Temperature dependence of the cyclotron-resonance linewidth in GaAs-$Ga_{1-x}Al_xAs$ heterojunctions

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The temperature dependence of the cyclotron-resonance linewidth has been measured in several GaAs-$Ga_{1-x}Al_xAs$ heterojunctions up to room temperature. For high temperatures ($T > 50$ K) the linewidth is consistent with scattering dominated by LO phonons. Below ~ 50 K the linewidths were much smaller and showed greater temperature dependences than expected from low-field mobility calculations. The values measured at 4 K were in general agreement with theoretical calculations in which screening was included self-consistently. The low-temperature linewidths varied slowly with electron concentration or inverse spacer-layer thickness, suggesting that scattering by either impurities in the GaAs or alloy disorder in the $Ga_{1-x}Al_xAs$ may be the dominant mechanism at high fields. The linewidth values lead to the deduction of a short-range scattering mobility limit of order 10^9 cm^2 V^{-1} s^{-1}.

I. INTRODUCTION

There have been many studies of cyclotron resonance (CR) in the two-dimensional electron gas (2D EG) formed in GaAs-$Ga_{1-x}Al_xAs$ heterojunctions.[1–18] However, interest has focused principally on measuring the resonance field (B_R) and the linewidth at low temperatures, whereas this paper will focus primarily upon the temperature dependence of the linewidth between liquid-helium and room temperatures.

The study of the CR linewidth is of interest because, being a local transition, the linewidth is largely determined by potential fluctuations of range less than or of the order of the cyclotron radius (homogeneous broadening).[19] Longer-range fluctuations (inhomogeneous broadening) will have a similar effect on all the Landau levels and so will make little contribution to the lifetime broadening in the linewidth. Thus we do not expect the cyclotron-resonance linewidth to be simply related to the low-field mobility or the density of states deduced from "thermodynamic" measurements such as de Haas–van Alphen[20] or specific-heat[21] studies, which are sensitive to the inhomogeneous broadening.

In addition, the extremely sharp discontinuous density of states formed in 2D systems at low temperatures and high fields is thought to result in greatly enhanced free-carrier screening which plays an important role in determining the low-temperature CR linewidth.[22–24] Maxima observed in the linewidth of high-quality GaAs-$Ga_{1-x}Al_xAs$ heterojunctions at fields corresponding to even filling factors[5,8,12,14] have been attributed to a reduction in the screening when the highest occupied Landau level is full and the density of states at the Fermi energy is small. Further evidence of strong screening in GaAs-$Ga_{1-x}Al_xAs$ heterojunctions at high fields comes from the unexpectedly large increase in the effective mass with temperature and from the reduced nonparabolicity relative to that found in bulk GaAs, which were attributed to temperature-dependent screening of the electron-phonon interaction.[15,25] Thus the CR linewidth in high-quality 2D systems provides a method of studying electron scattering in a highly screened system.

In this paper we present a study of the temperature and magnetic field dependence of the CR linewidth in a series of high-quality GaAs-$Ga_{1-x}Al_xAs$ heterojunctions. The CR has been studied as a function of temperature from ~ 2 to 280 K and of resonant field at both ~ 2 and 90 K, and the results are compared with theoretical calculations of the linewidths.

II. SCATTERING MECHANISMS AND THE CYCLOTRON-RESONANCE LINEWIDTH

Before presenting our experimental results, we will briefly consider the principal scattering mechanisms in GaAs-$Ga_{1-x}Al_xAs$ heterojunctions and how they might be expected to influence the CR linewidth. The principal scattering potentials in high-quality samples are ionized impurities, optic phonons, and acoustic phonons. Alloy-disorder scattering will make a contribution through penetration of the electronic wave function into the $Ga_{1-x}Al_xAs$, but mobility calculations suggest that this will be small.[26,27] Interface roughness scattering is thought to be negligible in the "state of the art" samples studied. Generally speaking optic-phonon scattering, which increases rapidly with temperature as the number of phonons rises exponentially, is dominant at high temperatures, while at lower temperatures acoustic-phonon and, finally, impurity scattering become more important.

Scattering from impurities in three different regions must be considered: (i) background impurities in the nominally undoped GaAs in which the 2D EG is formed, (ii) residual impurities in the undoped $Ga_{1-x}Al_xAs$ spacer layer, and (iii) ionized donors in the doped $Ga_{1-x}Al_xAs$ layer. The relative importance of these will depend on the sample quality and structure. A study of the low-field mobilities (μ_0) in a series of GaAs-$Ga_{1-x}Al_xAs$ heterojunctions which included the samples studied here[28] show that at 4.2 K the mobility of samples with a spacer-layer thickness (d) of <400 Å is dominated by impurities in the doped $Ga_{1-x}Al_xAs$ layer. For thicker spacer layers, acoustic phonons or more probably background impurities in the GaAs limit the mobility.

The influence of a scattering potential on the CR linewidth (ΔB) will depend on its form and range (a) relative to the cyclotron radius (r). Field dependence of the linewidth will also enter through the density of states, and it is important to treat the problem self-consistently. Consequently, the relaxation time (τ) derived from ΔB will not be the same as that derived from the low-field mobility (μ_0) and the scattering potentials dominating ΔB and μ_0 may be different.

In the limit of short-range potentials ($r \ll a$) the matrix element will be field independent and the field dependence of $\Delta B_{1/2}$ will only enter through the density of states. Ando and Uemura[19] have calculated that the CR half-width for short-range scattering potentials $\Delta B_{1/2}(\mathrm{SR})$ can be expressed as

$$\Delta B_{1/2}(\mathrm{SR}) = C(B_R/\mu_0)^{1/2} , \quad (1)$$

where C is a constant of order $\sqrt{(2/\pi)}$. Other authors have obtained similar results using different calculations.[29,30] The $B_R^{1/2}$ dependence of the linewidth is in contrast to classic theory, which predicts a field-independent linewidth ($\Delta B_{1/2}/B_R = 1/\omega\tau$), and originates from the field dependence of the Landau level degeneracy and the self-consistency of the scattering rate.

