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Collective cyclotron modes in high-mobility two-dimensional hole systems in GaAs–(Ga, Al)As heterojunctions: II. Experiments at magnetic fields of up to forty Tesla

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Abstract. The cyclotron resonance of very high-mobility holes in GaAs–(Ga, Al)As heterojunctions grown on (111), (311) and (100) substrates has been studied in high magnetic fields of up to 40 T. As the temperature is increased from ∼4 K to ∼20 K, the cyclotron resonance is found to shift to *lower* magnetic fields, the size of shift depending on the cyclotron frequency and the substrate orientation. These observations may be explained using the model of interacting hole subsystems developed by Cole *et al*.

1. Introduction

In [1], a model of interacting hole subsystems was developed which successfully explained the temperature-dependent behaviour of the cyclotron resonance spectra of high-mobility holes in GaAs–(Ga, Al)As heterojunctions at magnetic fields ∼0.5–4 T. This paper extends the findings of [1] to much higher magnetic fields (∼20–40 T), where the cyclotron resonance of such holes is found to shift to lower magnetic fields as the temperature is raised. It is shown that this effect may be understood in terms of the model developed in [1].

2. Experimental details

The GaAs–(Ga, Al)As heterojunctions used in this study were the same as those used in [1]; details can be found in section 2 and table 1 of that paper. Cyclotron resonance was measured at high fields by direct absorption of monochromatic far-infrared radiation from

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an optically pumped molecular gas (CH_3OH) laser [2] in pulsed magnetic fields of up to 50 T. The magnetic fields were generated using the long-pulse (∼10 ms) magnets at the Institute for Solid State Physics, Tokyo, and VSM, University of Leuven; these facilities are described elsewhere [4]. The substrates of the samples were wedged by between 0.5 and 2° to prevent interference therein distorting the cyclotron resonance lineshape. The samples were cooled by a stream of ^{4}He exchange gas, and the temperature could be varied between 4 K and 20 K. Sample temperatures were monitored by a thermocouple and by calibrated ruthenium oxide and Ge resistors. Previous studies [4] have established that the temperature of such heterojunction samples does not vary significantly ($\Delta T \leqslant 0.2$ K) during the magnet pulse.

3. Experimental cyclotron resonance data

The hole densities of the samples studied ([1], table 1) imply that only a single Landau level is populated at low temperatures ∼4 K and at the magnetic fields used in this study (i.e. the samples are in the quantum limit). Data obtained at a far-infrared energy of 10.4 meV are shown in figure 1(a) for sample 4, a (111) orientated heterojunction, and figure 1(b) for sample 2, the (100) orientation sample measured at low magnetic fields in [1]. In both cases, the single cyclotron resonance observed shifts to lower field as the temperature is raised; the shift is slightly smaller for the (111) oriented heterojunction. Similar measurements for sample 1 ((311)A substrate orientation) are plotted in figure 2(a), and also show a down-shift in cyclotron resonance field with increasing temperature at a far-infrared energy of 7.6 meV. At the same energy the shift was almost negligible for the (100) orientation heterojunction, sample 2 (figure 2(b)). The relatively poor signal-to-noise ratio obtained at this energy (cf figure 1) is a result of the smaller far-infrared power available [3].

4. Discussion

In high magnetic fields the hole energy spectrum is quantized into highly nonparabolic Landau levels. It is helpful to be familiar with the structure of these levels in the analysis of the temperature-dependent shift of the cyclotron resonance, and so we have calculated Landau level fans for (100), (111) and (311) orientation heterojunctions in the axial approximation (a detailed description of these calculations is found elsewhere [5, 6]). Calculated Landau fans for a p-type (100) accumulation layer with an areal hole density of $p_s = 3 \times 10^{15}$ m^{-2} (i.e. parameters applicable to sample 2) are shown in figure 3; the solutions to the coupled envelope-function equations take the form of four ladders of Landau levels of increasing harmonic oscillator index, N. The four series begin with Landau level indices $N = -2$, -1, 0 and 1 respectively, and the selection rule for cyclotron resonance in the axial approximation is $\Delta N = \pm 1$. The hole energy increases as one moves further away from the band-edge; thus, the lowest-energy hole Landau level (i.e. that populated at $T = 0$) is at the *top* of figure 3.

