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Combined intersubband-cyclotron resonances in a GaAs-$Ga_{1-x}Al_xAs$ heterojunction

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The quasi-two-dimensional electron gas in GaAs-$Ga_{1-x}Al_xAs$ heterojunctions is studied with far-infrared Fourier transform spectroscopy in a strip-line configuration that yields nearly perfect light polarization perpendicular to the electron layer. In this configuration, we observe simultaneously diamagnetically shifted intersubband resonance, combined intersubband-cyclotron resonances, and cyclotron resonance in tilted magnetic fields. In particular, this allows us to determine the depolarization shift of the $B=0$ intersubband resonance.

Intersubband resonances are the most characteristic excitations of quasi-two-dimensional (2D) electron systems.[1] Classically, they correspond to a bound motion perpendicular to the electron layer in the z direction and are excited most obviously by light polarized in this direction. Such polarization is attained in strip-line configurations which have already been utilized in the first studies of intersubband[2] and combined resonances[3] on Si, both carried out with far-infrared lasers. More recently, combined intersubband-cyclotron resonances also have been observed by inelastic light scattering in GaAs-$Ga_{1-x}Al_xAs$ quantum wells.[4,5]

Compared to the Raman experiments, far-infrared spectroscopy has the advantage that there is no illumination with visible light which increases the electron density above its equilibrium value. Fourier spectroscopy has the particular advantage that the intersubband frequency needs not be tuned by a gate voltage or a magnetic field to coincide with a fixed laser frequency.[6] Because of the weak transmittance of a strip line, Fourier spectroscopy of intersubband resonance in GaAs-$Ga_{1-x}Al_xAs$ heterojunctions was previously studied with radiation incident perpendicularly to the samples.[7-9] Then the light is polarized parallel to the electron layer and excitation of intersubband resonance was achieved in magnetic fields with directions tilted away from the surface normal. In such tilted magnetic fields, the light is coupled to intersubband resonance via cyclotron resonance. However, this scheme only works in the resonant situations $E_{10}\cong\hbar\omega_{c\perp}$ when the subband spacing E_{10} is a multiple $r=1,2$ of the cyclotron energy $\hbar\omega_{c\perp}=e\hbar B_\perp/m^*$ of the perpendicular magnetic field component $B_\perp$.[9]

Here we report on Fourier spectroscopy of GaAs-$Ga_{1-x}Al_xAs$ heterojunctions in a strip-line configuration. In this geometry, the magnetic field becomes an independent variable and tilted magnetic fields offer new spectroscopic possibilities. The observation of combined intersubband-cyclotron resonances allows us to determine experimentally the depolarization shift of the $B=0$ intersubband resonance.[10,11] We also discuss an enhancement of cyclotron masses due to coupling of electric subbands in tilted magnetic fields, and the excitation mechanism of cyclotron resonance with light polarized in the z direction, i.e., perpendicularly to the plane of its classical motion.

The present sample has an electron density $n_s=2.2\times10^{11}$ cm^{-2} at zero gate voltage V_g and is depleted at $V_g=-1.0$ V using the front Ag metallization (1000 Å) as a gate contact. The two-dimensional electron gas is separated from the sample surface by an undoped (330 Å) and doped (300 Å) $Ga_{1-x}Al_xAs$ ($x=0.36$) layer, as well as a GaAs cap layer (200 Å). The dc mobility $\mu\simeq210000$ cm^{2}V^{-1}s^{-1} at $T=4.2$ K. The experiments are carried out with a rapid-scan Fourier transform spectrometer at liquid-helium temperature $T\cong2$ K. Transmittance ratios $T(n_s)/T(n_s=0)$ are recorded and large numbers of scans (2×6000) are imperative to achieve the required low noise level of about 0.2%.

Spectra in tilted magnetic fields ($\theta=45°$) of various amplitudes B are depicted in Fig. 1. The inset shows the experimental configuration with its light path. At $B=0$, we detect intersubband resonance $0\rightarrow1$ between the ground ($i=0$) and the first excited ($i=1$) electric subband. At $B=1.5$ T, satellites to this main resonance are observed. They shift away from the intersubband resonance as the strength of the magnetic field is increased. These satellites represent combined intersubband-cyclotron transitions. At $B=3.5$ T, cyclotron resonance starts to develop at wave numbers $\bar{\nu}\cong30$ cm^{-1}. At lower magnetic fields, cyclotron resonance is not detectable at our noise level $\simeq0.2\%$.