For finite-range scattering potentials both the magnitude and the field dependence of the broadening will depend on the exact form of the potential. For a finite-range Gaussian potential[30,31] $\Delta B_{1/2}$ is given by

$$\Delta B_{1/2} = \Delta B_{1/2}(\mathrm{SR})/(1+\alpha^2)^{3/2} , \quad (2)$$

where $\alpha = a/\sqrt{2}r$. In contrast unscreened ionized impurity scattering should give a field-independent linewidth, but the inclusion of screening, which removes the long-range contributions, results in the linewidth having a field dependence similar to that to short-range scattering[30] (i.e., $\propto B_R^{1/2}$).

The field dependence of the resonance linewidth at 4.2 K measured in samples with lower mobilities than studied here[2,3,32–34] were in general agreement with Eq. (1), giving values for C of 0.65 ± 0.03. Interface roughness or, in the case of Ga-In-As, alloy scattering was suggested as the dominant scattering mechanisms. More recent studies of high-mobility $Ga_{1-x}Al_xAs$-GaAs heterojunctions have shown that the field dependence of the linewidth is more complex.

Maxima in the linewidth when an integral number of Landau levels are occupied[5,12,14] have been attributed to the filling-factor dependence of the screening,[22–24] with some recent suggestions that there may be some influence from localized states.[35,36] However, coupling to magnetoplasmons has also been suggested as the cause of linewidth maxima and cyclotron mass anomalies.[7,8] Slight misorientation of the samples relative to the magnetic field can also cause additional broadening when the cyclotron energy and subband separations are equal.[6,37–40]

There has been little study of the linewidth at higher temperature. Voisin *et al.*[3] observed a qualitative similarity between the temperature dependences of the inverse linewidth and the mobility. However, the samples studied had low mobilities [$(2-4)\times10^4$ cm^2 V^{-1} s^{-1} at low temperature] and the linewidths were of order 0.5 T or greater. In two higher-mobility samples Thiele *et al.*[41] saw a marked increase in linewidth with temperature up to 100 K but did not attempt any detailed analysis.

III. EXPERIMENTAL DETAILS

The samples studied were all grown at Philips Research Laboratories. Redhill,[42] by molecular-beam epitaxy (MBE) with undoped $Ga_{1-x}Al_xAs$ spacer-layer thicknesses (d) ranging from 400 to 1600 Å. The doping level of the $Ga_{1-x}Al_xAs$ (N_d) was 1.3×10^{18} cm^{-3} and the background acceptor concentrations in the GaAs (N_A), although not accurately known, were in the range $(2-4.5)\times10^{14}$ cm^{-3} (Ref. 28). The 2D electron density (n_s) of all the samples increased on illumination, and so measurements were made either in the dark or after saturation of the electron concentration by strong illumination with a red-light-emitting diode (LED). Sample details, including the 4-K electron densities (n_s) deduced from Shubnikov–de Haas oscillations and the low-field Hall mobilities, are summarized in Table I.

The results presented in this paper were obtained by

TABLE I. The electron densities (n_s), low-field mobilities (μ_0), and dc scattering times (τ_{dc}) at 4.2 K, deduced from Shubnikov–de Haas and Hall measurements in both the dark (dk) and (lt).

Sample	Spacer width (Å)	n_s(dk) (10^{11} cm^{-2})	μ_0(dk) (10^6 cm^2/V s)	τ_{dc}(dk) (10^{-11} s)	n_s(lt) (10^{11} cm^{-2})	μ_0(lt) (10^6 cm^2/V s)	τ_{dc}(lt) (10^{-11} s)
No. 1 (G139)	1,600	0.25	0.25	0.9	0.6	0.6	2.3
No. 2 (G63)	800	0.85	0.75	2.9	1.9	2.2	8.0
No. 3 (G29)	400	1.4	0.2	0.8	3.4	1.9	7.2
No. 8 (G71)	400	2.1	0.8	3.0	4.3	1.3	5.0

recording the field dependence of the transmission of fixed-frequency far-infrared (FIR) laser radiation through the sample. Using an optically pumped molecular-gas laser we were able to measure $\Delta B_{1/2}$ over the frequency range 20–240 cm^{-1}, corresponding to resonant fields between 1.5 and 18.5 T. The frequency or field dependence of the linewidth has been measured in several samples at ~ 2 K and, in sample No. 3 at 90 K. The temperature dependence of the cyclotron-resonance linewidth has been measured in all four samples, Nos. 1–4, up to a temperature of 240 K. Results were only taken in the equilibrium condition achieved by cooling in the dark, to ensure there was no thermal redistribution of impurity population on warming. The measurements were made at a frequency of 84.15 cm^{-1} ($B_R = 6.2$ T) for all the samples except sample No. 1, when a frequency at 58.62 cm^{-1} ($B_R = 4.3$ T) was used to avoid possible broadening of the resonance by Landau-level–(electric-)subband (LLSB) coupling.[6,37–40] At high temperatures the absorption was increased by recording the transmission through two pieces of the sample and, for the measurements at 84.15 cm^{-1}, by placing a circular polarizer directly in front of the sample. The sample substrates were wedged to reduce interference effects.

IV. RESULTS

It was mentioned earlier that at low temperatures (~ 4.2 K) the CR linewidth can show rapid broadening at fields corresponding to even filling factors and also when the subband separation is equal to the cyclotron energy in even slightly misaligned samples. These effects can complicate any analysis of the linewidth and so when studying the temperature dependence of the CR linewidth it is desirable to avoid making measurements at fields at which these effects occur.