Following the ideas of [1], the temperature-dependent shift of the cyclotron resonance (figures 1 and 2) suggests that coupled motion of more than one type of hole might be involved. From figure 3, the most obvious source for a second type of hole with a different cyclotron frequency is the thermal population of higher-energy Landau levels (i.e. levels further from the band edge). Figure 4 shows the cyclotron resonance field at a cyclotron energy of 10.4 meV for sample 2 (100) as a function of temperature, and lends weight to

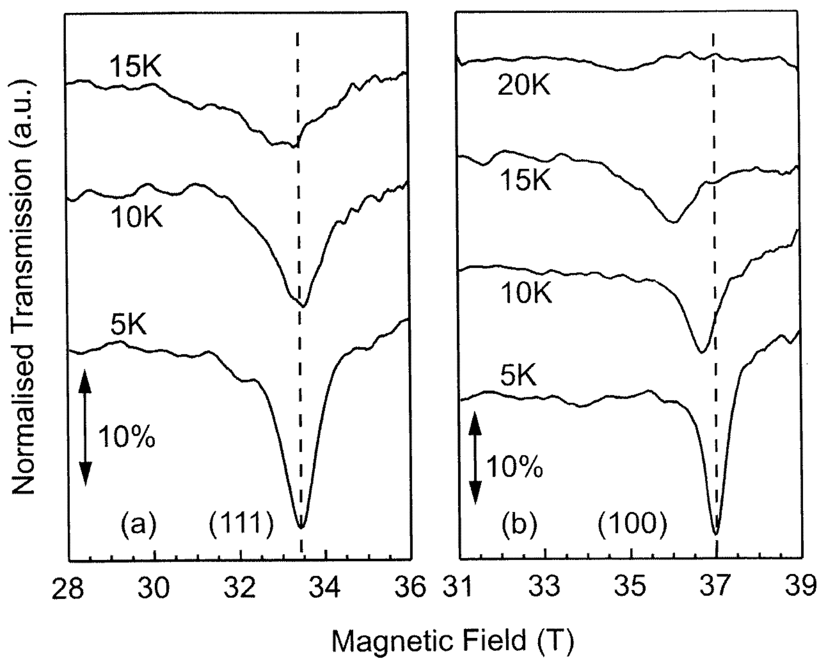

Figure 1. (a) Magnetotransmission spectra of sample 4, a (111) orientation heterojunction, at a far-infrared energy of 10.4 meV. Traces for three temperatures are shown and have been offset for clarity. (b) Similar spectra for sample 2, a (100) orientation heterojunction.

such an interpretation; the points represent data and the dashed curve is a fit to the function

$$B(T) = B(0) - A\,\mathrm{e}^{-\frac{\Delta}{kT}} \tag{1}$$

where A and $B(0)$ are constants and Δ represents a thermal activation energy. The fitted value of $\Delta = 3.9 \pm 0.4$ meV is very similar to the energy separation of the two lowest Landau levels expected for this sample (see figure 3). As a comparison, the hole population in the lowest Landau level has been evaluated at 37 T using Fermi–Dirac statistics and a full calculation of the Landau level energies (including level mixing) [6] for sample 2. The results of this calculation are shown in the form p_1/p_s in figure 4, where p_1 is the population of the lowest-energy hole Landau level (the uppermost level in figure 3) and p_s is the total hole density; note that there is an approximately linear relationship between the shift in the cyclotron resonance and the number of holes in higher Landau levels, $p_s - p_1$.

The results of a similar analysis for sample 1 ((311) orientation) are shown as an inset to figure 4; in this case, the cyclotron energy is 7.6 meV. The resonance positions have been fitted using equation (1) to yield an activation energy of $\Delta = 5.8 \pm 1$ meV; as in the case of sample 2 (see above), this is similar to the separation of the two lowest Landau levels. Furthermore, there is again an approximately linear relationship between the shift in the cyclotron resonance and the number of holes in higher Landau levels, $p_s - p_1$. (In the case of sample 1 the population of the Landau levels has been evaluated using an axial approximation calculation [5, 6].) However, as the temperature-dependent shift of the cyclotron resonance is best defined for sample 2 we shall restrict most of the detailed analysis which follows to this sample.