In magnetic fields $B\gtrsim4$ T, the satellite on the left-hand side has vanished but the satellite on the right-hand side remains clearly apparent. This observation is explained by level occupation since the filling factor $\nu=n_sh/eB_\perp=4$ at $B=3.2$ T. In higher magnetic fields, the combined resonance $E_{10}-\hbar\omega_{c\perp}$ which is composed of $i=0,n\rightarrow i=1$ $n-1$ transitions (n Landau index) becomes weak as its last initial state $i=0,n=1$ is depopulated. On the other hand, the resonance $E_{10}+\hbar\omega_{c\perp}$ consists of $0,n\rightarrow1,n+1$ transitions of which the $0,0\rightarrow1,1$ transition is left in the magnetic quantum limit ($\nu\leq2$) reached at $B=6.4$ T.

In Fig. 1, the position $\bar{\nu}=(167\pm1)$ cm^{-1} of the $B=0$ intersubband resonance moves to slightly lower values in low magnetic fields ($B\lesssim3.5$ T). This is presumably

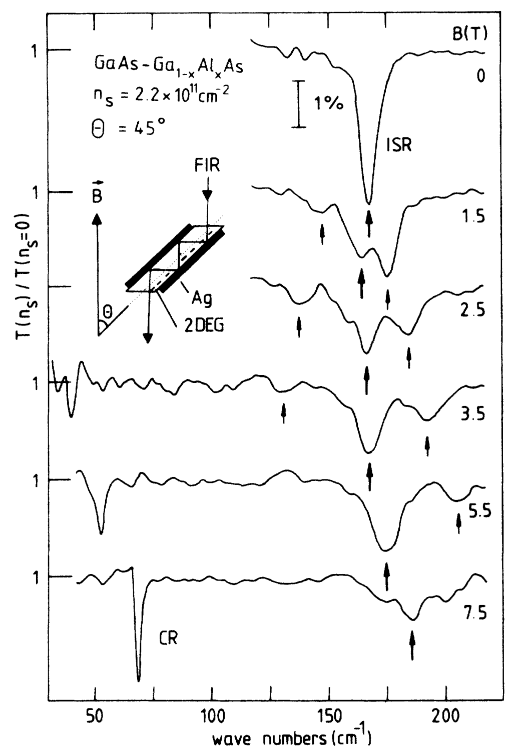

FIG. 1. Transmittance ratios measured for various amplitudes of a tilted magnetic field ($\theta=45°$). The geometry and the strip line with its light path are sketched in the inset. Horizontal bars on the ordinate indicate values $T(n_s)/T(0)=1$. Bold and light arrows mark positions of diamagnetically shifted intersubband resonances and combined intersubband-cyclotron resonances, respectively. Note the transfer of oscillator strength from intersubband (ISR) to cyclotron (CR) resonance.

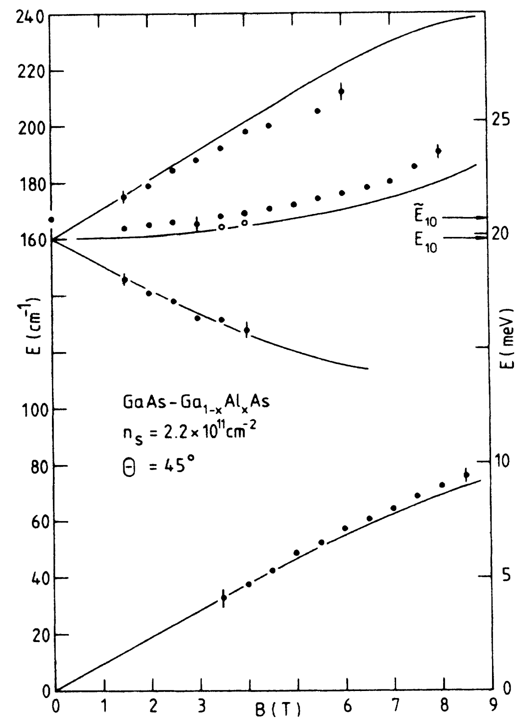

FIG. 2. Resonance energies vs magnetic field strength. The solid lines are calculated for the triangular-well approximation of the electric-surface potential ($F_s=1.59\times10^4$ V cm^{-1}, $m^*=0.068m_e$) by second-order perturbation theory. Arrows indicate the energy of the measured $B=0$ intersubband resonance $\tilde{E}_{10}$ which is depolarization shifted and the single-electron subband spacing E_{10} which is extrapolated from the positions of the combined resonances.

