Temperature-dependent cyclotron resonances in *n*-type GaAs

E. Batke,* K. Bollweg, and U. Merkt
Institut für Angewandte Physik, Universität Hamburg, Jungiusstraße 11, D-20355 Hamburg 36, Germany

C. M. Hu
Physikalisches Institut der Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany

K. Köhler and P. Ganser
Fraunhofer-Institut für Angewandte Festkörperphysik, Eckerstrasse 4, D-79104 Freiburg, Germany
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We report temperature-dependent cyclotron resonances of electrons in bulk GaAs in a temperature regime from about 10–300 K. Due to the nonparabolicity of the GaAs conduction band at sufficiently high temperatures and magnetic-field strengths, several individual Landau transitions are observed. A single line of strongly overlapping Landau transitions is found at higher temperatures and also in the case of small magnetic-field strength. Band coupling, electron-phonon interaction, and the electron spin influence the cyclotron resonance. However, from liquid-helium temperatures up to room temperature, the transition energies are essentially independent of temperature. Scattering times, which govern the broadening of the Landau transitions, decrease in magnitude with increasing magnetic-field strength as well as with temperature, and there is no simple relation to magnetotransport scattering times.

I. INTRODUCTION

In III-V semiconductor compounds, band coupling and interaction of the electron with the phonons imply an energy-dependent dispersion near the conduction-band edge. In these polar semiconductors the electron is coupled to the longitudinal-optical phonon and forms a quasiparticle, the polaron. The electron-phonon coupling renormalizes the electron effective mass and contributes to the conduction-band nonparabolicity. Both band coupling and the polaron effect of bulk[1–7] and quasi-two-dimensional[8–11] electron gases in zero and finite magnetic fields have attracted much attention. Recently, for quasi-two-dimensional and bulk electrons in GaAs, different temperature dependences of the cyclotron resonance positions were observed.[12,13] So far, it has not been clarified without a doubt what mechanisms are responsible for the differences in the temperature-induced shifts. As possible explanations, differences in the screening of the electron-phonon interaction[12,13] and in the polaron mass renormalization[14] were addressed.

A detailed comparison between quasi-two-dimensional and bulk electron systems is limited by the fact that temperature-dependent data are rather sparse for bulk GaAs. Therefore, we discuss here cyclotron resonance of conduction-band electrons in bulk GaAs at various magnetic-field strengths covering a temperature regime from liquid helium up to room temperature. Our main concern is to clarify the importance of temperature-induced changes of the conduction-band nonparabolicity. Surprisingly, we find that the transition energies between adjacent Landau bands are essentially independent of temperature in GaAs. At high magnetic-field strengths the experimental accuracy is better than 1% indicating that the influence of the temperature is extremely small. Temperature-induced shifts of the cyclotron resonance positions are only observed when the lines of several Landau transitions overlap and form a single line. This shift is explained by the thermal population of higher Landau bands and a corresponding exchange of oscillator strength. We will demonstrate how the temperature-dependent cyclotron resonance line shapes can be analyzed in a simple model. Cyclotron relaxation times that govern the broadening of individual Landau transitions will be discussed in comparison with magnetotransport scattering times.

II. EXPERIMENTAL ASPECTS

Our samples are epitaxial layers of GaAs grown on semi-insulating (100) substrates by molecular-beam epitaxy and doped with Si in the range of 10^{14} cm^{-3}. Temperature-dependent magnetotransport measurements using the van der Pauw technique[15] are performed at a low magnetic-field strength $B = 0.5$ T to characterize the $d = 6$-μm-thick epitaxial layers. A peak Hall mobility in excess of 160 000 cm^2 V^{-1} s^{-1} is found around 60 K and a value of about 8000 cm^2 V^{-1} s^{-1} at 300 K. Below about 50 K the electrons begin to freeze out into the donor levels and at liquid-helium temperatures there are virtually no free carriers present in the conduction band. In the saturation regime above 50 K we have an electron concentration $n_e \approx 1.9 \times 10^{14}$ cm^{-3} that is essentially independent of temperature.

Far-infrared (FIR) transmission is recorded in a Fourier spectrometer to study cyclotron resonance of conduction-band electrons in magnetic fields oriented parallel to the sample normal. The experiment is performed with unpolarized FIR radiation incidencing parallel to the magnetic-field direction. To exclude

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Fabry-Perot interferences from the substrate the sample is wedged. The sample, together with a resistance heater and a calibrated 100-Ω Allen-Bradley temperature sensor in close proximity, is mounted in a sample holder which is immersed in liquid helium and cooled by helium exchange gas. Polished brass tubes guide the FIR radiation and a Si-bolometer operating at liquid-helium temperatures detects the transmitted signals. Magnetic fields are provided by a superconducting solenoid with a field constant calibrated via nuclear-magnetic resonance to an accuracy of better than 0.1%. To correct for the spectral characteristics of the experimental setup, we determine the relative change in transmission $-\Delta T/T = [T(B_{\mathrm{ref}})-T(B)]/T(B_{\mathrm{ref}})$, where B and B_{ref} are the measurement and reference magnetic-field strengths, respectively.[16] The reference field B_{ref} is chosen sufficiently small to shift the associated resonance well apart from the frequency regime of interest for field B.

III. EXPERIMENTAL RESULTS

Figure 1 shows experimental cyclotron resonances at various magnetic-field strengths and temperatures. The arrows indicate experimental resonance positions. In Fig. 1(a) at a low magnetic field strength we observe a single line whose maximum shifts slightly to lower wave numbers with increasing temperature. Individual transitions between Landau bands $N \rightarrow N+1$ are not resolved at $B=3.91$ T. At $B=6.50$ T, as shown in Fig. 1(b), several Landau transitions are observed at sufficiently high temperatures. Due to the conduction-band nonparabolicity, higher-order transitions appear as satellites more or less shifted to lower wave numbers. It will be shown later that at 20 K the resonance is a single line owing to the fact that only the ground Landau band $N=0$ is populated. At 120 K three individual Landau transitions $0\rightarrow 1$, $1\rightarrow 2$, and $2\rightarrow 3$ are observed simultaneously. Due to enhanced broadening, individual transitions can no longer be resolved at 240 K. In the high magnetic-field limit $B=13.63$ T shown in Fig. 1(c), a small spin splitting of the $0\rightarrow 1$ cyclotron resonance transition is clearly observable at 20 K. At higher temperatures the enhanced broadening masks the spin splitting and a single nearly symmetric line is found. There is no evidence for higher-order Landau transitions, although one would expect them from the occupation of the Landau ladder at higher temperatures.