Cyclotron resonance transitions from thermally populated states will in general have

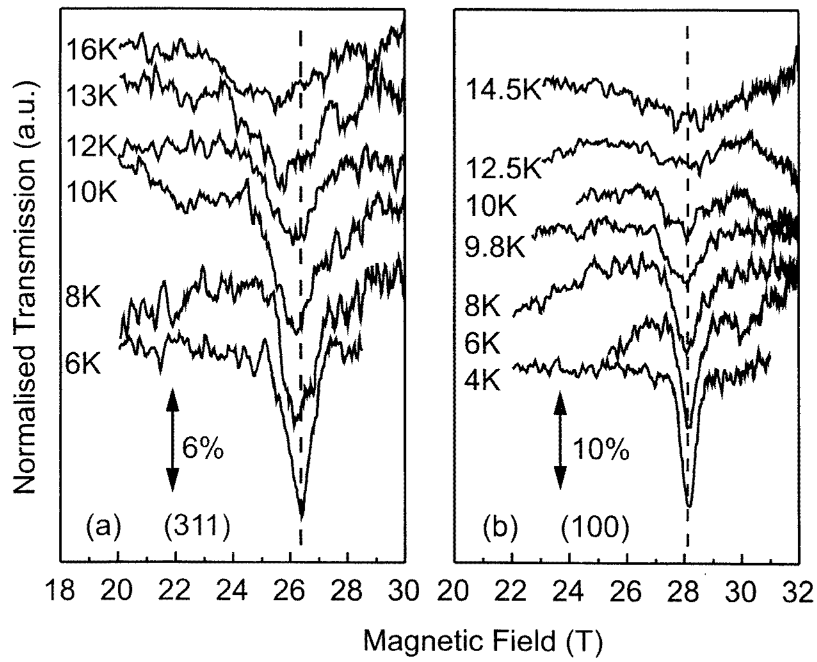

Figure 2. (a) Magnetotransmission spectra for sample 1, a (311)A orientation heterojunction, at a far-infrared energy of 7.6 meV and a number of temperatures (traces offset for clarity). (b) Similar data for sample 2, a (100) orientation heterojunction.

a different energy from transitions from the lowest level (figure 3). Thus, in a single-particle picture, multiple resonances would be expected at elevated temperatures, each with a temperature-dependent intensity, but at a *temperature-independent field*. However, over the range of field studied in the experiments, a single resonance is observed at a field which is generally *temperature dependent* (see figures 1 and 2). In order to explain such behaviour, we shall apply the model developed by Cooper and Chalker [7], which showed how strong Coulomb interactions could lead to the coupling of two single-particle cyclotron resonances of differing frequency into a single resonance corresponding to the centre-of-mass motion of the total carrier population. We have already shown in section 4 of [1] that the Cooper–Chalker model is equivalent to a purely *reactive* interaction between holes undergoing cyclotron motion at different frequencies. Under the high degree of localization (i.e. small cyclotron radii) expected at the high magnetic fields used in this study, there is little or no hole scattering between states and hence no dissipative interaction; this is in marked contrast to the situation at low magnetic fields [1].

In [1], the effect of Coulomb interactions was quantified using a hole–hole reactive scattering parameter, ω_0. The Cooper–Chalker approach allows ω_0 to be evaluated directly, as does the more recent model of Hu *et al* [8], which additionally takes into account the finite extent of the two-dimensional carrier wavefunctions in the z-direction perpendicular to the GaAs–(Ga, Al)As interface. Following [7] and [8], ω_0 is given by

$$\omega_0 = \mu C_{2D} \frac{e(\pi p_s)^{3/2}}{8\pi \epsilon_r \epsilon_0 B} \tag{2}$$

where C_{2D} is a factor depending on the hole spatial distribution. C_{2D} was found to be 1.6