caused by a partial suppression of the depolarization shift[11] discussed below. At $B\gtrsim5.5$ T, its position shifts to higher wave numbers. This we interpret as a diamagnetic shift. Hence, in accordance with the notation[12] for purely parallel ($\theta=90°$) magnetic fields, we address this resonance as diamagnetically shifted intersubband resonance. Its intensity significantly decreases, whereas the one of cyclotron resonance strongly increases as the amplitude of the magnetic field is increased.

Experimental resonance positions are given in Fig. 2 as closed circles. For fields $B=3.5$ and 4.0 T, the added energies of cyclotron resonance $\hbar\omega_{c\perp}$ and combined resonance $E_{10}-\hbar\omega_{c\perp}$ are indicated by the two open circles. Their distance $\cong0.4$ meV to the position of the diamagnetically shifted intersubband resonance is caused by depolarization which influences the position of the intersubband resonance but not the ones of cyclotron and combined resonances, provided the amplitudes of the latter are sufficiently small.[11]

The single-electron subband spacing E_{10} at $B=0$ thus is obtained when the positions of combined resonances $E_{10}\pm\hbar\omega_c$ are extrapolated to zero magnetic field (see Fig. 2). Comparison with the position $\tilde{E}_{10}$ of the observed intersubband resonance yields the depolarization shift $\tilde{E}_{10}-E_{10}=(0.9\pm0.1)$ meV. The difference between the depolarization shift in a finite ($\simeq0.4$ meV) and zero magnetic field ($\simeq0.9$ meV) may be caused by a suppression of the depolarization shift of the diamagnetically shifted intersubband resonance as its intensity becomes weaker in stronger magnetic fields (see Fig. 1). For inversion layers on Si, however, it was found that in the presence of depolarization the shift of the resonance peak due to the parallel component $B_\parallel$ is larger than the one obtained by a simple argument of the diamagnetic shift.[10] Hence, we think that the depolarization shift of intersubband resonance in $GaAs-Ga_{1-x}Al_xAs$ heterojunctions in tilted fields deserves a theoretical study.

To describe the positions of resonances that are not depolarization shifted, we calculate the single-electron eigenenergies

$$E_{i,n}=E_i+\hbar\omega_{c\perp}(n+\tfrac{1}{2})+\frac{e^2B_\parallel^2}{2m^*}[\langle z^2\rangle_{ii}-\langle z_{ii}\rangle^2]-\frac{e^2B_\parallel^2}{2m^*}\sum_{i'\neq i}\langle z_{i'i}\rangle^2\frac{1-(E_{i'i}/\hbar\omega_{c\perp})(2n+1)}{1-(E_{i'i}/\hbar\omega_{c\perp})^2} \qquad (1)$$

by second-order perturbation theory. To arrive at Eq. (1), we treat the effect of the parallel magnetic field $B_\parallel$ on the energies $E_i+\hbar\omega_{c\perp}(n+\frac{1}{2})$ in purely perpendicular magnetic fields as a small perturbation ($\hbar\omega_{c\parallel}=\hbar\omega_{c\perp}\tan\theta$

$\ll E_{10}$). We also introduce the abbreviation $E_{i'i} = E_{i'} - E_i$ and matrix elements, e.g., $z_{i'i} = \langle i' | z | i \rangle$ of the subband wave functions $| i \rangle$ at $B = 0$. The first two terms represent the so-called $\cos\theta$ law, stating that there is a Landau ladder with cyclotron energy $\hbar\omega_{c\perp} = e\hbar B\cos\theta/m^*$ on top of each electric subband. The third term is the diamagnetic shift due to the parallel component, and the last one describes coupling of electric subbands in tilted magnetic fields.

