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Intersubband energies in GaAs-$Ga_{1-x}Al_xAs$ heterojunctions

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We study the intersubband resonance between the ground and the first excited electric subband in GaAs-$Ga_{1-x}Al_xAs$ heterojunctions in a wide range of the two-dimensional electron density $N_s=(0.9-8.5)\times10^{11}$ cm^{-2}. The resonances are detected via the anticrossing of subband and Landau levels in tilted magnetic fields with Fourier transform spectroscopy.

The determination of subband spacings in GaAs-$Ga_{1-x}Al_xAs$ heterojunctions is of great interest as a means of characterizing the interface potential and its dependence on the inversion electron density N_s. Although subband energies have been investigated theoretically in some detail,[1] little experimental data exist. Originally, intersubband transitions were detected in Raman scattering,[2,3] but not studied systematically. One drawback of Raman scattering is the presence of strong band-gap radiation which causes quasiaccumulation conditions. More recently, intersubband resonances have been studied at infrared frequencies via cyclotron resonance—intersubband resonance coupling.[4-6]

Here we detect the intersubband resonance $0\rightarrow1$ via a splitting of the cyclotron resonance in tilted magnetic fields when the cyclotron resonance equals the intersubband resonance itself ($\hbar\omega_c=E_{10}$) or the combined intersubband cyclotron resonance ($\hbar\omega_c=E_{10}-\hbar\omega_c=E_{10}/2$). Combined intersubband-cyclotron resonances have previously been observed directly in metal-oxide-semiconductor (MOS) structures on Si with light polarization perpendicular to the interface.[7] Most of the present data have been measured at magnetic field strengths where the cyclotron resonance energy is half the subband spacing (coupling at half field), i.e., the resonance magnetic field is half of the one where the cyclotron energy equals the intersubband energy (coupling at full field). Coupling at half field has the advantage that the intersubband spacing can be determined even when the energy E_{10} lies within the reststrahlen band or is too high to be reached via coupling at full field.

In the experiments we measure the transmission of far-infrared radiation with a Fourier-transform spectrometer in constant magnetic fields at liquid-helium temperatures ($T\simeq2$ K). The incident radiation propagates in the direction of the magnetic field which is tilted with respect to the surface normal of the sample by the tilt angle θ. The electric field vector of the radiation is practically parallel to the inversion layer due to the high dielectric constant of GaAs and strongly excites cyclotron resonance. Coupling of cyclotron resonance to intersubband resonance is possible, since in tilted magnetic fields the cyclotron motion parallel to the layer and the quantized motion perpendicular to it are strongly coupled.[4-6] The effect of a tilted magnetic field on a quasi-two-dimensional electron gas can be described by perturbation theory.[4,8] In this case, the magnetic field component $B_\perp$ perpendicular to the interface determines the Landau ladder, whereas the component $B_\parallel$ causes anticrossing of Landau levels belonging to different electric subbands and small shifts of the subband energies ("diamagnetic shift").

Spectra for a sample with electron density $N_s=6.1\times10^{11}$ cm^{-2} are shown in Fig. 1 for tilt angles $\theta=33°$ and 12° in the upper and lower part, respectively. At the larger tilt angle $\theta=33°$ we observe clear splitting of the cyclotron resonance at frequency $\tilde{\nu}\simeq90$ cm^{-1}. At higher magnetic fields $B_\perp>12$ T the cyclotron resonances broaden and decrease in amplitude as a result of the coupling at full field ($\hbar\omega_c=E_{10}$, Ref. 4). We note that one of the transitions occurs right at the position of the undisturbed intersubband resonance ($B=0$) if the magnetic field is well away from the coupling regime (see upper part of Fig. 1, $\tilde{\nu}\simeq180$ cm^{-1}). The coupling is studied in the lower part of Fig. 1 at the smaller tilt angle $\theta=12°$. Then no coupling at half field ($\hbar\omega_c=E_{10}/2$) is observed ($\tilde{\nu}\simeq90$ cm^{-1}), but clear splitting is evident at full field ($\tilde{\nu}\simeq180$ cm^{-1}).