In order to choose suitable fields we studied all our samples as a function of magnetic field from approximately 2 to 14 T at either 4.2 or 2 K. A typical set of results obtained from sample No. 1 at electron densities of 3×10^{10} and 6×10^{10} cm^{-2} are shown in Fig. 1. Linewidth broadening at a filling factor of around 2 and a small peak due to subband coupling are seen, and at higher fields (> 10 T) the linewidth is already starting to be broadened by resonant polaron coupling. It is evident that these three effects can mask the background field dependence of the linewidth, making even a qualitative study of this difficult. However, in the quantum limit these resonance broadenings are superimposed onto a resonance linewidth which appears to be only a weak function of the magnetic field (in samples having a high absorption of the incident radiation the measured half-widths are insensitive to changes in the scattering rate. This is discussed later) and the temperature dependence of ΔB was always studied in the quantum limit, at fields close to the minimum in ΔB. Ideally, when studying several samples all measurements would be made at both the same filling factor and resonance field. This is, of course, not possible for samples with different electron densities and we decided, partly for experimental ease, to make measurements in all but one sample at the same frequency of 84.15 cm^{-1} ($\lambda = 118.8$ μm, $B_R = 6.2$ T), which is well away from both the resonant polaron and the regime where the filling factor is close to 2.

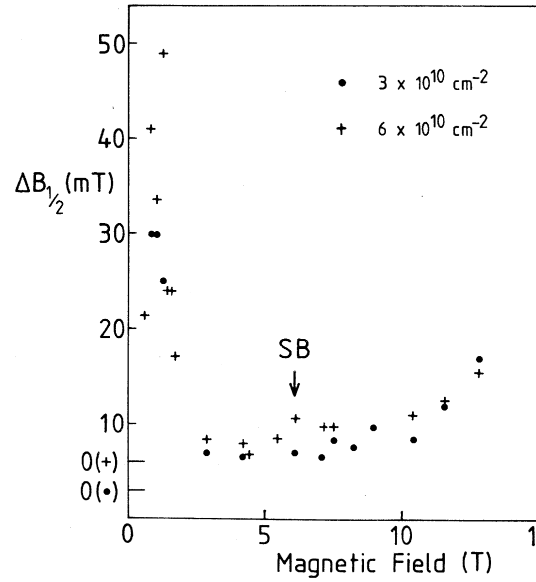

FIG. 1. The field dependence of the CR half-width of sample No. 1 at 1.6 K. Results are shown both before (●) and after (+) illumination with a red LED, giving carrier concentrations of 3×10^{10} and 6×10^{10} cm^{-2}. The approximate field at which subband–Landau-level coupling occurs is labeled "SB." Linewidth broadening is observed at low fields, corresponding to a filling factor of 2. The marks show the minimum theoretical linewidth ($m^*\omega_p/e$) for the two carrier concentrations.

Figure 2 shows experimental recordings of the CR at $\lambda = 118.8$ μm in sample No. 4 at several temperatures covering the range 20–120 K. The linewidth is strongly

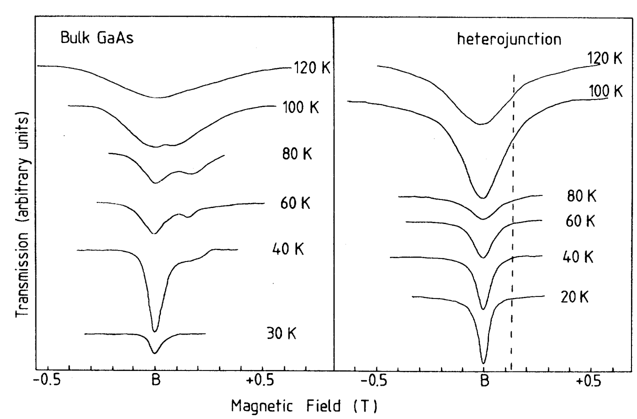

FIG. 2. Experimental recordings of the CR with $\lambda = 118.8$ μm in bulk GaAs and GaAs-$Ga_{1-x}Al_xAs$ heterojunction sample No. 4 at selected temperatures covering the range 20–120 K. The dashed line indicates the field position at which the $1\rightarrow2$ level transition should occur for the heterojunction.

temperature dependent, and will be discussed in detail below. CR transmission curves obtained at the same temperatures in a bulk sample of GaAs are also shown. The resonant field in the heterojunctions is strongly temperature dependent (this has been attributed to the temperature dependence of the electron-phonon coupling[15,25]) and so the curves have been plotted in terms of resonant field rather than absolute field to allow easier comparison of the linewidths. As the temperature increases, higher Landau levels become occupied, and because of the nonparabolicity of the conduction band this should result in a splitting or asymmetry of the resonance when the resonance broadening is less than or comparable to the difference in the resonant fields of the different transitions. This can be clearly seen in the measurements made on bulk GaAs; as the temperature increases, an asymmetry in the resonance appears which develops into a splitting above ~40 K and at temperatures around 60 K the $0 \rightarrow 1$ and $1 \rightarrow 2$ Landau transitions are well resolved. The transition probability increases with Landau quantum number and so the relative strength of the CR due to higher transitions is greater than expected from the electron distribution.