Figure 2 shows experimental spectra at $B=15$ T in the freeze-out regime for free and bound electrons. Figure 2(a) reflects the spin-split cyclotron resonance from the ground $N=0$ to the first excited $N=1$ Landau band. Transitions involving higher Landau bands $N>1$ do not contribute, since at the temperatures of the freeze-out regime only the ground level is populated. With increasing temperature the total oscillator strength increases due to stronger thermal population of the ground Landau band.

Figure 2(b) reflects the spin-split donor transition $1s\rightarrow 2p_{+1}$. It is strongest at liquid-helium temperatures, where essentially all electrons are bound to the 1s donor state. With increasing temperature, electrons are

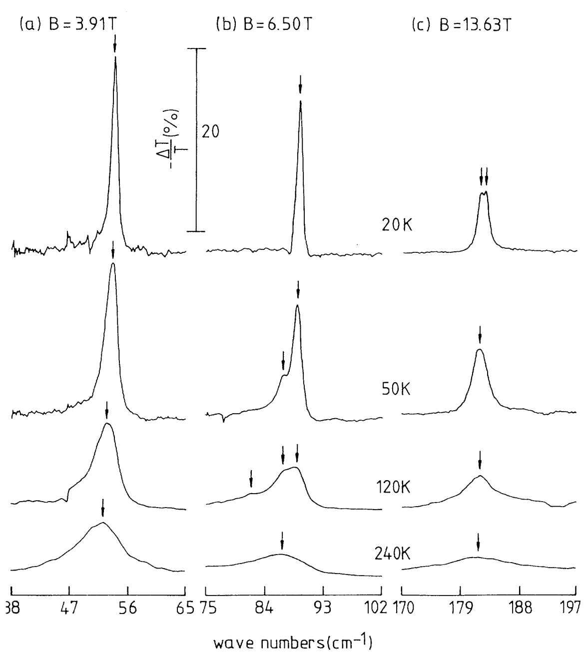

FIG. 1. Temperature-dependent cyclotron resonances of electrons in bulk GaAs at magnetic-field strengths (a) $B=3.91$ T, (b) 6.50 T, and (c) 13.63 T. The arrows mark resonance positions.

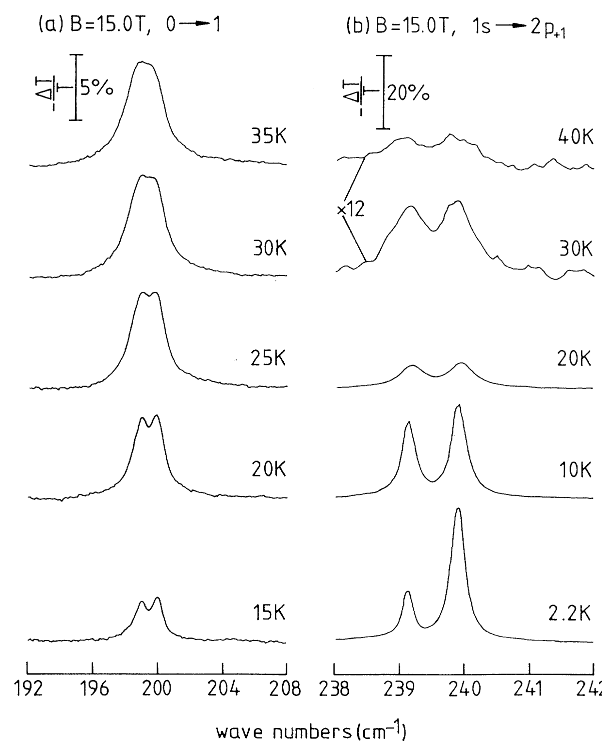

FIG. 2. Spin-split cyclotron resonances of (a) free and (b) bound electrons in n-GaAs at $B=15$ T and various temperatures.

thermally excited to higher donor states or to the conduction band, thus reducing the total oscillator strength. At a temperature of 2.2 K one of the two spin orientations is more strongly populated, leading to significantly different oscillator strengths. Note that the amplitudes of the weaker resonance with the smaller transition energy never exceeds the amplitude of the stronger one, and only in the high-temperature limit the oscillator strengths become equal in intensity.

The strengths of the two spin transitions shown in Fig. 2(a) for the free electrons seem to vary differently with temperature. Here, the maximum oscillator strength is located at the high-energy side of the resonance up to a temperature of 20 K. At 25 K both spin orientations exhibit equal strengths and above 30 K the maximum in oscillator strength is shifted to the low-energy side of the resonance. We will show later that we face here only a fictitious shift in oscillator strength, which is characteristic for bulk electrons in nonparabolic semiconductors.

Figure 3 shows the temperature dependence of the cyclotron resonance positions versus temperature for different magnetic-field strengths. The experimental resonance positions ω_{exp} are interpreted in terms of cyclotron masses, defined by the relation $m_c = eB/\omega_{\mathrm{exp}}$. At the low magnetic-field strength $B = 3.91$ T, the cyclotron mass increases nearly linearly up to a temperature of 200 K and then saturates. In Fig. 3(b) at $B = 6.50$ T cyclotron masses associated with different Landau transitions do not exhibit a significant variation with temperature. Within an experimental accuracy of about 1% the masses of the $0 \rightarrow 1$, $1 \rightarrow 2$, and $2 \rightarrow 3$ transitions are independent of temperature. This is confirmed for the $0 \rightarrow 1$ and $1 \rightarrow 2$ transitions up to a temperature of about 120 K and for the $2 \rightarrow 3$ transition even up to about 150 K. Above 120 K the $0 \rightarrow 1$ and $1 \rightarrow 2$ transitions strongly overlap and form a single resonance. In the temperature regime between 120 and 210 K the mass is roughly equal to the average mass of the two transitions at lower temperatures. Above about 210 K there is a slight increase in cyclotron mass with increasing temperature, which we attribute to an influence of the $2 \rightarrow 3$ transition.