The splitting at half field is explained by coupling of the $n=2$ Landau level of the ground electric subband E_0 to the $n=0$ Landau level of the excited subband E_1 as depicted in the right-hand inset of Fig. 2. Note that the observation of the splitting at half field (see transitions a,b in the

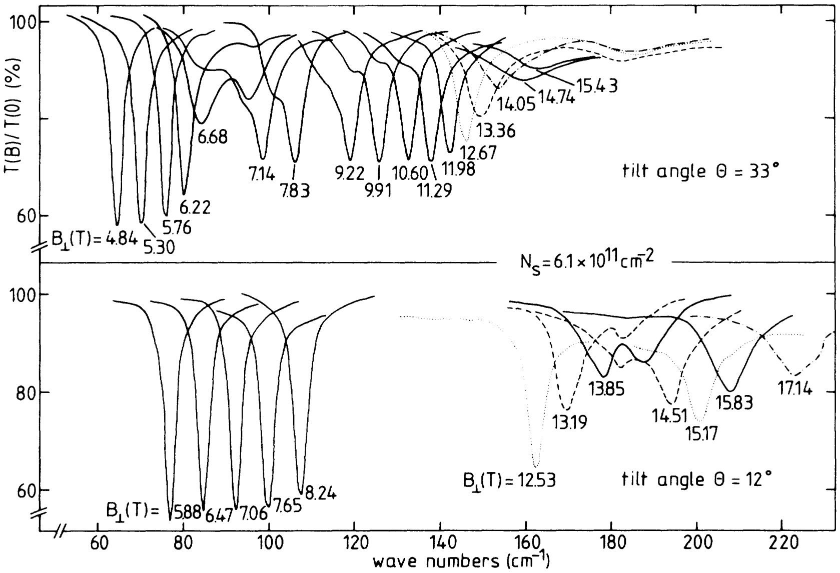

FIG. 1. Normalized transmission spectra of a GaAs-Ga$_{1-x}$Al$_x$As heterojunction in tilted magnetic fields.

right-hand inset of Fig. 2) is only possible when more than one Landau level is occupied. At partial filling of the $n=1$ Landau level cyclotron resonances $n=0 \rightarrow n=1$ (c) are also observed. Therefore, the anticrossing at half field allows one to investigate not only intersubband resonances but also cyclotron resonances of lower Landau states

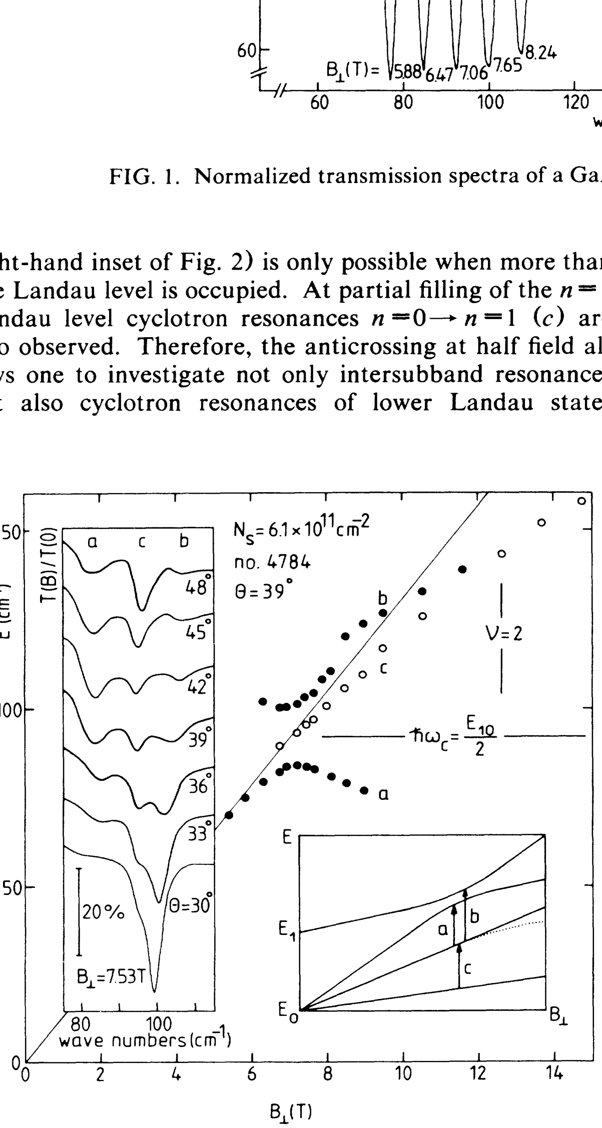

FIG. 2. Experimental resonance positions of coupled cyclotron-intersubband resonances. The left-hand inset shows spectra at a fixed magnetic field component $B_\perp$ for different tilt angles. Three resonances a, b, and c are observed as indicated in the right-hand inset.

which are not affected by the coupling. In Fig. 2 we show resonance positions versus the magnetic field component $B_\perp$ for the tilt angle $\theta=39°$. Although at magnetic fields up to 6 T the usual cyclotron resonance is detected, a pronounced splitting into three peaks a, b, and c occurs in the range 6.5–11 T. A negative slope of the energy versus magnetic field relation is present at magnetic field components $B_\perp < 7$ T for the resonance b and at $B_\perp > 7$ T for the resonance a, respectively. This behavior is easily understood by looking at the schematic level diagram in the right-hand inset of Fig. 2. The negative slope is characteristic for anticrossing at half field and does not occur at full field coupling.

