RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 43, NUMBER 8 15 MARCH 1991-I

Quenching of collective phenomena in combined intersubband-cyclotron resonances in GaAs

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(Received 16 November 1990)

Intersubband resonances of high-mobility electron inversion layers in AlAs-GaAs heterojunctions from the ground to the first excited subband are investigated with far-infrared spectroscopy in magnetic fields tilted with respect to the sample normal. In this configuration, combined intersubband-cyclotron transitions with changes in Landau-level index ΔN are allowed. Up to three different transitions $\Delta N=0, \pm 1$ are observed simultaneously, and their collective shifts are found to depend on the Landau-level filling factor. Compared to the main transition $\Delta N=0$, collective phenomena are observed to be suppressed for the combined resonances $\Delta N=\pm 1$. This allows one to determine the subband separation and the size of the collective shift at zero magnetic-field strength, providing a sensitive test of the interface potential in $Al_xGa_{1-x}As$-GaAs heterojunctions.

In quasi-two-dimensional (2D) space-charge layers in semiconductors the carriers are confined in one direction in a narrow potential establishing a discrete subband ladder.[1] A powerful tool to probe the confinement potential is provided by the study of intersubband resonances (ISR) induced by far-infrared (FIR) radiation. If coupling of the electron motions parallel and perpendicular to the 2D plane is weak, ISR excitation requires perpendicularly polarized FIR radiation. The ISR positions are then shifted collectively by depolarization and its final-state correction from the subband separations.[1] With a proper theory on hand the size of the collective shift might be determined by a self-consistent numerical calculation of the transition energies. However, this is a complex task and an approach is favorable that allows one to separate experimentally the single-particle from the many-body contribution to the ISR transition energy. Here we discuss how ISR in tilted magnetic-field configuration can be applied advantageously to separate the single-particle and the many-body contribution to the transition energy.

ISR in a magnetic field B tilted by an angle θ with respect to the 2D-plane normal were first explored for electrons on liquid helium[2] and on Si (Ref. 3) at constant excitation frequency in sweeping the surface charge density N_s. Recently frequency-domain studies of electron inversion layers in $Al_xGa_{1-x}As$-GaAs heterojunctions with FIR radiation at glancing incidence were also reported.[4] Assuming that the parallel magnetic-field component $B_{\parallel}=B\sin\theta$ induces a small perturbation, the 2D subband dispersion is fully quantized in[1,5,6]

$$E_{i,N}=E_i+(N+\tfrac{1}{2})\hbar\omega_{c\perp}+E_{\text{dia}}\,, \tag{1}$$

where i and N indicate subband and Landau-level quantum numbers, respectively. E_i is the subband-bottom energy in the absence of B and $\omega_{c\perp}=eB_{\perp}/m^*$ the cyclotron frequency determined by the perpendicular magnetic-field component $B_{\perp}=B\cos\theta$. The diamagnetic shift of the subband bottom by the parallel magnetic-field component $E_{\text{dia}}=e^2B_{\parallel}^2[(z^2)_{ii}-(z_{ii})^2]/2m^*$ is related to matrix elements $z_{ij}^m=\langle i|z^m|j\rangle$ in the absence of B in the direction z perpendicular to the 2D plane. Since the perpendicular and parallel motions are coupled in tilted magnetic-field configuration, combined transitions $i,N\rightarrow j,N'$ with change in Landau quantum number $\Delta N=N'-N=\pm 1, \pm 2, \ldots$ become possible in addition to the main transition $\Delta N=0$. Here we are concerned with a detailed analysis of the collective shift on transitions with different ΔN. Our experiment is compared to a theory[5] by Ando, and is in good agreement with the prediction. The collective shift depends on ΔN and the filling factor $\nu=2\pi l_{\perp}^2N_s$ with $l_{\perp}=(\hbar/eB_{\perp})^{1/2}$ of the Landau levels. It is suppressed for the combined resonances, allowing one to measure the single-particle subband separation in an optical resonance experiment.