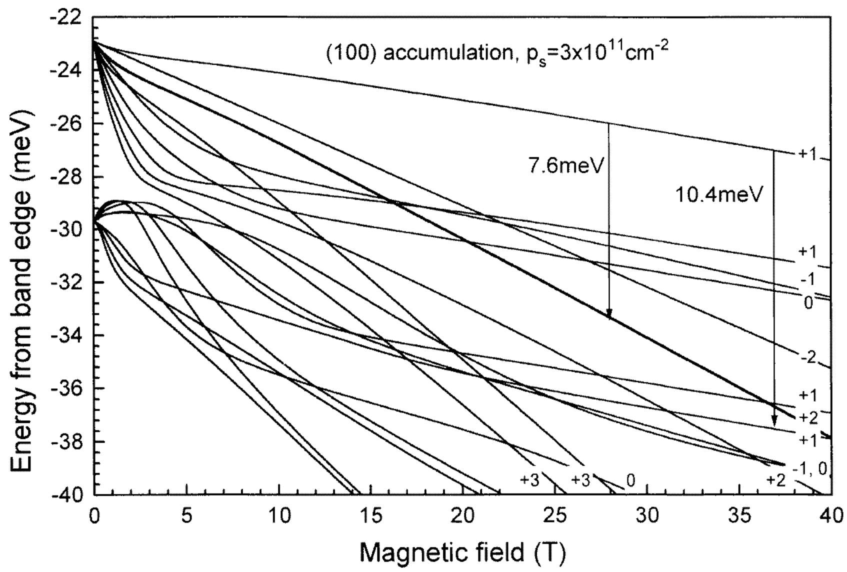

Figure 3. Calculated Landau level fans for a (100) orientation accumulation layer with $p_s = 3 \times 10^{15}$ m^{-2} (parameters appropriate for sample 2). The experimental cyclotron resonance energies and field positions for sample 2 are marked by arrows. Note that higher-energy hole states occur *lower* down the diagram; the hole ground state is the uppermost level. Levels originating from the fourth and higher subbands have been omitted for clarity. Axial approximation Landau states are characterized by their harmonic oscillator index, N, indicated on the right of the figure.

for a Wigner crystal but only very weakly dependent on the detailed arrangement of the carriers [8], as is expected from the long range of the Coulomb interaction. μ is a factor incorporating the softening of the Coulomb interaction due to the finite extent of the hole wavefunction [8] in the z-direction and is estimated to be 0.8 for sample 2. Substituting other parameters appropriate for sample 2 at 37 T into equation (2) yields $\omega_0 \approx 1.2$ meV.

Bearing in mind the cyclotron energy of 10.4 meV, a hole–hole interaction energy of this magnitude will certainly affect the experimental spectra when two or more single-particle modes of energy separation $\sim$1 meV are present. In order to model the influence of hole–hole interactions fully the single-particle frequencies of all the contributing cyclotron resonances must be included. The complexity of the Landau levels (see figure 3) at higher energies suggests many possible cyclotron transitions (the selection rule $\Delta N = \pm 1$ is applicable to axial approximation calculations [9]). The oscillator strength of each of these transitions is determined by the z-component overlap integral of the initial and final state envelope-functions [9]. At fields where the cyclotron resonance energy is comparable to the subband separation, the z-component of the hole wavefunction no longer retains the subband character pertaining to its low-field origins [9]. Therefore, whilst the cyclotron resonance at 7.6 meV occurs at a field corresponding to the calculated $N = 1 \rightarrow N = 2$ single-particle transition (figure 3), the cyclotron resonance at 10.4 meV lies between two possible transitions (figure 3), perhaps indicating that the observed resonance represents a mixture of single-particle transitions. Transitions from the higher Landau levels cannot be identified at present without full oscillator strength calculations.

In order to model the experimental data we characterize all of the single-particle