In contrast to the bulk results there is no splitting and little or no observable asymmetry in any of the heterojunctions studied, despite the CR linewidth for a single transition being similar in the bulk and 2D samples. When the different bulk resonances cease to be resolved at 120 K the resonance is broader than that in the 2D system, implying that the higher-level transitions are not being observed in the latter. This is surprising in view of the hot-electron studies of the cyclotron resonance of Seidenbusch *et al.*,[10] where higher-level transitions were resolved for electric fields corresponding to electron temperatures of 50–100 K. These authors observed a splitting between the resonances due to the two lowest transitions of ~0.1 T, which is consistent with measurements of the conduction-band nonparabolicity in GaAs-$Ga_{1-x}Al_xAs$ heterojunctions[15] and the additional polaron coupling for the higher transition. Two factors may be expected to influence the appearance of higher-level transitions in the CR line shape in 2D systems. First, screening of the electron-phonon interaction, which will reduce the polaron contribution to the nonparabolicity and therefore the transition separations, is thought to be strong in heterojunctions for temperatures below ~100 K (Refs. 15 and 25). Second, the population of higher subbands may give additional transitions intermediate between the lowest subband transitions, although these will be weaker. Nonetheless, the resonances were sufficiently narrow for observation of the $1 \rightarrow 2$ level transition to be expected, as illustrated in Fig. 2 where the field position of the second resonance predicted by the measured band nonparabolicity alone[15] is marked as a dashed line. The nonobservation of a resolved second resonance will mean that the experimental linewidths may be a slight overestimate of the true linewidth.

In Fig. 3 the true resonance linewidth ($\delta B_{1/2}$) is plotted as a function of temperature for all four samples studied. If, as was the case for these samples at low temperatures, a sample absorbs a significant proportion of the incident radiation the half-width ($\Delta B_{1/2}$) at which the absorption is half that at resonance will not give the uncertainty broadening directly. In order to deduce $\delta B_{1/2}$ it is necessary to correct for the finite carrier concentration, using a Drude formalism.[43] This gives an experimental half-width $\Delta B_{1/2}$ which is related to the true linewidth $\delta B_{1/2}$ by the relation

$$\Delta B_{1/2} = \delta B_{1/2} + m^* \omega_p / e \ , \tag{3}$$

where $\omega_p = Z_0 N_s e^2 / m^*(1+\sqrt{\epsilon})$, Z_0 is the impedance of free space, and ϵ is the dielectric constant of GaAs. The result of this is that there is an additive finite linewidth even for a perfect system where $\tau, \mu \rightarrow \infty$, and for higher carrier concentrations this can seriously limit the accuracy of the value of $\delta B_{1/2}$ (e.g., for $N_s = 2 \times 10^{11}$ cm^{-2}, $m^* \omega_p / e = 25$ mT). In principle, the strength of the absorption at resonance could also be used to determine the carrier concentration; however, the accuracy is rather limited once the absorption becomes large, because of slight uncertainties in the exact polarization of the light and the complete homogeneity of the sample. The right-hand scale of the figure shows the cyclotron lifetime τ_c, deduced from $\tau_c = m^*/e\, \delta B_{1/2}$.

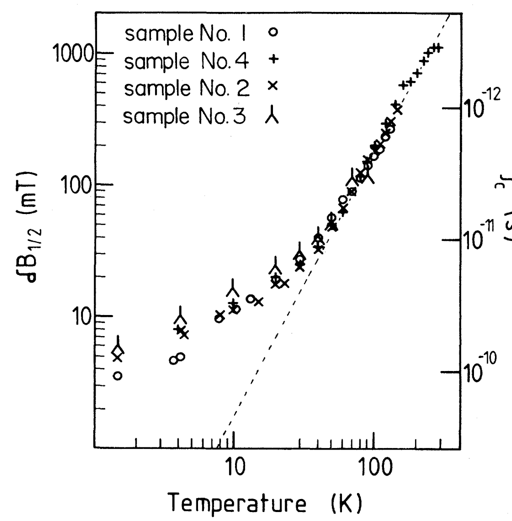

FIG. 3. The temperature dependence of the true CR half-width in four GaAs-$Ga_{1-x}Al_xAs$ heterojunctions. The data for sample No. 1 were taken at $\lambda = 170.6$ μm and for the other three samples at $\lambda = 118.8$ μm. The right-hand scale shows the equivalent high-field scattering time τ_c.

At high temperatures (> 50 K) the half-widths of all four samples had similar values and temperature dependences, increasing approximately as T^2. Below 50 K, $\delta B_{1/2}$ increased less rapidly and at a rate which varied somewhat between samples. The linewidths of samples Nos. 3 and 4 were slightly larger and varied approximately as $T^{0.5}$, while those of the lower-electron-concentration samples, Nos. 1 and 2, showed a little more temperature dependence, falling to very low values by 1.5 K. For example, in sample No. 1 at ~1.5 K, $\delta B_{1/2}/B_R \approx 1/2000$.

These results can be explained qualitatively as follows: at high temperatures the linewidth is dominated by optic-phonon scattering, which decreases rapidly with temperature, while at lower temperatures the scattering rate becomes increasingly limited by acoustic-phonon, ionized-impurity, and possibly allow-disorder scattering, which are less temperature dependent. However, linewidth theories in which screening is not treated self-consistently do not give an adequate quantitative explanation for these results on two points. First, the linewidths of sample Nos. 1 and 2 have a rather greater temperature dependence than expected from either acoustic-phonon scattering, for which a $\sqrt{T}$ dependence is predicted, or impurity scattering, which should give a temperature-independent linewidth at low temperatures. Second, the low-temperature linewidths of all the samples studied are considerably smaller than expected from theoretical calculations of the resonance broadening due to acoustic phonons. For acoustic phonons, scattering calculations suggest that the CR broadening due to deformation-potential scattering will be larger than that due to piezoelectric scattering. Sarkar and Nicholas[30] and Chaubey and Van Vliet[44] have both derived expressions for $\delta B_{1/2}$ due to the deformation-potential broadening in the high-temperature approximation of the form