Our samples are modulation-doped AlAs-GaAs heterojunctions as described previously[7,8] with electron density $N_s\simeq 2.1\times 10^{11}$ cm^{-2} and mobility in excess of 5×10^5 cm^2/V s at liquid-helium temperatures. The 2D channel can be depleted via a semitransparent front gate. Advantageously, ISR is studied in transmission at 2 K with a rapid-scan Fourier-transform spectrometer using the grating-coupler technique.[7] Experimentally, we determine the relative change in transmission $-\Delta T/T=[T(0)-T(N_s)]/T(0)$ which is proportional to the real part of the high-frequency conductivity $\tilde{\sigma}_{zz}(\omega)$ in the direction perpendicular to the 2D plane.[9]

Figure 1 shows experimental $-\Delta T/T$ at tilt angles $\theta\simeq 23°$ and 45° for an electron inversion layer on GaAs with $N_s=(2.1\pm 0.1)\times 10^{11}$ cm^{-2}. The spectra reflect ISR from the occupied ground $i=0$ to the first excited

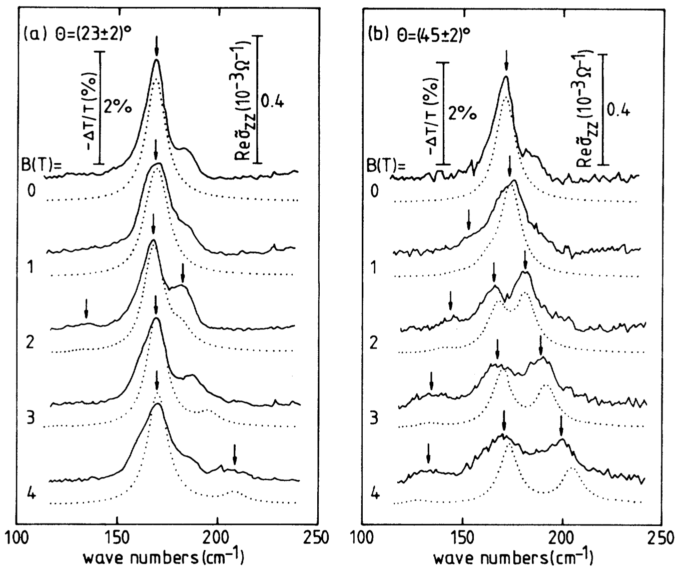

FIG. 1. Intersubband resonance $0 \rightarrow 1$ of an electron inversion layer on GaAs with $N_s = (2.1 \pm 0.1) \times 10^{11}$ cm^{-2} in a magnetic field B tilted by angles (a) $\theta = (23 \pm 2)°$ and (b) $(45 \pm 2)°$ with respect to the 2D-plane normal. Experimental resonance positions are marked by arrows. The dotted lines represent the real part of the high-frequency conductivity $\tilde{\sigma}_{zz}(\omega)$ as discussed in the text. The baselines of the measured $-\Delta T/T$ and calculated real part of $\tilde{\sigma}_{zz}(\omega)$ are shifted for clarity with respect to each other.

subband $i = 1$. At $B = 0$ the ISR line shape is split into a strong resonance around 170 cm^{-1} and a shoulder about 15 cm^{-1} higher in energy. By fitting the main resonance to a Lorentzian, we find that the ISR broadening is more than 1 order of magnitude larger than can be expected from the dc mobility. This is unusual if compared to earlier observations on Si, where the experimental and calculated ISR half-widths do not deviate that strongly.[10-13] From our experiment it cannot be ruled out that inhomogeneity in N_s causes the broad and split ISR line shape. However, in electron ISR experiments on liquid-helium surfaces, sidebands were observed as well and attributed to the collective modes of a strongly correlated system.[2,14] Electron-electron interactions might also broaden the ISR.[1] At present the mechanisms ruling the linewidth and line shape of electron ISR in GaAs are not well understood and deserve theoretical attention.

As shown most prominently for $\theta \simeq 45°$ in Fig. 1(b), the main ISR splits into several resonances at finite B. Up to three are observed simultaneously. The one close to the ISR position at $B = 0$, increasing marginally with increasing B, is the transition $\Delta N = 0$, whereas the other two are combined intersubband-cyclotron resonances $\Delta N = \pm 1$. The combined resonance $\Delta N = -1$ decreases in position with increasing B and disappears when the magnetic quantum limit is reached. Higher-order transitions $\Delta N = \pm 2, \pm 3, \ldots$ are too weak to be observed here. Qualitatively, at $\theta \simeq 23°$ we observe the same transitions $\Delta N = 0, \pm 1$; however, the oscillator strengths of the combined resonances compared to the main transition are much smaller. Therefore the combined transition $\Delta N = -1$ could be observed only in a narrow magnetic-field regime around 2T.