We extract the value $E_{10}/2$ in Fig. 2 from the center of the energy gap formed by the resonances a and b. In the vicinity of this gap, the resonance c lies very close to the solid line $E=\hbar eB_\perp/m^*$ determined in purely perpendicular magnetic fields ($m^*=0.07m_e$). At the magnetic field component $B_\perp$, where the resonance c crosses the energy $E_{10}/2$, the resonance positions of resonances a and b reach their maximum and minimum, respectively. This further supports our way to evaluate the energy $E_{10}/2$ from the center of the gap.

The resonance position a approaches the solid line at magnetic fields $B_\perp < 6$ T. Resonances b and c show a more complicated behavior: Above the center of the energy-gap resonance, b increases over the solid line and then merges into resonance c which lies below it. This is qualitatively explained by the combination of two effects, namely, the influence of the coupling at full field and the change of the filling factor $\nu=N_s h/eB_\perp$, which depends only on the magnetic field component $B_\perp$ perpendicular to the interface.[9] Since the sample is tilted considerably ($\theta=39°$), the full field coupling already bends down the Landau level $n=1$ at magnetic fields $B_\perp > 8$ T, resulting in higher transition energies for resonance b and lower ones for resonance c (see dotted line in the right-hand inset of Fig. 2). At magnetic fields $B_\perp > 12.6$ T ($\nu < 2$) the Landau level $n = 1$ is depopulated and only resonance *c* is left in the spectra.

The left-hand inset in Fig. 2 shows experimental spectra measured at the constant magnetic field component $B_\perp = 7.53$ T. Increasing the tilt angle, much of the oscillator strength is transferred from resonance *b* to *a*. This is a consequence of the diamagnetic shift which increases the energy $E_{10}/2$ from 93 cm^{-1} to 101 cm^{-1} in the range $\theta = 30°-48°$, in good agreement with perturbation theory.[8] The resulting shift of the oscillator strength is most easily understood if one considers the spectrum for the angle $\theta = 48°$. To transfer back the oscillator strength into resonance *b* one must increase the magnetic field $B_\perp$ corresponding to the slightly higher diamagnetically shifted intersubband energy. Since the diamagnetic shift is approximately proportional to $\tan^2\theta$, it is a small effect provided the tilt angle is not too large. In the extraction of intersubband energies we have restricted ourselves to tilt angles $\theta < 48°$ and the diamagnetic shifts are always less than 10% of the intersubband energies E_{10}. The smallness of the diamagnetic shift and the fact that outside the coupling regime the transition energies fall on the solid line (see Fig. 2) determined in purely perpendicular magnetic fields demonstrate that the observed phenomena in tilted magnetic fields can be understood within the framework of simple perturbation theory.[8]

We have measured E_{10} for various samples, both at half and at full field coupling as indicated in Table I. At a given tilt angle the splitting of the cyclotron resonance is much less at half field coupling compared to the coupling at full field (see Fig. 1). Therefore one needs higher tilt angles $\theta \sim 39° - 48°$ to study the coupling at half field. The density N_s has been determined *in situ* from Shubnikov-de Haas studies. Except for sample 4890, only the density in the dark is given in Table I. However, intersubband energies have also been extracted at higher electron densities that were obtained by utilizing the persistent photoeffect of above-band-gap radiation. For this we have exposed the samples to light pulses (~ 0.1 s) in order to increase the density stepwise. The infrared transmission has always been measured after this procedure in the absence of band-gap radiation. This avoids the formation of so-called quasiaccumulation conditions;[10] however, it does not mean necessarily that the depletion potential remains completely unchanged.[11]