$$\delta B_{1/2} = A(B_R T)^{1/2} , \tag{4}$$

where A is a constant equal to 0.028 (Ref. 30) or 0.053 (Ref. 44), taking the appropriate physical constants from *Landolt-Börnstein*[45] and the deformation potential to be 7 eV. There is some debate over the correct value of the deformation potential[46,47] and we have taken the lowest acceptable value to obtain a minimum theoretical linewidth. The wave vector associated with a cyclotron transition is of order $2\pi/a$, which at 6 T corresponds to an acoustic phonon of energy $\sim$20 K. As the temperature decreases, the phonons will become increasingly long range and in the low-temperature limit emission processes will dominate the scattering and the linewidth will be independent of temperature. Sarkar and Nicholas[30] have calculated that in this limit $\delta B_{1/2}$ is given by

$$\delta B_{1/2} = 0.054 B_R^{3/4} . \tag{5}$$

Equations (4) and (5) are equal at a temperature of 9.3 K when $B_R = 6.2$ T (the resonance field for a wavelength of 118.8 μm) and $A = 0.028$, suggesting that the linewidth will decrease with temperature as $\sqrt{T}$ until the emission limit is reached at around 10 K.

Comparing the predicted linewidths with experiment, we find considerable discrepancies. For example, substitution of the measured low-field mobility (μ_0) at 4.2 K for sample No. 2 (0.75×10^6 cm^2/V s) into Eq. (1) for short-range scatterers gives a half-width of 0.059 T, while for acoustic-phonon scattering, Eqs. (4) and (5) give half-widths of 0.14 and 0.21 T, respectively, taking $A = 0.028$ and $B = 6.2$ T. These compare with a measured half-width of 0.005 T.

As mentioned before, the relationship between the low-field dc mobility [and its associated dc scattering time τ_{dc} ($=\mu m^*/e$)] and the resonance linewidth is not straightforward. The high-field scattering time τ_c deduced from $\delta B_{1/2}$ and shown in Fig. 2 can be over an order of magnitude longer (10^{-10} s at 1.5 K) than τ_{dc} for the same samples [$(0.8-3)\times10^{-11}$ s; see Table I]. In complete contrast, the so-called quantum lifetime τ_q deduced from the damping of Shubnikov–de Haas oscillations as a function of magnetic field[48] often has values over an order of magnitude *lower* than τ_{dc}. In order to compare the linewidths with the low-field mobilities in a way which demonstrates the scattering processes, we must consider the self-consistency of the level width. An increase in the scattering probability will broaden the level and, hence, reduce the density of states in the level, which acts to reduce the scattering rate. We would thus expect the level width to vary as $\mu_0^{-1/2}$, as found in the short-range scattering formula (1). However, the linewidth in the quantum limit is determined by scattering processes involving wave vectors q determined by the magnetic field, and not by the Fermi wave vector, as in the case of the low-field mobility at low temperatures. Thus, the constant of proportionality between $\delta B_{1/2}$ and $\mu_0^{-1/2}$ is likely to be different for different scattering mechanisms, and in particular $\delta B_{1/2}$ is unlikely to be sensitive to the long-range potentials fluctuations which limit τ_{dc} in wide spacer-layer samples.

This is illustrated in Fig. 4, where $C'(\Delta B_{1/2})^{-2}$ is compared with the low-field mobilities μ_0 calculated by

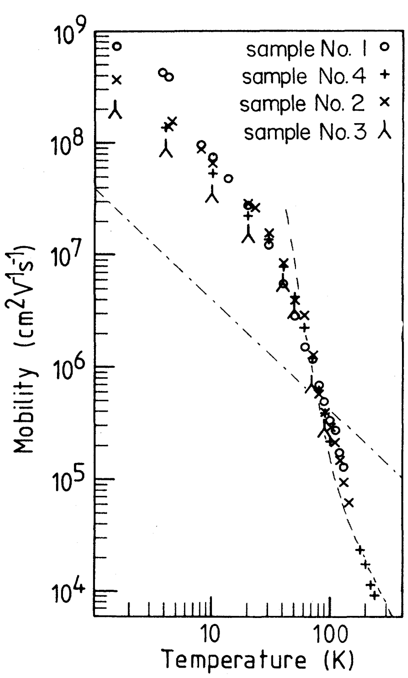

FIG. 4. The temperature dependence of the sample mobility calculated from the CR half-widths plotted in Fig. 3 using Eq. (1) and taking $C = 0.38$. The dashed and dashed-dotted lines show the optic- and acoustic-phonon-limited zero-field mobilities calculated by Walukiewicz *et al.* (Ref. 26) for a sample with $n_s = 2.2\times10^{11}$ cm^{-2}.

Walukiewicz *et al.*[26] for a GaAs-$Ga_{1-x}Al_xAs$ heterojunction with $n_s=2.2\times10^{11}$ cm^{-2} as a function of temperature. The constant C' was chosen to give a fit between μ_0 and the results from sample No. 4 around 200 K. This gives a value of $C'=0.9$ T, which corresponds to a value of $C=0.38$ Eq. (2). This is quite close to the value of 0.65 expected for short-range scattering, and at temperatures above $\sim$60 K there is good agreement between the temperature dependence of the mobility derived from the linewidths and the calculated optic-phonon-limited mobility. Even closer agreement would in fact be given by a simple power law, with $\mu\propto T^4$. Below 50 K the mobility derived from the linewidth, μ(CR), falls below the calculated optic-phonon-limited mobility but remains much larger than the acoustic-phonon limit. The temperature dependence is, however, quite close to that expected for the acoustic phonons ($\propto T$). Finally, at around 2 K, the mobility and linewidth show signs of saturating, and there is little further narrowing when measurements are made at even low temperatures.[49] The values of μ(CR) at low temperature are much larger than the measured values of μ_0 given in Table I or even those which would be deduced from the high-field relaxation time τ_c.