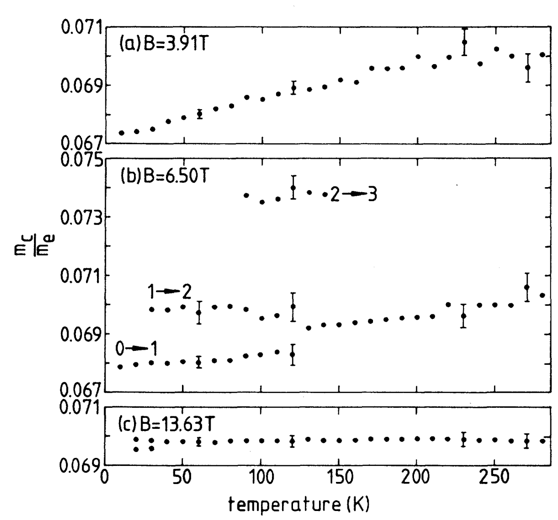

FIG. 3. Cyclotron resonance positions of conduction-band electrons in GaAs interpreted in terms of cyclotron masses vs temperature of magnetic-field strengths (a) $B = 3.91$ T, (b) 6.50 T, and (c) 13.63 T.

In the high magnetic-field limit $B = 13.63$ T shown in Fig. 3(c), the two mass values at 20 and 30 K correspond to the spin splitting of the $0 \rightarrow 1$ transition. Above 40 K both spin transitions merge and the cyclotron mass is constant to an accuracy of better than 1% in the whole temperature regime. We also like to notice here that the center of the spin-split cyclotron resonance shown in Fig. 2(a) shifts to lower frequencies only by about 0.5 cm^{-1} in the temperature range between 10 and 40 K. In terms of a nonparabolic cyclotron mass, this means that there is only a very minor increase of less than 0.3%.

In summary, within our experimental accuracy of about 1%, the positions of resolved Landau transitions in bulk GaAs are essentially independent of temperature. In case of a mixed line shape as in Fig. 1(a) or in the high-temperature limits of Fig. 1(b), information on the positions of individual Landau transitions can only be gained via a cyclotron resonance line-shape calculation. Detailed information on the spin splitting can also only be obtained from a comparison with calculated line shapes. We will describe in the next section a simple model to analyze the experimental line shapes.

IV. THEORETICAL LINE SHAPES

In sufficiently high magnetic fields the conduction-band states of GaAs can be written as

$$E_{N,s}(k_z) = E_N + \frac{\hbar^2 k_z^2}{2m_{N,s}^*(k_z)} + s g_N^* \mu_B B \ , \tag{1}$$

where N is the Landau-band index, $\hbar k_z$ is the quasi-momentum of the electron parallel to the magnetic-field direction, and $s = \pm\frac{1}{2}$ is the spin quantum number. E_N represents the Landau-band edges, $m_{N,s}^*(k_z)$ is an energy-dependent effective mass, and g_N^* is an effective Landé g factor. In a single-particle approximation, band-structure calculations predict a Landé g factor[6] of

$$g_N^* = g_0 + g_1(N + \tfrac{1}{2})B \ . \tag{2}$$

In Eq. (2), g_0 is the effective Landé factor at the conduction-band edge and the second term is a correction related to the nonparabolicity of the GaAs conduction band. Despite some controversy in the past about the sign and magnitude of g_0,[17,18] the commonly accepted value at liquid-helium temperatures is $g_0 \approx -0.44$.[18,19] Spin-resonance experiments performed on quasi-two-dimensional electron inversion layers in GaAs have revealed a positive g_1 close to the predicted bulk value[6] of 0.0078 T^{-1}.[20]

In cyclotron resonance, electric dipole transitions $N \rightarrow N+1$ occur between Landau bands that are conserving electron spin and momentum $\hbar k_z$. In a nonparabolic system the transition energies

$$\hbar\omega_{N,s}(k_z)=E_{N+1}-E_N+\frac{\hbar^2 k_z^2}{2}\left[\frac{1}{m^*_{N+1,s}(k_z)}-\frac{1}{m^*_{N,s}(k_z)}\right]+sg_1\mu_B B^2 \tag{3}$$

depend on the momentum $\hbar k_z$ and the spin factor g_1.

The optical response of the electron gas can be calculated if the high-frequency conductivities $\sigma_\pm(\omega)$ for left and right circular polarizations are known. According to our experiment, which employs unpolarized FIR radiation, wedged substrates, and a detector not sensitive to polarization, the relative change in transmission is given by[21]

$$-\frac{\Delta T}{T}=1-\frac{T_+[\sigma_+(\omega)]+T_-[\sigma_-(\omega)]}{T_+(0)+T_-(0)}, \tag{4}$$

with

$$T_\pm[\sigma_\pm(\omega)]=\frac{4}{\left|(1+\sqrt{\varepsilon})\cos\frac{\omega d n_\pm}{c}+i\frac{\sqrt{\varepsilon}+n_\pm^2}{n_\pm}\sin\frac{\omega d n_\pm}{c}\right|^2}, \tag{5}$$

where ε is the relative dielectric constant of the semiconductor and $n_\pm^2=\varepsilon-i\sigma_\pm(\omega)/(\omega\varepsilon_0)$ are the complex indices of refraction of the epitaxial layer. For the high-frequency conductivities we propose the expressions[22,23]

$$\sigma_\pm(\omega)=\frac{e\tau}{B}\sum_{N,s}\int_{-\infty}^{+\infty}dk_z[n_{N,s}(k_z)-n_{N+1,s}(k_z)](N+1)\times\frac{\omega_{N,s}(k_z)}{1+i[\omega\pm\omega_{N,s}(k_z)]\tau}, \tag{6}$$