The solid lines in Fig. 2 are calculated from Eq. (1) using energies and matrix elements of the triangular-well approximation[1] $eF_s z$ of the electric surface potential. The field $F_s = 1.59\times10^4$ V cm^{-1} is chosen to yield the observed single-electron subband spacing $E_{10} = 19.8$ meV at $B = 0$. The mass $m^* = 0.0680 m_e$ is measured in perpendicular magnetic fields and is slightly higher than the band-edge mass $0.0663 m_e$. This is explained by band nonparabolicity[13] which otherwise is not important to describe the present experiments.

The data points for $B = 3.5$ and 4.0 T in Fig. 2 reveal a marked asymmetry of the resonance positions $E_{10} \pm \hbar\omega_{c\perp}$ with respect to the subband spacing E_{10}. This we describe by apparent cyclotron masses $m_i^*(\theta)$ which are readily derived from Eq. (1) using the common definition.[14] We obtain

$$\frac{1}{m_i^*(\theta)} = \frac{1}{m^*} - \sum_{i' \neq i} \frac{(z_{i'i})^2 E_{i'i}}{\hbar^2} \frac{(\hbar\omega_{c\parallel}/E_{i'i})^2}{1 - (\hbar\omega_{c\perp}/E_{i'i})^2} \, . \tag{2}$$

The masses $m_i^*(\theta)$ are independent of Landau index n and exceed the effective mass m^*, the enhancement being larger in higher subbands. This explains the asymmetry of the positions of the combined resonances $E_{10} \pm \hbar\omega_c$ since they involve masses $m_{i=1}^*(\theta)$ and $m_{i=0}^*(\theta)$, respectively. According to Eq. (2), the masses increase when the parallel magnetic field component is increased. In Fig. 2, this is seen as a deflection of the cyclotron energy from a straight line.

At $B = 4$ T, we experimentally determine masses $m_0^*(\theta) = (0.070 \pm 0.001) m_e$ and $m_1^*(\theta) = (0.080 \pm 0.005) m_e$ for subbands $i = 0,1$. From Eq. (2), we obtain $m_0^*(\theta) = 0.070 m_e$ and $m_1^*(\theta) = 0.071 m_e$ for the triangular-well model. A self-consistent theory[11,15] yields $m_0^* = 0.069 m_e$ and $m_1^* = 0.073 m_e$ for a realistic acceptor density $N_A = 2\times10^{14}$ cm^{-3}.[16] For the ground subband $i = 0$, there is good agreement between the experimental and both calculated values. For subband $i = 1$, the value of the self-consistent theory is higher than the one of the triangular-well model but still it is too low.

In order to describe the observed intensities, we calculate oscillator strengths $f_{i,n\to i',n'}$ for z polarization from the perturbated wave functions.[11,17] In Fig. 3, values for the triangular-well approximation are given normalized to the oscillator strength of the intersubband transition at $B = 0$. Strength of intersubband transitions $0,n \to 1,n$ are only given in the range of magnetic fields where they contribute according to their filling factors. For clarity reasons, strengths of combined resonances are only depicted for transitions $0,n \to 1,n+1$. The leading term of perturbation theory for the oscillator strength of cyclotron

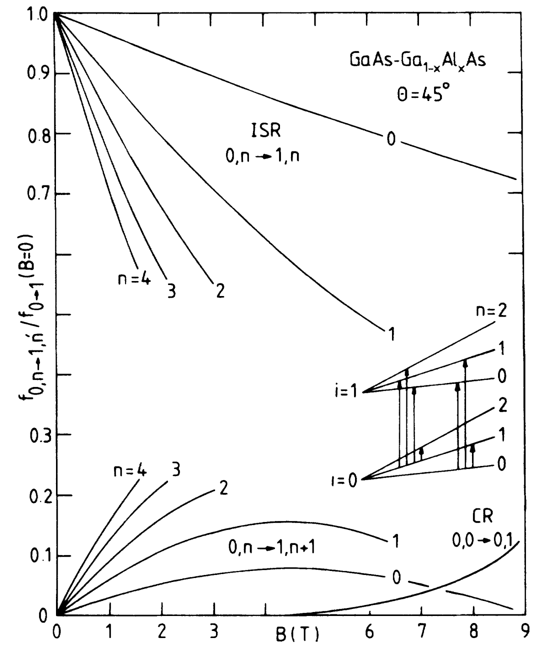

FIG. 3. Oscillator strengths of diamagnetically shifted ISR, CR, and combined transitions $0,n \to 1,n+1$. The strengths are calculated by second-order perturbation theory for the triangular-well approximation ($F_s = 1.59\times10^4$ V cm^{-1}, $m^* = 0.068 m_e$). The inset shows transitions starting from the initial states $(i,n) = (0,1)$ and (0,0).

