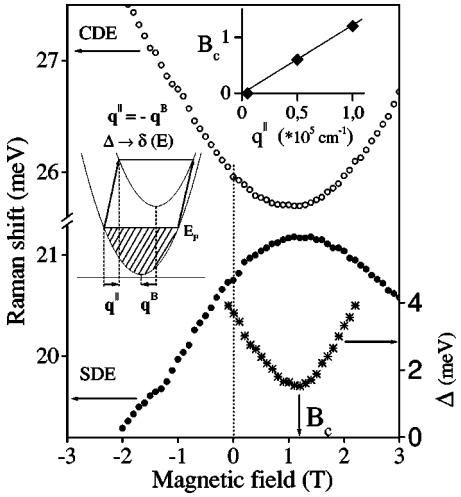

FIG. 2. Magnetic-field dependence of the SPE bandwidth, and CDE and SDE energies. The inset shows measurements and calculations of B_c versus $q^{||}$. In our calculations, we used $\Delta z = 54$ Å. The complete elimination of the effect of in-plane magnetic field on the SPE bandwidth is illustrated by the diagram of energy levels.

The technique employed in measuring the intersubband resonance with a nonzero in-plane momentum was inelastic scattering of light emitted by a titanium-sapphire laser tunable above the fundamental band gap. In order to obtain a required flexibility in changing the mutual alignment of the in-plane momentum ($\vec{q}^{\|}$) and magnetic field ($\vec{B}_{\|}$), a two-fiber optical system was used in our experiments (see the diagram on the left of Fig. 1). One fiber conducted the laser light to the sample, whereas the second collected the scattered light. Through the inelastic light scattering process, an in-plane momentum was transferred to intersubband excitations. The transferred momentum was determined by the configuration of the fibers over the sample surface. The angle between $\vec{q}^{\|}$ and $\vec{B}_{\|}$ was tuned by rotating the sample holder around the z axis in the horizontal magnetic field without changing the fixed fiber configuration. The experimental technique was described in greater detail elsewhere.[7]

Figure 1 shows examples of inelastic light scattering spectra recorded without a magnetic field and at a magnetic field of 1.2 T. An in-plane momentum of 1×10^5 cm^{-1} perpendicular to $\vec{B}_{\|}$ was transferred to intersubband excitations. The spectra contain three main components: a broad band at 23.5 meV associated with the intersubband single-particle excitation (SPE) continuum and two narrow lines corresponding to two intersubband collective modes, namely, spin and charge density excitations (SDE and CDE).[8] The first is associated with Coulomb interaction between an electron in the first excited subband and a hole left behind in the ground subband (excitonic shift), whereas the second is associated with the macroscopic polarization of the quasi-2DES perpendicular to the QW plane (depolarization shift). The excitonic shift reduces the SDE and CDE energies with respect to the SPE energy, whereas the depolarization shift increases the CDE energy.[8,9] When a magnetic field is applied, the SPE band narrows (Fig. 1, top). The SPE bandwidth (Δ) achieves a minimum at $B_c = 1.2$ T and increases in the range of higher fields. At the same magnetic field, B_c, the energies of both the collective modes have extrema, namely, the CDE energy has a minimum, and the SDE energy has a maximum (Fig. 2). Neither Δ nor the CDE (SDE) energy conserves under the magnetic field reversal, which is an indication of a *rotational anisotropy* of the intersubband excitation energies.

The experimental data can be understood if we note that the primary effect of $B_{\|}$ on the quasi-2D system is shifts of the quantum subbands in the momentum space.[1] At $B_{\|}=0$ and $q^{\|}=0$, the SPE energies coincide for all electron states in the ground subband. The shifts of the quantum subbands induced by the in-plane magnetic field result in lifting the degeneracy of the SPE levels. Each SPE is supplemented with an energy contribution $\hbar^2/m(\vec{k},\vec{q}^B)$, where $\vec{k}$ is the electron in-plane momentum and $\vec{q}^B = e/\hbar c[\vec{\Delta}z\times\vec{B}]$ is the separation between the ground and first excited subbands in the momentum space. Here, $\vec{\Delta}z$ is a vector aligned with the z axis and equal to $|z_{00}-z_{11}|$, where $z_{nn} = \int dz\,\psi_n^*(z) z \psi_n(z)$ [$\psi_n^*(z)$ is the z component of the electron wave function in the nth subband]. The SPE energies form a continuous band with a bandwidth $2\hbar^2/mk^Fq^B$, where $\vec{k}^F$ is the electron Fermi momentum in the ground subband. The SPE bandwidth conserves under the rotation of $\vec{B}_{\|}$ around the z axis.