where the broadening of all Landau transitions is described by the same phenomenological cyclotron relaxation time τ. The inclusion of an energy-dependent scattering time is straightforward, the τ has to be replaced simply by a $\tau_{N,s}$. In Eq. (6), $n_{N,s}(k_z)$ is the population of the energy state $E_{N,s}(k_z)$ and the factor $(N+1)$ comes from the dipole matrix element of the transition $N\rightarrow N+1$. Applying Fermi-Dirac statistics, the population is derived from

$$n_{N,s}(k_z)=\frac{eB}{(2\pi)^2\hbar}\left[1+\exp\frac{E_{N,s}(k_z)-\mu}{kT}\right]^{-1}, \tag{7}$$

with the chemical potential μ defined by the total electron density

$$n_e=\sum_{N,s}\int_{-\infty}^{+\infty}dk_z n_{N,s}(k_z). \tag{8}$$

In parabolic systems, the broadening of individual Landau transitions is ruled only by the scattering time. Due to the energy dependence of the effective mass in GaAs, dipole transitions with different momenta $\hbar k_z$ contribute in addition to the halfwidth of the resonance. The optically measured cyclotron resonance positions do not always simply reflect the separations at the Landau-band edges $E_{N+1,s}(0)-E_{N,s}(0)$, but also can depend on the cyclotron relaxation time. Only when $\omega_c\tau$ is sufficiently large, the cyclotron resonance positions will be determined by dipole transitions occurring in a small energy interval at the band edges. This can be justified from the density of states, which diverges proportional to $E^{-1/2}$ at the band edges. With decreasing $\omega_c\tau$ the broadening of the transitions increase and a cyclotron resonance line shape can be formed with resonance position shifted to lower energies with respect to $E_{N+1,s}(0)-E_{N,s}(0)$. This shift might also be viewed in terms of a scatterer-induced broadening of the density of states. The broadening lifts the divergencies of the density of states at the Landau-band edges and shifts the maxima to higher energies with respect to $E_{N,s}(0)$.[24]

A. Landau-band energies

From Eqs. (3)–(8), one can calculate the optical response of the conduction-band electrons in GaAs provided that the energy dispersion Eq. (1) and the Landé factor Eq. (2) are known. In principle, the description of the energies $E_{N,s}(k_z)$ as a function of temperature would require a sophisticated multiband calculation including resonant and nonresonant electron-phonon couplings, to account for the combined influences of band coupling and the polaron effect. To keep the calculation simple and the number of parameters as small as possible, we use the two-band model with effective energy gap E_g^* to describe the conduction-band nonparabolicity due to band coupling.[25] This model predicts energies

$$E_{N,s}(k_z)=\left\{\left[\frac{E_g^*}{2}\right]^2+E_g^*\left[\hbar\omega_c(N+\tfrac{1}{2})+\frac{\hbar^2k_z^2}{2m_0}+sg_N^*\mu_B B\right]\right\}^{1/2}-\frac{E_g^*}{2}, \tag{9}$$

where $\omega_c = eB/m_0$ is the cyclotron frequency with the bare-mass m_0 at the conduction-band edge. The two-band model with effective energy gap is surprisingly accurate if compared with more sophisticated theoretical approaches. This can be justified by comparing the predicted cyclotron masses to the ones obtained with a five-band $\mathbf{k}\cdot\mathbf{p}$ calculation.

At sufficiently small B and N and neglecting the electron spin, Eq. (9) yields cyclotron masses of

$$m_{c,N} = \frac{\hbar e B}{E_{N+1} - E_N} \approx m_0 + \frac{2\hbar e}{E_g^*} B(N+1) , \tag{10}$$

while the five-band model[6] gives

$$m_{c,N} \approx m_0 + m_1 B(N+1) . \tag{11}$$

In Eq. (11), m_1 is a factor related to the nonparabolicity of the conduction band. Both m_0 and m_1 are complicated functions of various band gaps and interband matrix elements.[6,7] Note that Eqs. (11) and (12) are of the same form, i.e., the dependences on the magnetic-field-strength B and Landau-band index are identical. Equations (10) and (11) are valid in the limit $\omega_c \tau \gg 1$, where the cyclotron resonance positions reflect the Landau-band separations at zero momentum. It was argued in Ref. 26 that one should add to the right-hand sides of Eqs. (10) and (11) a term kT/E_g^*, accounting for the average kinetic energy of the electron parallel to the magnetic-field direction. This correction has to be considered only if the broadening of the cyclotron resonance is of the order of the thermal energy, i.e., if $\omega_c \tau$ is sufficiently small. To be discussed later, in our experiment $\omega_c \tau$ is sufficiently large that the experimental resonance positions reflect essentially the Landau-band separations.

The bare-mass m_0 cannot be determined experimentally in a straightforward manner, since electron-phonon interactions renormalize the mass at band edge.[8] However, in GaAs with a Fröhlich coupling constant $\alpha \approx 0.07$ the difference between m_0 and the renormalized mass $m_0^* \approx m_0(1+\alpha/6)$ is small, and we replace m_0 by m_0^* in Eq. (9). We determine m_0^* from the Zeeman splittings of the $1s \rightarrow 2p_{+1}$ and $1s \rightarrow 2p_{-1}$ transitions of the shallow donor and obtain a value $m_0^* \approx (0.0663 \pm 0.0002) m_e$ in agreement with previous experiments.[27] The effective energy gap $E_g^* = 0.90$ eV is chosen to fit the observed $0 \rightarrow 1$ cyclotron resonance positions at low temperatures.