resonances $0,n \to 0,n+1$ is given by the expression

$$\frac{f}{f_{0\to1}} = 2(n+1)\tan^2\theta \left(\frac{z_{10}}{l_\perp} \right)^2 \frac{(\hbar\omega_{c\perp}/E_{10})^3}{[1 - (\hbar\omega_{c\perp}/E_{10})^2]^2} \, . \tag{3}$$

Here we introduce the cyclotron radius $l_\perp = (\hbar/eB_\perp)^{1/2}$. Figure 3 shows that the strength of cyclotron resonance is negligibly small in lower magnetic fields but strongly increases in higher ones.

Experimental intensities are determined by integrating the spectra assuming Lorentzian line shapes if necessary. Ratios $I/I_{0\to1}$ of the intensities of diamagnetically shifted intersubband transitions and intersubband resonance at $B = 0$ can be compared directly with the calculated ratios of oscillator strengths $f/f_{0\to1}$ since these resonances are excited within a narrow range ($\lesssim 20$ cm^{-1}) of frequencies. This leaves practically unaltered the transmittance $T(n_s = 0)$ of the sample and the light field[18] inside the strip line. There is only qualitative agreement between experiment and theory. To give an example, the ratio 0.6 ± 0.1 at $B = 6.5$ T must be compared with the theoretical value $f/f_{0\to1} = 0.79$ of Fig. 3.

Qualitatively, the intensities of the combined resonances are also described by perturbation theory, including their decrease of intensity in higher magnetic fields. They are strongest in the range $B = 1.5$ to 3 T since they no longer melt together with the intersubband resonance, and transitions involving higher Landau indices $n = 2$–4 with strong oscillator strengths contribute in this range (see Fig. 3).

Cyclotron resonance is clearly observed only in magnetic fields $B \gtrsim 4$ T with strongly increasing intensity at higher fields (see Fig. 1). This proves that we have z polarization to a high degree and that cyclotron resonance is excited via intersubband resonance. The intensity ratio $I/I_{0\to 1} = 0.2 \pm 0.05$ at $B = 8.5$ T is a factor of about 2 larger than the value $f/f_{0\to 1} = 0.10$ of Eq. (3) calculated with numbers $z_{10} = 46$ Å and $f_{0\to 1} = 0.75$ of the triangular-well model (see also Fig. 3). We think, that most of the discrepancy is due to different light modes in the strip-line and different transmittances of the sample at the widely apart frequencies of cyclotron and intersubband resonance. However, we also note that perturbation theory is not expected to provide a very good description of the intensities for the highest field $B = 8.5$ T studied since the cyclotron energy $\hbar\omega_{c\perp} = 10.2$ meV is no longer small compared to the subband spacing $E_{10} = 19.8$ meV.

In conclusion, we observe diamagnetically shifted intersubband resonance, combined intersubband-cyclotron resonances, and cyclotron resonance in tilted magnetic fields. This allows us to determine experimentally the depolarization shift of the $B = 0$ intersubband resonance. Qualitatively, we can describe the single-electron energies and the resonance intensities by second-order perturbation theory using the triangular-well approximation of the electric-surface potential. A more quantitative description will provide a very stringent test for self-consistent theories, especially in regard of the enhanced cyclotron masses of excited subbands, the depolarization shift in tilted magnetic fields, and the observed intensities.

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[17]Intensities of transitions $0,n \rightarrow 1,n$ are obtained from Eq. (2.18) of Ref. 11 whose first factor should read $(N'!/N!)^{1/2}$. Combined and cyclotron resonances are calculated by a somewhat different approach which will be explained in a forthcoming paper.

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