A detailed analysis of the experiment requires knowledge of the high-frequency conductivity $\tilde{\sigma}_{zz}(\omega)$ in tilted magnetic fields. The dotted lines in Fig. 1 show the calculated real part of $\tilde{\sigma}_{zz}(\omega)$ according to Eqs. (2.46) and (2.47) of Ref. 5 predicted by Ando within the framework of the density-functional theory for sufficiently weak parallel magnetic fields. For simplicity we have assumed a two-subband system in the electric quantum limit at zero temperature. The linewidth is described by a phenomenological scattering time $\tau = 0.9 \times 10^{-12}$ s independent of magnetic field and frequency, as deduced from the $B = 0$ spectra. The agreement with the experimental $-\Delta T/T$ is satisfactory but not perfect. Our calculated $\tilde{\sigma}_{zz}(\omega)$ is not strictly valid at high magnetic fields because mixing between subbands increases with B. We attribute differences in experimental and theoretical amplitudes at smaller fields to our assumption of a constant scattering time. In spite of this simple assumption the resonance positions at sufficiently small B are excellently described by the theoretical $\tilde{\sigma}_{zz}(\omega)$.

To determine the transition energies $\tilde{E}_{10,\Delta N}$ in tilted magnetic fields, we have to evaluate the poles of $\tilde{\sigma}_{zz}(\omega)$. This is most easily accomplished for a two-subband system by considering the limit of infinite scattering time τ, and treating the transitions $0,N \rightarrow 1,N'$ as well separated in frequency space. After some algebra we obtain from Ref. 5

$$\tilde{E}^2_{10,\Delta N} = (E_{10} + \Delta N \hbar \omega_{c\perp} + \Delta E_{\rm dia})^2 + \gamma_{11} C_{\Delta N} E^2_{10} , \quad (2)$$

where $E_{10} = E_1 - E_0$ is the subband separation in the absence of B, and $\Delta E_{\rm dia}$ is the difference of the diamagnetic shifts of both subbands. The last term in Eq. (2) is the collective shift of the transition ΔN in tilted magnetic fields, given as a product of the collective shift γ_{11} in the absence of B with a correction factor $C_{\Delta N}$. The correction factor is defined by

$$C_{\Delta N} = \frac{2}{\nu} \sum_{\substack{N \\ \text{occupied}}} J_{N,N+\Delta N}(\Delta_{10})^2 \quad (3)$$

with $\Delta_{10} = (l_\perp / l_\parallel^2)(z_{11} - z_{00})$ and

$$J_{N,N'}(x) = J_{N',N}(-x) = \left[\frac{N'!}{N!}\right]^{1/2} \left[\frac{x}{2^{1/2}}\right]^{N-N'} \times L_{N'}^{N-N'}\left[\frac{x^2}{2}\right] \exp\left[-\frac{x^2}{4}\right] .$$

The expression $J_{N,N'}(x)$ essentially describes the overlap integral of cyclotron orbits displaced from each other by $(z_{11} - z_{00})/l_\parallel^2$ in $k_\parallel$ space. Equation (3) can be evaluated analytically at integer filling factors in the limit $\Delta_{10} \ll 1$. In this limit we can approximate the associated Laguerre polynomials $L_N^\alpha(x^2/2)$ by $L_N^\alpha(0) = (n+\alpha)!/n!\alpha!$. Table I summarizes the result for the transitions $\Delta N = 0, \pm 1$ at integer filling factors ν larger than two. The correction factors for even and odd integers are different, i.e., the $C_{\Delta N}$ depend on ν. In the magnetic quantum limit $\nu \lesssim 2$, however, $C_{\Delta N}$ is independent of the filling factor. In this

TABLE I. Correction factors C_0 and $C_{\pm 1}$, calculated from Eq. (3) in the limit $\Delta_{10} \ll 1$ for even and odd filling factors $\nu = 2\pi l_1^2 N_s$ larger than two. In the magnetic quantum limit $\nu \leq 2$ the correction factors are independent of the filling factor and given by $C_{-1}=0$, $C_{+1}=\Delta_{10}^2/2$, and $C_0 = 1-\Delta_{10}^2/2$.