Figure 4 shows calculated band edges E_N for the first seven Landau bands as a function of the magnetic-field strength. The calculation does not include the resonant polaron effect and the electron spin. Resonant polaron coupling lifts the degeneracy of the energies E_N with the one-phonon line $\hbar\omega_{LO} + E_0$, where $\hbar\omega_{LO}$ is the longitudinal-optical (LO) phonon energy, and induces level anticrossing.[8]

B. Oscillator strengths

If all Landau transitions are described by the same phenomenological relaxation time τ, the relative oscillator strengths are approximately given by $(n_N - n_{N+1})(N+1)$, where n_N is the electron density in

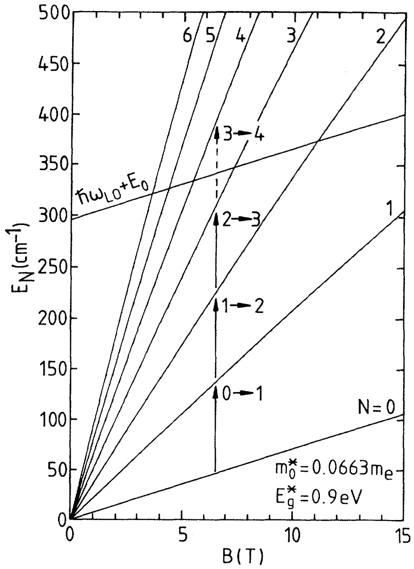

FIG. 4. Energies of the Landau-band edges E_N vs magnetic-field strength for electrons in bulk GaAs. The calculation assumes the two-band model. The electron spin and the resonant polaron effect are not considered. The arrows indicate Landau transitions $N \rightarrow N+1$ at $B = 6.5$ T. Electrons excited from the Landau band $N = 3-4$ (dashed arrow) can relax to lower Landau bands due to the emission of longitudinal-optical phonons.

the Landau-band N. Figure 5 shows the normalized oscillator strengths $(n_N - n_{N+1})(N+1)/n_e$ of some Landau transitions versus temperature for various magnetic-field strengths calculated for $n_e = 1.9 \times 10^{14}$ cm^{-3}, the total electron density of our sample in the saturation regime. At low temperatures, the $0 \rightarrow 1$ transition dominates. With increasing temperature higher Landau bands are thermally populated and the corresponding Landau transitions gain in strength. At $B = 3.91$ T the $0 \rightarrow 1$ transition dominates up to about 120 K, whereas at higher temperatures the $1 \rightarrow 2$ transition is stronger. Finally, roughly above 200 K the $2 \rightarrow 3$ transition carries the highest oscillator strength. In Figs. 5(b) and 5(c) qualitatively similar variations of the relative oscillator strengths are calculated for magnetic-field strengths $B = 6.50$ and 13.63 T. The $0 \rightarrow 1$ transition is strongest in the whole temperature regime at $B = 13.63$ T, since the Landau-band separations are large and the thermal population of higher bands is suppressed.

Generally, the number of Landau transitions that contribute to the cyclotron resonance line shape increases with temperature. However, in polar semiconductors there is a limitation. As an example, in Fig. 4 some Landau transitions are marked by arrows for a magnetic-field strength $B = 6.50$ T. Experimentally observed in Fig. 1(b) are only the transitions $0 \rightarrow 1$, $1 \rightarrow 2$, and $2 \rightarrow 3$. Electrons that are excited from the Landau band $N = 3-4$ as shown in Fig. 4 with a dashed arrow can relax via emission of LO phonons to the lower Landau bands, provided free states are available there. Since n_e is small, this condition is fulfilled here. The LO-phonon influences imply

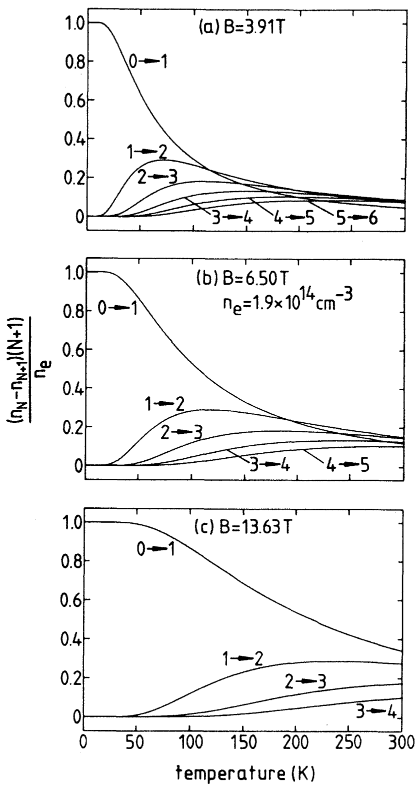

FIG. 5. Normalized oscillator strengths of cyclotron resonance transitions $N \rightarrow N+1$ vs temperature for bulk electrons in GaAs at magnetic-field strengths (a) $B = 3.91$ T, (b) 6.50 T, and (c) 13.63 T.

a strong damping of the $3 \rightarrow 4$ transition, distributing the oscillator strength over a wide-frequency regime. Hence, a significant contribution to the cyclotron resonance line shape is not expected from transitions that involve Landau bands with energies exceeding the one-phonon line $\hbar\omega_{LO}+E_0$. Essentially, only the energetically lowest Landau bands contribute and the maximum number of Landau transitions is limited to the highest integer less than the ratio ω_{LO}/ω_c.

C. Details of the line-shape calculation

The calculation of the optical response is performed as follows. For a given electron density n_e we solve Eq. (8) iteratively for the chemical potential μ using a total of 50 Landau bands. If the spin is included, 25 spin-split Landau bands are considered. In the present experiment the electron spin is important only in the high magnetic-field limit $B \geq 13.63$ T at low temperatures. The magnitude of the spin splitting at $B = 6.50$ and 3.91 T is too small, so that it can be neglected. With the chemical potential the population of the states $E_{N,s}(k_z)$ is determined from Eq. (7). Introducing the cyclotron relaxation time τ the optical resonance is calculated from Eqs. (3)–(6) with the relative dielectric constant of GaAs $\varepsilon = 12.8$. The parameters n_e, τ, g_0, and g_1 are varied for best agreement with the experiment. Our calculation assumes the following:

(1) A temperature dependence of the band gap E_g^* is neglected. In principle, the influence of band coupling changes with temperature, and one could expect a temperature dependence of the Landau-band separations. However, the cyclotron resonance positions do not show a variation with temperature for resolved Landau transitions. It is not clear yet whether the temperature dependence of band coupling is too small in GaAs to be observed or if there are influences canceling this temperature variation. For the sake of simplicity, we will assume that the Landau-band separations do not depend on temperature.

(2) Transitions that involve Landau bands with energies larger than the one-phonon line $\hbar\omega_{LO}+E_0$ do not give a measurable contribution to the cyclotron resonance line shape. This can be justified due to influences of the LO phonons which strongly damp these transitions.