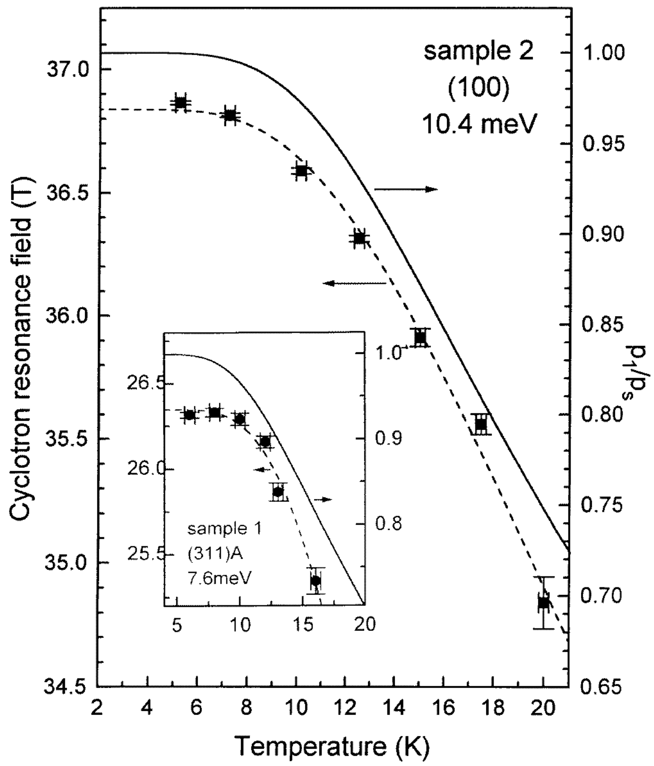

Figure 4. The observed temperature dependence of the cyclotron resonance field for sample 2 at a laser energy of 10.4 meV. The dotted line shows the fit to these points using equation (1) (see text). The solid line shows the fraction of the total hole population in the lowest Landau level, as a function of temperature (see text). The inset shows the cyclotron resonance field, fit and hole population of lowest Landau level for sample 1 ((311)A) at a laser energy of 7.6 meV as a function of temperature.

cyclotron resonance transitions from the thermally populated levels using a single mean energy, ω_2. Cyclotron resonance transitions from the lowest hole Landau level occur at an energy ω_1 and correspond to an $N = 1 \rightarrow N = 2$ transition in the axial scheme illustrated in figure 3. At the lowest temperatures used in the measurements ($\approx$4 K), nearly all of the holes lie in the lowest energy level (that at the top of figure 3). Thus the cyclotron resonance oscillator strength lies in a single dominant mode, which we label the *major* cyclotron mode. As higher Landau levels (i.e. levels lower down figure 3) are thermally populated, an additional collective cyclotron mode (which we label the *minor* mode) will gain in oscillator strength. The energies and relative oscillator strengths of the two modes will be determined by their single-particle frequencies, ω_1 and ω_2, and the hole–hole interaction energy ω_0, according to the expressions given in [1, 7, 8]. Using equation (7) of [1], we have evaluated the cyclotron frequency of the dominant mode for $\omega_0 = 1.2$ meV and $\omega_1 = 10.4$ meV. This is plotted as the fractional shift of the cyclotron frequency of the major mode, $(\omega(T) - \omega(0))/\omega(0)$, against the fractional concentration of holes in higher levels, $(p_s - p_1)/p_s$, in figure 5(a) for a range of different ω_2. Experimental values from sample 2 (at a cyclotron energy of 10.4 meV) are also shown in the form $(B(4\text{ K}) - B(T))/B(4\text{ K})$ [10]. In the regime of 'weak coupling', where $\omega_0 < |\omega_2 - \omega_1|$, the major cyclotron mode always shifts to higher energy at constant field (or shifts to lower fields at constant energy, as in the experiments) as $(p_s - p_1)$ increases, irrespective of the sign of $(\omega_2 - \omega_1)$. For the case $\omega_2 < \omega_1$, the mean cyclotron frequency of the total hole system is weighted to a lower value by the increasing $(p_s - p_1)$; thus, the upshift in the major mode frequency is accompanied by a transfer of oscillator strength to the minor mode. This change in oscillator strength is greater than that expected in the single-particle approximation, where the oscillator strength of the minor mode is in direct proportion to $(p_s - p_1)$.

Turning to the 'strong coupling' case ($\omega_0 > |\omega_2 - \omega_1|$; figure 5(a), lowest trace), the major cyclotron mode shifts toward ω_2 with increasing $(p_s - p_1)$, and for strong enough coupling the oscillator strength will lie in a single mode at the weighted mean of the single-particle frequencies [1, 7, 8].

The relative oscillator strength of the major mode (i.e. the ratio of major mode strength to the total in all of the cyclotron modes) is plotted in figure 5(b) for the same parameters as used in figure 5(a). The experimentally observed absorption strengths (integrated cyclotron resonance areas) are plotted in figure 5(b) for comparison, normalized to the strength at $T \approx 4$ K, where it is assumed that all of the oscillator strength is in the major mode. The large uncertainty in the experimental absorption strength data is a result of the significant background fluctuations produced in a pulsed measurement. Nevertheless, there is clear evidence for the loss of oscillator strength from the cyclotron mode observed as the temperature is increased. A satisfactory overall fit to the data in figures 5(a) and 5(b) is found with $\omega_2 = 8.5$ meV; the curve corresponding to $\omega_2 = 8.5$ meV is plotted bolder than the others in both figures. Note that when the Landau level energies calculated for sample 2 in the axial approximation are examined (see figure 3), a number of possible transitions from thermally populated levels can be found with energies close to this value.