The most obvious reasons for a discrepancy between the theoretical and experimental low-field mobilities and μ(CR) are the range of the scattering potentials and the enhanced effects of free-carrier screening in high magnetic fields. Numerical calculations of the CR linewidth where screening is included self-consistently have been made by Lassnig *et al.*[24] and Ando and Murayama,[23] who considered scattering from charged ions in the $Ga_{1-x}Al_xAs$ and GaAs layers and concluded that the background impurities in the GaAs were the dominant factor for spacer-layer thicknesses greater than $\sim$20 nm. Unfortunately, the parameters used by these authors do not correspond precisely to the structures studied here, and so a direct comparison with the experimental results is not possible. The best correspondence is for sample No. 3, which has a minimum linewidth of 0.006 T. This compares with a minimum linewidth of 0.01 T calculated by Ando and Murayama for a sample with a similar electron concentration at a field of 5 T when $N_A=1\times10^{14}$ cm^{-3}, and of 0.09 T when $N_A=1\times10^{15}$ cm^{-3}. Given that for these samples N_A probably lies in the range of $(2-4.5)\times10^{14}$ cm^{-3} (as deduced from transport measurements[28]) these calculated values are closer to the experimental measurements, although still somewhat bigger. The large temperature dependence of the linewidth is also consistent with the self-consistent screening calculations of Lassnig *et al.*,[24] which predict a strongly temperature-dependent linewidth even when limited by ionized-impurity scattering. The conclusion that scattering by the background impurities in the GaAs is dominant, as suggested by these theories, is also consistent with the weak dependence of the linewidths on spacer-layer thickness, as can be seen in Figs. 2 and 3, despite almost an order-of-magnitude change in carrier concentration.

In a recent study of a slightly lower-mobility heterojunction at low temperatures, Chou *et al.*[18] came to a similar conclusion, namely that scattering from the acceptors in the GaAs was dominant; however, they found that the linewidth was also very strongly carrier-concentration dependent. This was attributed to the reduction of screening for low Landau-level occupancies, ν $(=hn_s/eB)$. The data presented here, where n_s has been changed by changing either the spacer-layer thickness or by illumination, rather than by the use of a back gate, do not seem to show such a pronounced effect. This can be seen in Fig. 1, where $\Delta B_{1/2}$ is shown for two carrier concentrations (3×10^{10} and 6×10^{10} cm^{-2}) in the same sample, No. 1, from 2.5 to 13 T, corresponding to $0.1<\nu<1$. In this range the corrected linewidth ($\delta B_{1/2}$) varies by at most a factor of 3, with the majority of the change occurring at high fields where the onset of resonant polaron coupling is known to cause the resonance to broaden. Data from the higher-density samples lead to similar conclusions, although the errors rapidly become very large due to the dominant contribution to the linewidth from the electron concentration [Eq. (3)]. In the case of sample No. 1, where the carrier concentration was changed by the persistent photoconductive effect, it should also be borne in mind that both the wave function and the distribution of scattering centers will have been changed in the process of illumination.

One process which may also be significant in limiting the cyclotron linewidth at high fields is alloy scattering due to the penetration of the wave function into the $Ga_{1-x}Al_xAs$ barrier. Calculations[26,50] show that the barrier penetration is almost linearly proportional to n^* in the density range of our samples, where $n^*=(n_s+\frac{32}{11}n_{\mathrm{dep}})$ (Ref. 51); n_{dep} is the depletion charge in the GaAs, which is estimated to be $\simeq3\times10^{10}$ cm^{-2} from the subband separations in our samples,[40] giving values of n^* in the range $1\times10^{11}<n^*<3\times10^{11}$ cm^{-2}. The fraction of the wave function inside the barrier is only of the order of 1% (Refs. 19, 26, and 50) and the alloy-scattering-limited low-field mobilities are of order 10^8 cm^2 V^{-1} s^{-1} and above for low n^* values at low temperatures.[19,26] Since alloy scattering is a short-range process, we would expect the mobility values deduced from Eq. (2) to be a good estimate, and the data of Fig. 3 suggest that the alloy scattering may well be responsible for limiting the linewidth and scattering times in the extreme case of high magnetic fields and low temperatures, despite its negligible contribution to the low-field mobility. This would also account for the weak carrier-concentration dependence of the linewidths. Further support for this idea comes from the recent reports of Goldman *et al.*,[52] who found that very well developed fractional quantum-Hall-effect phenomena could be found in heterojunctions in which the alloy scattering was suppressed by the inclusion of a thin AlAs penetration barrier. To the best of our knowledge no calculations of the linewidth due to alloy disorder have been performed.

A study has also been made of the field dependence of the resonance linewidth at higher temperatures. The linewidth of sample No. 3 at 90 K is plotted against B_R in Fig. 5 and was found to be roughly constant over the field range covered. At this temperature we would expect

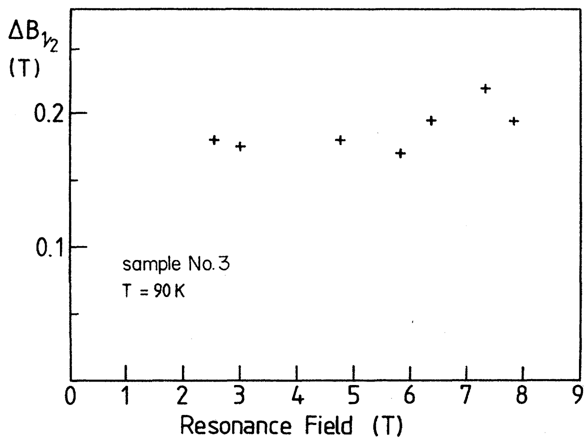

FIG. 5. The resonance field dependence of the CR half-width of sample No. 3 at 90 K with $n_s = 1.4 \times 10^{11}$ cm^{-2}. At this temperature the linewidth is dominated by optic-phonon scattering.