Figure 3 shows the measured intersubband energies in comparison with the theoretical results of Stern and Das Sarma.[1] The closed symbols indicate intersubband energies measured in the dark, the corresponding open symbols indicate energies for the sample after illumination. At densities $N_s \approx 6 \times 10^{11}$ cm^{-2} the data of three samples differ from each other ($\tilde{\nu} = 165-225$ cm^{-1}), well outside the range of the experimental uncertainties $\Delta N_s \approx 0.1 \times 10^{11}$ cm^{-2} and $\Delta\tilde{\nu} \approx 1$ cm^{-1}. The comparison of experiment and theory suggests that we have, in fact, samples with different depletion charge densities N_{depl}. In order to determine N_{depl}, we have measured by the van der Pauw method the unintentional background doping of a thick epitaxial GaAs layer grown under the same conditions as the optically investigated samples. We find for the background doping $N_A = (1.0 \pm 0.5) \times 10^{14}$ cm^{-3}, which corresponds to a depletion charge density $N_{depl} = (0.5 \pm 0.2) \times 10^{11}$ cm^{-2}.

The agreement between experiment and theory is very good if one considers the uncertainty of the experimentally determined depletion charge. The intersubband energies increase with electron density N_s and roughly follow the theoretical curves calculated for fixed depletion charges. The tendency for the density dependence in most samples to have a somewhat smaller slope than theoretically calculated may result from some reduction of the depletion charge after illumination. Such effects have previously been observed in MOS structures on Si.[10] The difference between samples at a given density N_s we interpret to result from variations of the depletion potential which is not easily probed by other methods. In particular, the intersubband energy of sample 4890 at density $N_s = 4.7 \times 10^{11}$

TABLE I. Sample parameters and experimental conditions. The density N_s and the intersubband energy E_{10} are determined without band-gap illumination except for sample 4890. Tilt angle and type of coupling are indicated.

Sample	Density $N_s (10^{11}$ $cm^{-2})$	E_{10} (meV)	Tilt angle θ (deg)	Coupling
1530	0.9	17.2	2	E_{10}
4784	3.2	19.3	15,39	$E_{10}, E_{10}/2$
1320	5.3	26.0	39	$E_{10}/2$
4900	5.9	20.6	48	$E_{10}/2$
4890	4.7	31.6	36	$E_{10}/2$

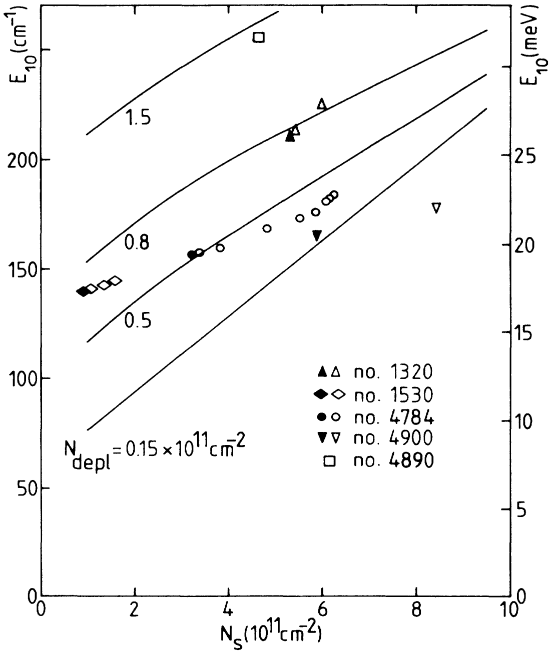

FIG. 3. Intersubband energies E_{10} vs electron density N_s for different samples (see Table I). The solid lines are theoretical results from Ref. 1 calculated for various depletion charge densities N_{depl}.

cm $^{-2}$ is the highest of all samples measured. In this sample a relatively thin (1-μm) GaAs buffer layer is terminated by an AlAs layer, and one expects a significantly steeper depletion potential as in the other samples with substantially thicker buffer layers. This consistently explains the higher subband spacing.

To conclude, we have used the anticrossing of cyclotron resonance and intersubband resonance to study the intersubband energies in GaAs-Ga$_{1-x}$Al$_x$As heterojunctions. In particular, the coupling at half field, i.e., the coupling of the cyclotron resonance $\hbar\omega_c$ and the combined resonance $E_{10}-\hbar\omega_c$ is found to be a valuable spectroscopic tool to investigate the subband structure of this quasi-two-dimensional electron gas. The diamagnetic shift due to the magnetic field component parallel to the interface is studied and turns out to be small compared to the intersubband energies. The different intersubband energies measured for different samples at comparable electron densities can only be explained by different depletion charge densities.

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