In our simple two-mode model, the relative oscillator strength of the minor mode is simply (1−(major mode strength)). At $T \approx 20$ K, the minor mode will have an oscillator strength similar to or even greater than that of the major mode (figure 5(b)). The lower frequency of this mode implies that a magnetic field of approximately 45 T would be required to observe it at a cyclotron energy of 10.4 meV. This is beyond the range of the current experiment, and so the low-energy minor mode was not observed.

The shift in cyclotron field for sample 4 ((111) orientation sample—see figure 1) appears somewhat smaller than that for sample 2 ((100) orientation sample), although the data for sample 4 are less clear. Given the sensitivity of the temperature dependence to the relative magnitudes of ω_0 and $(\omega_2 - \omega_1)$, it is not surprising that the exact size of the shift is sample dependent. Slightly more unexpected is the apparent temperature independence of the resonance position (≈28 T) for sample 2 at a cyclotron energy of 7.6 meV (figure 2(b)). A Coulomb coupling energy of $\omega_0 = 1.6$ meV is expected at this field (cf the higher field value above). In the weak-coupling regime, a higher value for ω_0 leads to an increased shift in cyclotron resonance position with temperature. However, in the strongly coupled regime, a temperature-independent resonance position occurs when $\omega_2 = \omega_1$. Of course the fact that transitions from more than one thermally populated level could contribute at elevated temperatures may result in behaviour different from the predictions of the simple 'two population' model discussed above.

We have also considered the influence of hole potential shape on the observed cyclotron masses. As the higher Landau levels are thermally populated, the hole distribution is pushed away from the GaAs–(Al, Ga)As interface; this might potentially provide an alternative mechanism for the drop in cyclotron mass with temperature. Calculations of the dominant $N = 1 \rightarrow N = 2$ transition energy have been carried out for both inversion and