optic phonons to be the dominant scattering mechanism, but calculation of their influence on the resonance broadening has proved complicated and a simple field and temperature dependence is not readily derived.[44,53,54] However, a simple qualitative argument can be made as follows. The matrix element for polar-optic-phonon scattering is proportional to q^{-1}, where q is the phonon vector. The characteristic wave vector of the Landau levels, of order $2\pi/a$, and varies as $B^{-1/2}$. The self-consistency of the scattering rate will then lead to a linewidth proportional to $B^{1/4}$. However, inelastic optic-phonon scattering should only be possible near the magnetic fields corresponding to the magnetophonon condition $N\omega_c = \omega_{\rm LO}$, as otherwise there is no final state for the electron. We may thus expect elastic scattering to be important which, with a matrix element proportional to B^{-1}, would give a field-independent linewidth, consistent with the experimental results. No evidence is seen for strong maxima in the linewidth at the magnetophonon condition $N\omega_c = \omega_{\rm LO}$ (corresponding to $B \simeq 22/N$ T), suggesting that elastic scattering does make the major contribution to the optic-phonon-limited linewidth.

V. CONCLUSIONS

A quantitative study has been made of the CR linewidth of GaAs-$Ga_{1-x}Al_xAs$ heterojunctions as a function of temperature and resonance field. At high temperatures (> 50 K) the linewidths showed the same temperature dependence as the square root of the low-field optic-phonon-limited mobility, consistent with simple theory. At lower temperatures the linewidth continued to fall, but less rapidly and at a rate which varied somewhat between samples. The absolute values of the low-temperature linewidths were substantially smaller than predicted by theories which do not include self-consistent screening, but approximate comparison with numerical calculations including screening self-consistently give much better agreement, assuming that scattering from impurities in the GaAs is dominant. This implies that in high magnetic fields the screening plays an important role in determining the CR linewidth and is strongly temperature dependent down to 1.5 K. Increasing the electron concentration by illumination or decrease of the spacer-layer thickness caused a small increase in the linewidth. This may suggest that remote alloy scattering due to the "tail" of the subband wave function in the $Ga_{1-x}Al_xAs$ barrier is a significant factor in the low-temperature linewidth, and the absolute values of the minimum linewidth are consistent with a short-range scattering mobility limit calculated from alloy scattering.

[1]H. L. Stormer, R. Dingle, A. C. Gossard, W. Wiegmann, and M. D. Sturge, Solid State Commun. **29**, 705 (1979).

[2]P. Voisin, Y. Guldner, J. P. Vieren, M. Voos, P. Delescluse, and N. T. Linh, Appl. Phys. Lett. **39**, 982 (1981).

[3]P. Voisin, Y. Guldner, J. P. Vieren, M. Voos, P. Delescluse, and N. T. Linh, Physica B+C **117&118B**, 634 (1983).

[4]J. C. Maan, Th. Englert, D. C. Tsui, and A. C. Gossard, Appl. Phys. Lett. **40**, 609 (1982).

[5]Th. Englert, J. C. Maan, D. C. Tsui, and A. C. Gossard, Solid State Commun. **45**, 989 (1983).

[6]Z. Schlesinger, J. C. M. Hwang, and S. J. Allen, Phys. Rev. Lett. **50**, 2098 (1983).

[7]Z. Schlesinger, S. J. Allen, J. C. M. Hwang, P. M. Platzman, and N. Tzoar, Phys. Rev. B **30**, 435 (1984).

[8]Z. Schlesinger, W. I. Wang, and A. H. MacDonald, Phys. Rev. Lett. **58**, 73 (1984).

[9]W. Seidenbusch, G. Lindemann, R. Lassnig, J. Edlinger, and E. Gornik, Surf. Sci. **142**, 375 (1984).

[10]W. Seidenbusch, E. Gornik, and G. Weimann, Physica B+C **134B** , 134 (1985).

[11]W. Seidenbusch, Phys. Rev. B **36**, 1877 (1987).

[12]W. Seidenbusch, E. Gornik, and G. Weimann, Phys. Rev. B **36**, 9155 (1987).

[13]M. Horst, U. Merkt, W. Zawadzki, J. C. Maan, and K. Ploog, Solid State Commun. **53**, 403 (1985).

[14]H. Sigg, P. Wyder, and J. A. A. J. Perenboom, Phys. Rev. B **31**, 5253 (1985).

[15]M. A. Hopkins, R. J. Nicholas, M. A. Brummell, J. J. Harris, and C. T. Foxon, Phys. Rev. B **36**, 4789 (1987).

[16]K. Ensslin, D. Heitmann, H. Sigg, and K. Ploog, Phys. Rev. B **36**, 8177 (1987).

[17]F. Thiele, U. Merkt, J. P. Kotthaus, G. Lommer, F. Malcher, U. Rossler, and G. Weimann, Solid State Commun. **62**, 841 (1987).

[18]M. J. Chou, D. C. Tsui, and G. Weimann, Phys. Rev. B **37**, 848 (1988).

[19]T. Ando and Y. Uemura, J. Phys. Soc. Jpn. **36**, 959 (1974).

[20]J. P. Eisenstein, H. L. Stormer, V. Narayanamurti, A. Y. Cho, A. C. Gossard, and C. W. Tu, Phys. Rev. Lett. **55**, 875 (1985).