A symmetry between the direct SPE's ($q^{\|}=0$) at $B_{\|}\neq0$ and indirect SPE's ($q^{\|}\neq0$) can be easily detected at $B_{\|}=0$. In the latter case, the analogue of $\vec{q}^B$ is $\vec{q}^{\|}$, and SPE energies form a band with a width $2\hbar^2/mk^Fq^{\|}$. The SPE bandwidth now conserves under the rotation of $\vec{q}^{\|}$ around the z axis. So, since both $q^{\|}$ and $B_{\|}$ are nonzero, the rotational symmetry is broken. The SPE bandwidth is determined by both $\vec{q}^{\|}$ and $\vec{q}^B$. If the following resonance condition is fulfilled:

$$\vec{q}^B = -\vec{q}^{\|}, \tag{1}$$

all SPE's have the same energy (see the plot of energy versus momentum in Fig. 2). It is worth noting that, even if all

SPE's had the same energy, the SPE band would not turn to a δ-function. In reality, it is always broadened owing to the short phase coherence time of SPE's.[8,10]

In accordance with the above discussion, B_c is the magnetic field at which condition (1) is satisfied. This assignment is directly supported by an experimental observation of a linear dependence of B_c on $q^{\|}$, (see the inset to Fig. 2). Given the value of B_c measured at known $q^{\|}$, we have calculated Δz ($\Delta z = q^{\|} l_B^2$, where $l_B = \sqrt{c\hbar/eB}$ is the magnetic length), which is a parameter characterizing the asymmetry of the confining potential. Taking into account the uncertainties in $q^{||}$ and B_c of $\pm 0.05 \times 10^5$ cm^{-1} and ± 0.1 T, respectively, we have found that Δz equals 55 ± 7 Å. For comparison, we have calculated Δz using the local-density approximation[11] with the known sample parameters and have obtained $\Delta z = 54$ Å, which is in perfect agreement with the experiment.

Similarly to the SPE bandwidth, the energies of collective modes are expected to reach their extrema at B_c. This is a direct consequence of the fact that both the excitonic and polarization shifts are very week functions of $q^{\|}$, as long as $q^{\|}$ is small, compared with the inverse average distance between electrons in the ground and first excited subbands.[12] This condition covers the whole range of $q^{\|}$, which can be scanned using inelastic light scattering. The constant excitonic and polarization shifts at $q^{\|}=0$ can therefore be used as a good zero approximation over the entire range of studied $q^{\|}$. Given that condition (1) is satisfied, the SPE spectrum becomes the same as in the case of $q^{\|}=0$ and $B=0$, and since the excitonic and polarization shifts are merely constants, the energies of both collective modes should be equal to their values at $q^{\|}=0$ and $B=0$. Since the CDE dispersion under an in-plane magnetic field is positive, and the SDE dispersion is negative (Fig. 2), one arrives at a conclusion that the CDE energy has a minimum at B_c, whereas the SDE energy has a maximum. Therefore, the CDE (SDE) extremum can also be used in determining B_c. The CDE mode is especially convenient for this purpose since its scattering efficiency is more than an order of magnitude higher than that of the SDE mode, therefore its energy can be determined with a very high accuracy.