(3) Transitions that involve Landau bands with energies well below the LO-phonon energy are described by the same relaxation time τ. In principle, the cyclotron relaxation time will depend on the energy, i.e., the Landau-band index. This is particularly important if Landau bands are involved that lie close to the LO-phonon energy. However, the major contribution to the cyclotron resonance line shape comes from transitions that involve Landau bands that do not cross the one-phonon line. For these transitions, we do not expect a strong energy dependence of the scattering time. The relaxation time involved here might be viewed as a scattering time averaged over several individual Landau transitions.

V. COMPARISON OF EXPERIMENTAL AND THEORETICAL SPECTRA

Figure 6 shows calculated cyclotron resonance line shapes versus wave numbers at various temperatures for magnetic-field strengths $B = 3.91$, 6.50, and 13.63 T. Best fits to the experimental spectra of Fig. 1 are shown by solid curves with base lines $-\Delta T/T = 0$ as indicated by the horizontal bars. A satisfactory fit is only achieved by neglecting transitions involving Landau bands with energies larger than the one-phonon line. For comparison, the upward shifted dashed curves count all transitions and ignore LO-phonon damping phenomena. The line shapes at 20 K reflect for all magnetic-field strengths the $0 \rightarrow 1$ transition, which exhibits a spin splitting at $B = 13.63$ T. The influence of the electron spin on the $0 \rightarrow 1$ transition will be discussed in more detail in the following section. Note the asymmetry of the line shapes at 20 K in Figs. 6(a) and 6(b) and the negative values of $-\Delta T/T$. This asymmetry is of optical origin and is caused by interference in the 6-μm-thick epitaxial layer. With increasing temperature and magnetic-field strength the interference effect becomes less pronounced.

The interpretation of the spectra at $B = 13.63$ T shown in Fig. 6(c) is straightforward. In the whole temperature regime only the $0 \rightarrow 1$ transition is observable. Higher Landau transitions do not contribute, although one can

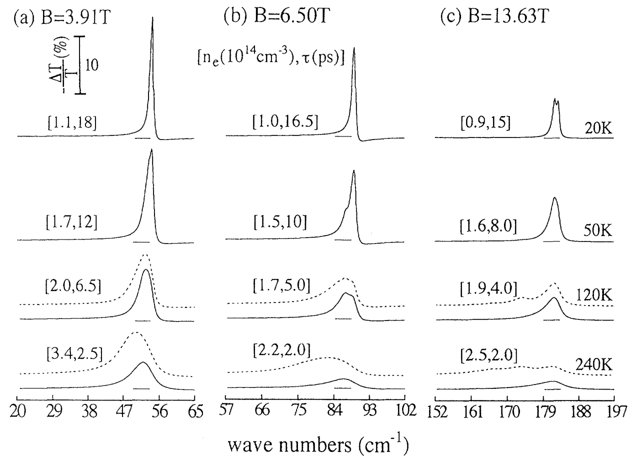

FIG. 6. Calculated cyclotron resonance line shapes vs wave numbers for bulk electrons in GaAs. The solid curves with base lines $-\Delta T/T=0$ marked by horizontal lines are best fits to the experimental spectra of Fig. 1 and include LO-phonon influences as described in the text. The upward shifted dashed curves show the predicted line shapes if phonon influences are ignored.

expect them from the population of the Landau bands [see the dashed lines in Fig. 6(c)]. For best agreement with experiment, spin splitting of the resonance has to be considered for temperatures below 50 K. At higher temperatures, where the spin is not resolved, it is tempting to fit the cyclotron resonance line shape with the classical single-oscillator high-frequency conductivities $\sigma_{\pm}(\omega) = n_e e \tau \omega_c / \{B[1+i(\omega \pm \omega_c)\tau]\}$. This approach gives electron densities n_e that decrease in magnitude with increasing temperature. The decrease is virtual and arises from the drop in oscillator strength of the $0 \rightarrow 1$ transition with increasing temperature as shown in Fig. 5(c). A single-oscillator fit thus cannot provide information on the real value of n_e. The cyclotron mass that can be deduced from our fit does not depend on temperature in agreement with the experimental result shown in Fig. 1(c). Influences of the finite scattering time on the resonance position are not important at 13.63 T. In the temperature regime from 10 to 300 K, $\omega_c \tau$ varies from about 600 to 70. The calculation shows that the deviation of the resonance position from the $0 \rightarrow 1$ Landau-band edge separation is less than 0.6% in the whole temperature regime. This shift is within our experimental accuracy of 1% and cannot be observed experimentally.

The cyclotron resonance line shape at $B=6.50$ T is more complicated, because three Landau transitions have to be considered, namely the $0 \rightarrow 1$, $1 \rightarrow 2$, and $2 \rightarrow 3$ transitions. The calculated solid curves in Fig. 6(b) count only the $0 \rightarrow 1$ and $1 \rightarrow 2$ transitions but neglect the $2 \rightarrow 3$ transition. Incorporation of the latter is complicated. The position, broadening, and the strength of the $2 \rightarrow 3$ transition cannot be calculated in a simple manner, since it is affected by the resonant polaron coupling. In Fig. 1(b) the position of the $2 \rightarrow 3$ transition at 120 K is separated about 5 cm^{-1} from the position of the $1 \rightarrow 2$ transition. This has to be compared to a separation of 2.2 cm^{-1} between the $0 \rightarrow 1$ and $1 \rightarrow 2$ transitions. Equation (9) predicts for the positions of the $1 \rightarrow 2$ and $2 \rightarrow 3$ transitions a difference of about 2 cm^{-1}. Hence, a shift of about 3 cm^{-1} is due to the resonant polaron effect. Although the $2 \rightarrow 3$ transition gains in weight with increasing temperature, the dominating contribution to the cyclotron resonance position is governed by the $0 \rightarrow 1$ and $1 \rightarrow 2$ transitions up to about 210 K. This we conclude from the experimental cyclotron mass shown in Fig. 3(b), which between 120–210 K reflects roughly the average mass of the $0 \rightarrow 1$ and $1 \rightarrow 2$ transitions. Above 210 K the slight mass increase is due to a stronger contribution of the $2 \rightarrow 3$ transition. Since we neglect the $2 \rightarrow 3$ transition in our calculation, the theoretical line shape shown in Fig. 6(b) at 240 K does not exhibit the associated slight shift in resonance position to lower wave numbers. However, this shift is small and our calculation can, even at the highest temperatures, be considered good. At $B=6.5$ T, $\omega_c \tau$ varies between 30–300 in the whole temperature regime. Thus, a 1% shift of the cyclotron resonance positions to lower energies with respect to the separations at the Landau-band edges can be expected. However, up to about 120 K the shift is negligible and above there is no chance to observe it, since several Landau transitions strongly overlap.