[21]E. Gornik, R. Lassnig, G. Strasser, H. L. Störmer, A. C. Gossard, and W. Wiegmann, Phys. Rev. Lett. **54**, 1820 (1985).

[22]R. Lassnig and E. Gornik, Solid State Commun. **47**, 959

(1983).

[23]T. Ando and Y. Murayama, J. Phys. Soc. Jpn. **54**, 1519 (1985).

[24]R. Lassnig, W. Seidenbusch, E. Gornik, and G. Weimann, in *Proceedings of the 18th International Conference on the Physics of Semiconductors, Stockholm, 1986*, edited by O. Engström (World Scientific, Singapore, 1987), p. 593.

[25]M. A. Brummell, R. J. Nicholas, M. A. Hopkins, J. J. Harris, and C. T. Foxon, Phys. Rev. Lett. **58**, 77 (1987).

[26]W. Walukiewicz, H. E. Ruda, J. Lagowski, and H. C. Gatos, Phys. Rev. B **30**, 4571 (1984).

[27]T. Ando, J. Phys. Soc. Jpn. **51**, 3900 (1982).

[28]J. J. Harris, C. T. Foxon, D. E. Lacklison, and K. W. J. Barnham, Superlatt. Microstruct. **2**, 563 (1986).

[29]M. Prasad and S. Fujita, Solid State Commun. **21**, 1105 (1977).

[30]C. K. Sarkar and R. J. Nicholas, Surf. Sci. **113**, 326 (1982).

[31]M. Prasad and S. Fujita, Physica A **91**, 1 (1978).

[32]G. Abstreiter, J. P. Kotthaus, J. F. Koch, and G. Dorda, Phys. Rev. B **14**, 2480 (1976).

[33]R. J. Wagner, T. A. Kennedy, B. D. McCombe, and D. C. Tsui, Phys. Rev. B **22**, 945 (1980).

[34]M. A. Brummell, R. J. Nicholas, L. C. Brunel, S. Huant, M. Baj, J. C. Portal, M. Razeghi, M. A. DiForte-Poisson, K. Y. Cheng, and A. Y. Cho, Surf. Sci. **142**, 380 (1984).

[35]R. J. Nicholas, M. A. Hopkins, D. J. Barnes, M. A. Brummell, H. Sigg, D. Heitmann, K. Ensslin, J. J. Harris, C. T. Foxon, and G. Weimann, Phys. Rev. B (to be published).

[36]H. Sigg, D. Weiss, and K. von Klitzing, in Proceedings of the 7th International Conference on the Electronic Properties of Two-dimensional Systems, Santa Fe, 1987 [Surf. Sci. (to be published)].

[37]G. L. J. A. Rikken, H. Sigg, C. J. G. M. Langerak, H. W. Myron, J. A. A. J. Perenboom, and G. Weimann, Phys. Rev. B **34**, 5590 (1986).

[38]A. D. Wieck, J. C. Maan, U. Merkt, J. P. Kotthaus, and K. Ploog, in *Proceedings of the 18th International Conference on the Physics of Semiconductors, Stockholm, 1986*, edited by O. Engström (World Scientific, Singapore 1987), p. 601.

[39]A. D. Wieck, J. C. Maan, U. Merkt, J. P. Kotthaus, K. Ploog, and G. Weimann, Phys. Rev. B **35**, 4145 (1987).

[40]R. J. Nicholas, M. A. Hopkins, J. J. Harris, and C. T. Foxon, Superlatt. Microstruct. **2**, 319 (1986).

[41]F. Thiele, W. Hansen, M. Horst, J. P. Kotthaus, J. C. Maan, U. Merkt, K. Ploog, G. Weimann, and A. D. Wieck, in *Proceedings of the International Conference on High Magnetic Fields in Semiconductor Physics*, edited by G. Landwehr (Springer-Verlag, Berlin, 1986), p. 252.

[42]C. T. Foxon, J. J. Harris, R. G. Wheeler, and D. E. Lacklison, J. Vac. Sci. Technol. B **4**, 511 (1986); C. T. Foxon and J. J. Harris, Phillips J. Res. **41**, 313 (1986).

[43]K. W. Chiu, T. K. Lee, and J. J. Quinn, Surf. Sci. **58**, 182 (1976).

[44]M. P. Chaubey and C. M. Van Vliet, Phys. Rev. B **34**, 3932 (1986).

[45]Landolt-Börnstein: *Numerical Data and Functional Relationships in Science and Technology*, edited by O. Madelung, M. Schulz, and H. Weiss (Springer-Verlag, Berlin, 1982), Vol. 17.

[46]P. J. Price, Phys. Rev. B **32**, 2643 (1985).

[47]W. Walukiewicz, H. E. Ruda, J. Lagowski, and H. C. Gatos, Phys. Rev. B **32**, 2645 (1985).

[48]J. P. Harrang, R. J. Higgins, R. K. Goodall, P. R. Jay, M. Laviron, and P. Delescluse, Phys. Rev. B **32**, 8126 (1985).

[49]A. M. Suckling, D. J. Barnes, R. G. Clark, S. R. Haynes, R. J. Nicholas, Y. Y. Journaux, J. J. Harris, and C. T. Foxon (unpublished).

[50]G. Bastard, Appl. Phys. Lett. **43**, 591 (1984).

[51]F. Stern, Phys. Rev. B **5**, 4891 (1972).

[52]V. J. Goldman, M. Shayegan, and D. C. Tsui, Phys. Rev. Lett. **61**, 881 (1988).

[53]B. Horovitz and A. Madhukar, Solid State Commun. **32**, 695 (1979).

[54]M. Prasad and M. Singh, Phys. Rev. B **29**, 4803 (1984).