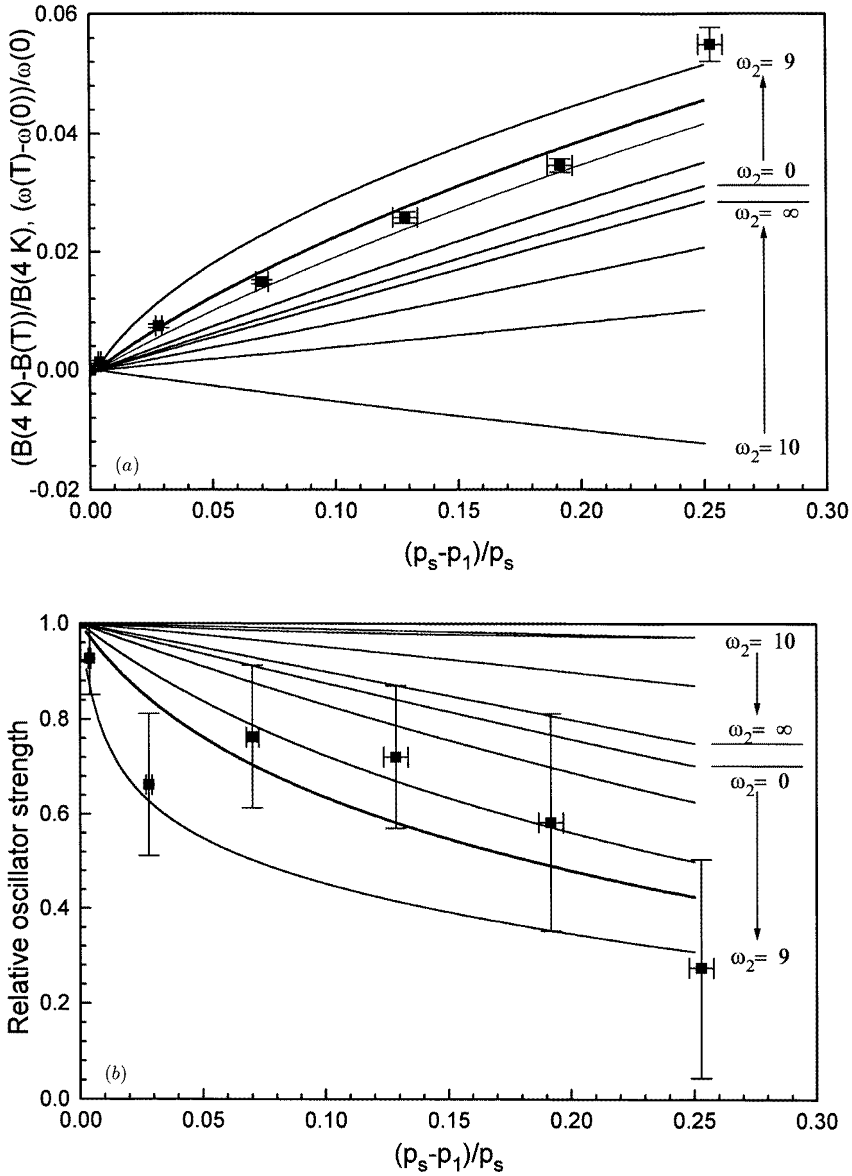

Figure 5. (a) The points show the experimental fractional shift of the cyclotron resonance, $(B(4\ \mathrm{K}) - B(T))/B(4\ \mathrm{K})$, for sample 2 at a cyclotron energy of 10.4 meV. Solid lines show the calculated $(\omega(T) - \omega(0))/\omega(0)$ for the major cyclotron mode using parameters appropriate for sample 2, as a function of the fractional hole concentration in higher Landau levels, $(p_s - p_1)/p_s$. The following values of ω_2 have been used: 0, 6, 8, 8.5 (bold), 9, 10, 11, 13, ∞. The other input parameters are $\omega_1 = 10.4$ meV and $\omega_0 = 1.2$ meV. (b) The points show the experimental relative oscillator strength for sample 2 as a function of $(p_s - p_1)/p_s$. Solid lines show majority mode oscillator strength evaluated from the model (see text) for the same parameters as (a).

accumulation layers [6], showing that the transition is rather insensitive to potential shape; the energy is ~3% lower for the case of an accumulation layer than for an inversion layer over the field range 20–40 T. By contrast, these two potential shapes result in HH1–LH1 intersubband splittings of 6.8 meV and 9.8 meV respectively. Empirically this suggests that stronger hole confinement increases the energy of the main cyclotron resonance transition; since increasing the temperature tends to reduce the hole confinement, one would expect the cyclotron energy to decrease if this mechanism dominated. As the observed shift is in the opposite direction and much larger, it seems that the influence of the shape of the potential well is of minor importance in the current context.

Finally, we re-emphasize the fact that the details of the higher hole Landau levels and the cyclotron oscillator strengths will vary with heterojunction orientation and magnetic field. This explains in a qualitative manner why the size of the shift of the cyclotron resonance position differs in the various cases shown in figures 1 and 2. Although the cyclotron resonance data for the samples 1 and 4 are less clear than those for sample 2, the apparent thermal activation of the shift in cyclotron resonance field is consistent with thermal population of higher hole Landau levels. This strongly suggests that the mechanism for the shifts observed is the same in all of the samples studied.

5. Summary and conclusions

The cyclotron resonance of very high-mobility holes in GaAs–(Ga, Al)As heterojunctions grown on (311), (111) and (100) substrates has been studied in high magnetic fields of up to 40 T. As the temperature was increased from $\sim$4 K to $\sim$20 K, the cyclotron resonance was found to shift to *lower* magnetic fields. The magnitude of the effect in the quantum limit has been found to be sample and frequency dependent. The direction of the shift is opposite to that found at small fields [1] and appears thermally activated with a characteristic energy consistent with thermal population of higher hole Landau levels. We suggest that the observed cyclotron resonance results from a number of Coulomb coupled 'single-particle' inter-Landau level transitions, along the lines suggested by Cooper and Chalker [7] for a system of interacting electrons in the ultra-quantum limit. In a previous paper [1], we have shown that our semi-classical model for cyclotron resonance of coupled carrier systems reproduces the results of Cooper and Chalker in the high-field limit.

Both the shift in cyclotron field and the drop in absorption strength with increasing temperature found for the (100) sample at fields $\sim$37 T have been shown to be consistent with the predictions of a Coulomb coupled model. More quantitative oscillator strength calculations are expected to highlight the relative importance of specific transitions in contributing to the observed cyclotron resonance. Finally, for a full explanation of the influence of the Coulomb interactions on two-dimensional hole systems at elevated temperatures the model must include more than two interacting modes.

Acknowledgments

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