Figure 6(a) shows the predicted temperature dependence of the cyclotron resonance line shapes at $B=3.91$ T. As observed experimentally in Fig. 1(a) no individual Landau transitions are resolved. The solid curves include only transitions $N \rightarrow N+1$ with $N \leq 4$, since higher-order transitions are strongly damped due to LO-phonon influences. The dashed curves, considering all Landau transitions, do not provide a satisfactory fit to the experimental spectra. With increasing temperature the cyclotron resonance position shifts to lower wave numbers, which means that the cyclotron mass increases. This arises from the shift of the oscillator strength to higher Landau transitions as demonstrated in Fig. 5(a). In Fig. 5(a) above about 200 K all Landau transitions $N \leq 4$ have very similar oscillator strengths. Therefore, the cyclotron mass reflects the average mass of all transitions between 200–300 K. This explains the cyclotron mass saturation observed above 200 K in Fig. 3(a). At $B=3.91$ T the finite scattering time can, in principle, account for a shift of the cyclotron resonance with respect to the Landau-band edge separations of about 2% in the whole temperature regime. However, due to a strong overlap of several individual Landau transitions it cannot be verified experimentally.

A. Spin splitting

The spin of the electron has a significant impact on the band structure in semiconductors. In GaAs the spin degeneracy of conduction-band states at a given **k** vector is lifted except in certain symmetry directions due to spin-orbit interactions. This spin splitting in the absence of a magnetic field turns into the Zeeman splitting at finite field strengths B governed by the Landé g factor of Eq.

(2).[28] The Landé factor is a fundamental quantity that can be related to band separations and interband matrix elements and its knowledge can provide a test of band-structure calculations.

Information on the quantities g_0 and g_1 can at best be gained from a calculation of the experimental line shapes at $B=15$ T shown in Fig. 2. In the limit $\omega_c\tau \gg 1$, which applies here, the predicted spin splitting of the $0\rightarrow 1$ transition is

$$\Delta E_{10}=|E_{1,+(1/2)}(0)-E_{1,-(1/2)}(0)|=g_1\mu_B B^2 \ . \quad (12)$$

The magnitude of the splitting does not depend on g_0 and is proportional to the square of the magnetic-field strength. Information on g_0 can only be gained from the relative spin intensities, since the thermal populations of the two spin states of the ground Landau band relate to $g_0^*=g_0+g_1B/2$.

Recently, we have analyzed the relative spin amplitudes of the cyclotron resonance line shapes of free and bound electrons shown in Fig. 2 to gather information on the effective Landé factor. The calculation was performed in the framework of a two-dimensional model for the density of states, neglecting an influence of the momentum parallel to the magnetic-field direction.[29] This approach is appropriate only for the calculation of the line shape of the bound electrons, but not for the free electrons. Within the framework of this approximation one does not obtain the correct value for g_0, since the temperature dependence of the relative spin amplitudes can only be explained with a temperature-dependent g_0. We would like to correct this here and give an explanation for the temperature-induced fictitious exchange of oscillator strength from the high-energy to the low-energy side of the spin-split free-electron $0\rightarrow 1$ Landau transition of Fig. 2(a).

Figure 7 shows a calculation of the spin-split free-electron cyclotron resonance line shape, illustrating the influence of the cyclotron scattering time. At a scattering time of 70 ps the two spin transitions are well resolved with the stronger populated spin state exhibiting a higher oscillator strength. Both spin lines are asymmetric, exhibiting a low-energy tail which arises from dipole transitions with momenta $\hbar k_z>0$. With decreasing scattering time the lines broaden and a stronger overlap occurs. Although the relative occupation of the spin states is not changed in the calculation, since the total electron density, the temperature, and the Landé g factor are kept constant, there is a fictitious exchange of oscillator strength from the low-energy to the high-energy side of the resonance. It is characteristic for bulk electrons in semiconductors with a sufficiently small g factor, where nonparabolicity induces an asymmetry of the spin lines.

We have analyzed the line shapes of Fig. 2 and find that the spin splitting can be explained with a temperature-independent effective Landé factor. The experiment is in excellent agreement with the B^2 dependence of the resonance splitting predicted by Eq. (12). For the free and bound electrons we obtain $g_0\approx -0.4\pm 0.1$. Since our experiment is not sensitive to the absolute sign of the Landé factor, g_0 is assumed to be negative in accordance with previous experiments.[18,19] The factor g_1 differs for free and bound electrons. For free electrons we obtain $g_1\approx 0.010\ \mathrm{T}^{-1}$, whereas for bound electrons we find $g_1\approx 0.0075\ \mathrm{T}^{-1}$.

B. Electron densities and cyclotron relaxation times

In Fig. 8(a) the temperature dependence of the total electron density n_e obtained from cyclotron resonance and magnetotransport experiments are compared. The electron densities obtained from the Hall effect at a

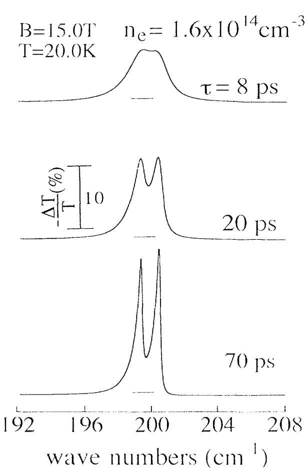

FIG. 7. Influence of the scattering times τ on the spin-split $0\rightarrow 1$ electron cyclotron resonance in GaAs. The horizontal lines mark base lines $-\Delta T/T=0$.