	C_{-1}	C_0	C_{+1}
Even filling factor	$\frac{\Delta_{10}^2}{4}\left(\frac{\nu}{2}-1\right)$	$1-\frac{\Delta_{10}^2}{4}\nu$	$\frac{\Delta_{10}^2}{4}\left(\frac{\nu}{2}+1\right)$
Odd filling factor	$\frac{\Delta_{10}^2}{8\nu}(\nu-1)^2$	$1-\frac{\Delta_{10}^2}{4\nu}(\nu^2+1)$	$\frac{\Delta_{10}^2}{8\nu}(\nu+1)^2$

case we have $C_{-1}=0$, $C_{\pm 1} = \Delta_{10}^2/2$, and $C_0 = 1-\Delta_{10}^2/2$.

Figure 2 shows the correction factors $C_{\Delta N}$ for the transitions $\Delta N = 0, \pm 1$ at a comparatively large tilt angle of $\theta = 45°$ and a density $N_s = 2.1 \times 10^{11}$ cm^{-2} vs B. The dotted lines represent the limit $\Delta_{10} \ll 1$, the solid lines the exact numerical evaluation of Eq. (3). Please note the oscillations in $C_{\Delta N}$ with filling factor. C_0 shows maxima at even-integer filling factors, whereas C_{+1} and C_{-1} exhibits dips. These oscillations arise from occupational influences. C_0 does not strongly depend on B for filling factors larger than two. C_{+1} and C_{-1} increase and decrease, respectively, with magnetic-field strength. The correction factor C_{-1} vanishes in the magnetic quantum limit, reflecting the fact that the transition $\Delta N = -1$ is no longer possible. The limit $\Delta_{10} \ll 1$ is a surprisingly good approximation, although it slightly underestimates C_0 and overestimates $C_{\pm 1}$. At smaller tilt angles, $\theta < 45°$, the limit $\Delta_{10} \ll 1$ approximates Eq. (3) even better. Qualitatively, with decreasing θ, C_0 increases and $C_{\pm 1}$ decreases in magnitude. At sufficiently small B the correction factors for the higher-order transitions $\Delta N = \pm 2, \pm 3, \ldots$ are negligibly small, e.g., in the limit $B \to 0$ we have $C_{\pm 2} = C_{\pm 1}^2/3$.

Since for the combined resonances $C_{\Delta N}$ is smaller than C_0, the main transition $\Delta N = 0$ and the combined transitions $\Delta N = +1, +2, \ldots$ become degenerate in energy at small but finite B [see Eq. (2)]. To describe correctly the transition energies, we have to find the poles of $\tilde{\sigma}_{zz}(\omega)$ including coupling between the nearly degenerate levels. From Ref. 5 we deduce that coupling of the main to the combined transitions $\Delta N = +1, +2, \ldots$ is described by the equation

$$\tilde{E}_{10,\Delta N \pm}^2 = \tfrac{1}{2}\{\tilde{E}_{10,\Delta N}^2 + \tilde{E}_{10,0}^2 \pm [(\tilde{E}_{10,\Delta N}^2 - \tilde{E}_{10,0}^2)^2 + 4C_0 C_{\Delta N}\gamma_{11}^2 E_{10}^4]^{1/2}\} . \tag{4}$$

Figure 3 summarizes measured ISR positions as a function of the magnetic-field strength B for tilt angles $\theta \simeq 23°$ and 45°. The dashed lines indicate transition energies for $\Delta N = 0, \pm 1$ predicted by Eq. (2). In our experiment coupling is important for the transitions $\Delta N = 0$ and $+1$. The solid lines represent coupled energies $\tilde{E}_{10,1\pm}$ according to Eq. (4). The agreement with the experiment is excellent at least up to about 4 T. The deviations between the experimental and the calculated transition energies at higher magnetic fields are due to increased Landau-level mixing, changing the subband dispersion described by Eq. (1).[15] The small differences in $C_{\Delta N}$ caused by taking the limit $\Delta_{10} \ll 1$ of Eq. (3) or the exact numerical results are not important for our experiment. The filling-factor dependence of $C_{\Delta N}$ is also too weak to be resolved at small B. The matrix elements and subband separation E_{10} are cal-