Figure 2 shows that the CDE (SDE) energy ($E_{C(S)}$) about $\vec{q}^{\|} \perp \vec{B}_{\|}$ is described by a parabola with a maximum (minimum) at B_c. By rotating $\vec{q}^{\|}$ around the z axis, we have found that the same quadratic term is present at all arbitrary orientations of $\vec{q}^{\|}$ and $\vec{B}_{\|}$. On the contrary, the linear term decreases with decreasing angle between $\vec{q}^{\|}$ and $\vec{B}_{\|}$. As a consequence, the $B_{\|}$ at which $E_{C(S)}$ has a minimum (maximum) shifts to lower magnetic fields. An example of $E_{C(S)}$ measured at $\vec{q}^{\|} \| \vec{B}_{\|}$ is shown in the top (bottom) inset to Fig. 3. The energy $E_{C(S)}$ has its minimum (maximum) located at zero-magnetic field exactly. Using this fact, we have drawn up a simple approximation for $E_{C(S)}$ in an in-plane magnetic field. The energy $E_{C(S)}$ at arbitrary orientations of $\vec{q}^{\|}$ and $\vec{B}_{\|}$ was decomposed into a quadratic isotropic part (E_i), measured at $\vec{q}^{\|} \| \vec{B}_{\|}$, and a linear anisotropic part (E_a), obtained by subtracting E_i from $E_{C(S)}$ (see the insets to Fig. 3). The angular dependence of E_a for a set of magnetic fields is shown in Fig. 3. At a fixed magnetic field, it is a sinusoid

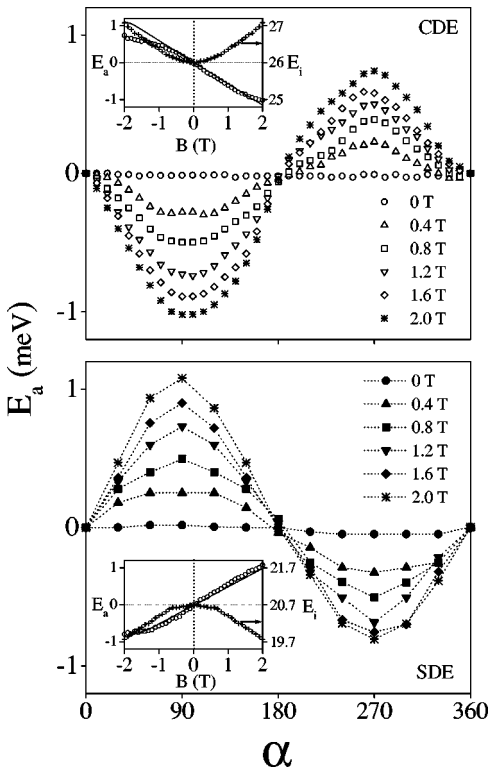

FIG. 3. Measured anisotropic energies of CDE (top) and SDE (bottom) versus angle α between the magnetic field and momentum for different magnetic fields ($q^{||} = 1.0 \times 10^5$ cm^{-1}). The top (bottom) inset shows the CDE (SDE) anisotropic energy measured at $\vec{q}^{||} \perp \vec{B}_{||}$ and CDE (SDE) isotropic energy measured at $\vec{q}^{||} \| \vec{B}_{||}$. The solid lines are anisotropic energies calculated by the TDLDA approximation.

with a period of 360°. The anisotropic energy can thus be expressed in terms of the scalar product $(\vec{q}^{B}, \vec{q}^{\|})$, whereas the entire $B_{\|}$-dependent part of $E_{C(S)}$ is then proportional to $q^{B2} - 2(\vec{q}^{\|}, \vec{q}^{B})$. The factor -2 in front of $(\vec{q}^{B}, \vec{q}^{\|})$, reflects the fact that $E_{C(S)}$ has a minimum (maximum) when condition (1) is fulfilled.

The experimental results were compared to theoretical calculations based on the TDLDA approximation. The modification of the electron spectrum due to an in-plane magnetic field was included in the first order of the perturbation theory.[13] One specific case of theoretically calculated E_a at $\vec{q}^{\|} \perp \vec{B}_{\|}$ is illustrated by the insets to Fig. 3. The agreement between the experiment and theory is almost perfect in the magnetic-field range of -1 to 2 T, but notably worse in the range of $B_{\|} < -1$ T, where the measurements of E_a deviate from the linear function. It is noteworthy that at $B_{\|} < 0$ T the SPE band broadens as the absolute value of the magnetic field increases. As a result, the collective modes emerge in the SPE continuum at a field of only $B_{\|} \approx -1$ T and are Landau damped. This leads to a broadening of the CDE (SDE) line and an effective shift of its peak towards the SPE band. On the contrary, the CDE (SDE) line in the range $B_{\|} > 0$ is not affected by the SPE continuum at fields of up to 3 T. It is, therefore, not surprising that the agreement with the theory is remarkably better in the latter case.