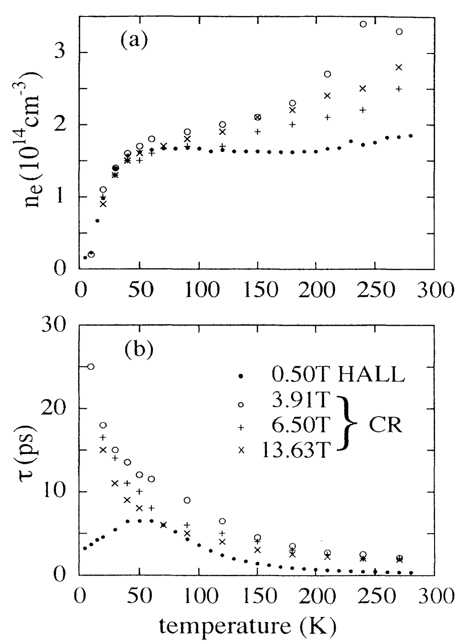

FIG. 8. (a) Electron densities n_e and (b) scattering times τ deduced from cyclotron resonance and magnetotransport experiments. The experimental error is about 10–20 %.

magnetic-field strength of $B=0.5$ T are essentially independent of temperature above 50 K. At lower temperatures, the electron densities decrease due to carrier freeze out into the donor levels. The data points reflect the ratio n_e/r_H, where r_H is the Hall factor. In the high-field limit $\omega_c\tau_{\mathrm{DC}}\gg 1$, where τ_{DC} is the transport scattering time at zero magnetic field, the Hall factor approaches one, whereas in the low-field limit, $\omega_c\tau_{\mathrm{DC}}\ll 1$ it depends on detailed scattering mechanisms.[30] Below 150 K it is justified to assume $r_H=1$ since $\omega_c\tau_{\mathrm{DC}}>1$, whereas above $\omega_c\tau_{\mathrm{DC}}<1$, and the densities might be about 10–20 % larger than the given values.[31–33] Both the absolute values and the temperature dependence of n_e obtained either from cyclotron resonance or magnetotransport agree well, supporting our model calculation of the line shapes and the assumptions made.

In Fig. 8(b) we compare temperature-dependent scattering times deduced from cyclotron resonance and magnetotransport. The Hall data reflect the product $\tau_{\mathrm{DC}}r_H$. This temperature dependence is well known and was intensively studied before.[31–33] At temperatures below 50 K the transport scattering time is dominated by ionized impurity scattering. Above 50 K there is an enhanced contribution of acoustic-phonon scattering and around liquid-nitrogen temperatures, optical-phonon scattering takes over and limits the mobility at higher temperatures. In comparison to this, cyclotron relaxation times are different in magnitude and exhibit a different temperature dependence. Cyclotron relaxation times decrease monotonically with increasing magnetic-field strength and temperature. In particular, in the temperature regime where ionized impurity scattering dominates, the cyclotron relaxation times exceed the magnetotransport scattering times by a factor up to 5. Surprisingly, also in the high-temperature limit cyclotron scattering times are up to a factor of 3 larger. There is no simple relation between the cyclotron relaxation time τ and the scattering time τ_{DC} as in a quasi-two-dimensional system where $\tau\propto\sqrt{\tau_{\mathrm{DC}}/B}$ if the scattering potentials are of short range.[22] Thus, the mobility data in bulk GaAs cannot be deduced from cyclotron resonance in a simple manner.

C. Cyclotron masses

Our experiment can be explained well with the assumption that the Landau-band separations are essentially independent of temperature, i.e., that the cyclotron masses are constant. In the framework of the two-band model, the temperature dependence of the cyclotron masses Eq. (10) is governed by the temperature dependences of the conduction-band edge mass m_0 and the effective energy gap E_g^*. In GaAs the band gap decreases with increasing temperature[34] and a simultaneous decrease of m_0 could be expected.[6] In fact, from magnetophonon transport experiments a drop of the bare mass of about 4% in the temperature regime up to 300 K was deduced.[35,36] The nonparabolicity terms in Eqs. (10) and (11) increase with decreasing energy gap and can partly compensate for the temperature variation of m_0. However, the degree of compensation is smaller than 10% if estimated from the second term of Eq. (10). A full compensation would require at least a 100% change of the nonparabolicity term with temperature, which cannot be justified from calculations. Presently, we do not have a satisfactory explanation for the different temperature dependences of the masses deduced from our cyclotron resonance experiment and the magnetophonon experiment.

The temperature-induced polaron mass renormalization in the bulk was only calculated at the conduction-band edge, neglecting a possible contribution to the dispersion.[5,14] Qualitatively, with increasing temperature the polaron mass reaches a maximum value at some finite temperature and approaches the bare conduction-band edge mass in the limit of high temperatures. Numerical values for GaAs are only given in a limited temperature regime from 0 to 150 K for which a small mass variation of the order of 0.6% is predicted.[14] To our knowledge, the temperature dependence of the combined influence of band coupling and electron-phonon interactions on the cyclotron mass has not been calculated yet. Perhaps we face here a nearly complete and accidental cancellation of the temperature shifts associated with band coupling and the polaron effect in GaAs.

VI. CONCLUDING REMARKS

The temperature-dependent cyclotron resonance of conduction-band electrons in bulk GaAs is studied with Fourier-transform spectroscopy in the frequency domain. Band coupling, the polaron effect, and the electron spin influence the transition energies between adjacent Landau bands. We find essentially no temperature dependence of the transition energies between individual Landau bands in the temperature regime from about 10 to 300 K. No observable contribution to the cyclotron resonance line shape is found from Landau transitions that involve Landau bands with energy larger than the one-phonon line $\hbar\omega_{\mathrm{LO}}+E_0$. This is attributed to the influences of electron-LO-phonon interactions which strongly damp such transitions. Calculations of the cyclotron resonance line shape indicate cyclotron relaxation times which strongly depend on temperature and magnetic-field strength with no obvious relation to magnetotransport scattering times. Theoretical work is needed to clarify the differences in magnitude and temperature dependences of cyclotron relaxation times and magnetotransport scattering times.

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*Present address: Physikalisches Institut der Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany.

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