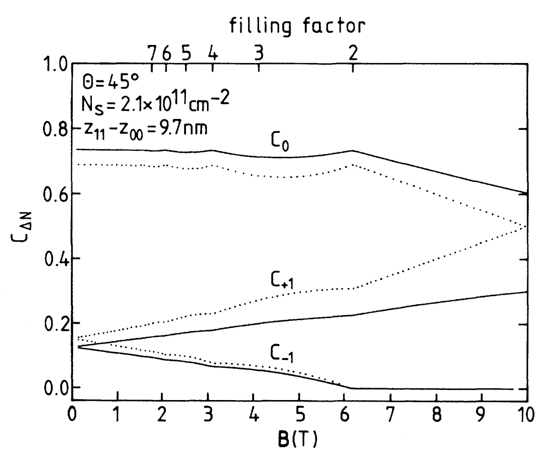

FIG. 2. Calculated correction factors C_0 and $C_{\pm 1}$ vs magnetic-field strength B for an electron inversion layer on GaAs at tilt angle $\theta = 45°$. Dotted lines reflect the limit $\Delta_{10} \ll 1$ of Eq. (3), solid lines represent the exact numerical result.

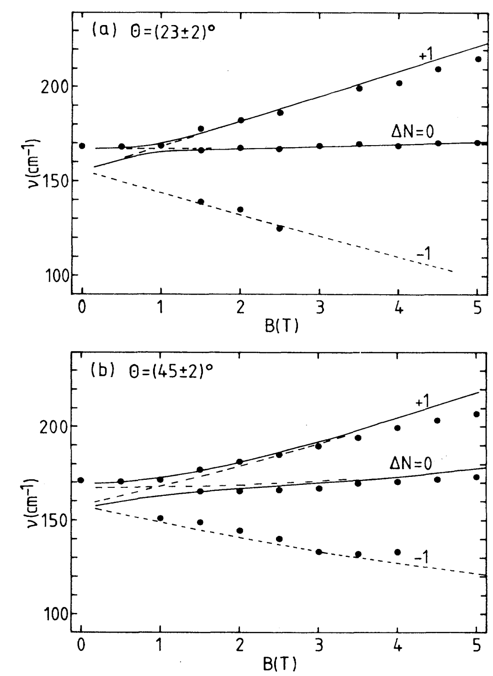

FIG. 3. Intersubband resonance energies from the ground to the first excited subband for 2D electrons on GaAs with $N_s = (2.1 \pm 0.1) \times 10^{11}$ cm^{-2} vs magnetic-field strength B at tilt angles (a) $\theta = (23 \pm 2)°$ and (b) $(45 \pm 2)°$. $\Delta N = 0, \pm 1$ indicate the change in Landau-level quantum number associated with the transitions. Dashed lines are calculated from Eq. (2), solid lines represent the coupled transitions $\Delta N = 0$ and $\Delta N = +1$ according to Eq. (4).

culated using the self-consistent variational formalism of Stern.[16] This ansatz requires knowledge of the depletion charge $N_{\rm depl}$, influencing the triangular-shaped interface potential. In Fig. 3 we have taken $N_{\rm depl}=0.75\times10^{11}$ cm^{-2}, determined previously from ISR experiments in parallel magnetic fields.[8]

At sufficiently small tilt angles, as shown in Fig. 3(a), we can neglect mode coupling. In the limit of vanishing B the squared energies predicted by Eq. (2) for the transitions $\Delta N=0, \pm1$ extrapolate to

$$\tilde{E}^2_{10,\Delta N}=E^2_{10}\{1+\gamma_{11}[1-|\Delta N|+[(2-|\Delta N|)/4] \times\pi N_s\tan^2\theta(z_{11}-z_{00})^2]\}\ , \qquad (5)$$

i.e., at small θ, $\tilde{E}_{10,0}$ reflects the ISR transition energy $\tilde{E}_{10}$ $(B=0)$ and $\tilde{E}_{10,\pm1}$ the subband separation E_{10} $(B=0)$. From our experiment we deduce for $N_s=(2.1\pm0.1)\times10^{11}$ cm^{-2} a subband separation of about 156 cm^{-1} and a collective shift of about (14 ± 4) cm^{-1}. These values are consistent with results obtained previously from ISR experiments in parallel magnetic fields at the same surface charge density.[8]

In conclusion, ISR of electron inversion layers on GaAs are studied with FIR spectroscopy in tilted magnetic fields. In addition to the main ISR transition with conserved Landau quantum number, combined intersubband-cyclotron resonances are observed. The collected shift of the transition energies due to depolarization and its final-state correction are analyzed. The experiment confirms the shifts predicted by Ando in the framework of the density-functional theory.

We would like to thank J. P. Kotthaus and U. Merkt for valuable discussions and the Deutsche Forschungsgemeinschaft for financial support.

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