After testing the theoretical model on the dependence of $E_{C(S)}$ on $B_{\|}$ at fixed $q^{\|}$, we employed it in simulating $E_{C(S)}$

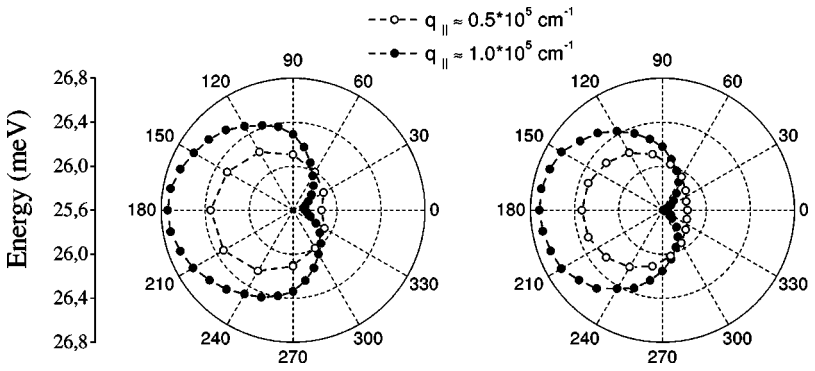

FIG. 4. Polar plot of the measured (left) and calculated (right) total energy of the CDE mode at $B=1$ T and two values of $q^{\|}$: 1.0 and 0.5 $\times 10^5$ cm^{-1}. The effective mass of CDE is assumed to be $0.011m_0$.

as a function of $q^{\|}$ at a fixed $B_{\|}$, which situation is considerably more difficult for an accurate experimental study. At small magnetic fields, the total energy was found to be symmetrical under the interchange of $q^{\|}$ and q^B. Therefore, it can be approximated as

$$E_{C(S)}=E^0_{C(S)}+\frac{\hbar^2}{2m_{C(S)}}\left(\vec{q}^{\|}-\frac{e}{\hbar c}[\vec{\Delta}z\times\vec{B}]\right)^2, \qquad (2)$$

where $E^0_{C(S)}$ is the CDE (SDE) energy at $B_{\|}=0$ and $q^{\|}=0$. The factor in front of the brackets is expressed in terms of an effective mass that is different for each collective mode.[14] In the QW's under investigation, $m_C=0.011\pm0.0025m_0$ for CDE, and $m_S=-0.013\pm0.003m_0$ for SDE. Equation (2) resembles a similar expression for quasi-2D electrons in a small in-plane magnetic field included in the first order of the perturbation theory with $m_{C(S)}$ substituted for the electron effective mass and Δz substituted for z_{nn}. Figure 4 shows the measurements and calculations by Eq. (2) of the angular dispersion of the entire CDE energy at $B=1$ T and two different values of $q^{\|}$, namely, 1.0 and 0.5×10^5 cm^{-1}. The rotational anisotropy of the total CDE energy observed in the experiment is fairly accurately reproduced by the calculations.

In conclusion, we have demonstrated a dispersion anisotropy of intersubband excitations in an asymmetrical quasi-2D electron system induced by an in-plane magnetic field. The anisotropic energy is found to be a linear function of the magnetic field and in-plane momentum of the excitations. We have used resonance condition (1) to measure Δz due to the asymmetry of the QW confining potential. Our experimental technique has allowed us to measure Δz at small magnetic fields, when the coupling between different quantum subbands is negligible. In addition to the possibility of measuring Δz, the symmetry between the magnetic-field-induced shift in the momentum space and the in-plane momentum of the collective excitations, which is an obvious consequence of Eq. (2), opens a remarkable opportunity to study the dispersion of intersubband collective modes. The experimentally accessible range of in-plane momenta can be increased by a factor of more than two by adding the shift to the transferred momentum. Moreover, one can get around tremendous experimental problems associated with fine tuning of the in-plane momentum by using an experimental configuration similar to that described in this paper, where the in-plane momentum is fixed and the in-plane magnetic field is varied.

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[14] The effective mass is a phenomenological parameter defined by the properties of the quasi-2D system, namely, the electron concentration, confining potential, and others, and can be different in different structures. The only universal component here is the expression in the brackets, which is the lowest-order approximation to the CDE and SDE energies in a parallel magnetic field.