Physica 117B & 118B (1983) 634-636
North-Holland Publishing Company

ELECTRON MOBILITY AND LANDAU LEVEL WIDTH IN MODULATION-DOPED GaAs-Al_xGa_{1-x}As HETEROJUNCTIONS

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We report Far Infrared cyclotron resonance experiments in the high mobility two-dimensional electron gas occuring in modulation doped Al_xGa_{1-x}As-GaAs heterojunctions. Our data extend over a wide range of temperatures and resonance magnetic fields. The width of the cyclotron resonance line depends strongly on the resonance magnetic field, and the data are interpreted in the framework of Ando and Uemura's theory. We have also investigated the temperature dependence of the linewidth, which is found to behave like the reciprocal Hall mobility.

There is now great fundamental interest in the high mobility two dimensional electron gas (TDEG) which occurs at selectively doped heterojunction interfaces [1,2], especially in the unique quantum magneto-transport properties of these systems which arise from the quasi-discrete nature of the two dimensional density of states under strong magnetic fields. In this context, an optical determination of the Landau levels broadening in the TDEG is of actual interest.

We report here an investigation of the far infrared (FIR) cyclotron resonance (CR) in selectively doped Al_xGa_{1-x}As-GaAs heterojunctions. The two-dimensional character of the electron system gives rise to quantum oscillations [3] in the CR amplitude first observed [4] in Si inversion layers. Similar experiments were previously reported [2], but in a heterojunction where the mobility (5000 $cm^2V^{-1}s^{-1}$) was smaller than in our structures. For this reason we were able to observe more quantum oscillations and to study them in more detail than in Ref.2. We present also a study of the CR linewidth as a function of the resonance magnetic field B_r and as a function of the temperature. The relation between the linewidth and the mobility at zero magnetic field is discussed in the framework of the theory of Ando and Uemura [5] for the Landau level broadening in a TDEG.

The heterostructures used here are listed in Table I. They were grown by molecular beam epitaxy on a (100) semi-insulating Cr-doped GaAs sustrate. The GaAs layer was p-type (N_A-$N_D \lesssim 10^{14}$ cm^{-3}), with a thickness of 4 μm. Si ($6\times10^{17}cm^{-3}$) was used as the n-type dopant in the Al_xGa_{1-x}As layer whose thickness was 1000 Å. A thin spacer layer of undoped Al_xGa_{1-x}As with a thickness d given in Table I was grown between the GaAs and Si-doped Al_xGa_{1-x}As layers, to decrease the coulombic interaction between the electrons and their parent donors. Hall measurements at 4.2 K give mobilities in the range of 20 000 to 71 000 $cm^2V^{-1}s^{-1}$. The FIR transmission is studied at fixed photon energies as a function of the magnetic field B applied perpendicularly to the interface. The FIR sources were carcinotrons (λ = 1 mm, 700 μm, 600 μm) or an optically pumped FIR laser. The magnetic field was provided by a superconducting (0-6 T) or by a Bitter (0-20 T) magnet.

Sample	d(Å)	x	$\mu_o(cm^2V^{-1}s^{-1})$ 4.2 K	n_s (cm^{-2}) (dark)
S_1	30	0.3	20 000	9.1 10^{11}
S_2	60	0.3	32 000	8 10^{11}
S_3	120	0.3	50 000	8.5 10^{11}
S'	90	0.25	71 000	7.5 10^{11}

Table I : parameters of the heterojunctions used in this study. d is the thickness of the undoped Al_xGa_{1-x}As spacer layer.

Figure 1 shows a typical spectrum obtained at 1.6 K in sample S' for a photon energy $\hbar\omega$=1.68 meV. The CR line amplitude is modulated by oscillations, as observed in Si space charge layers [4]. These oscillations are caused by the modulation

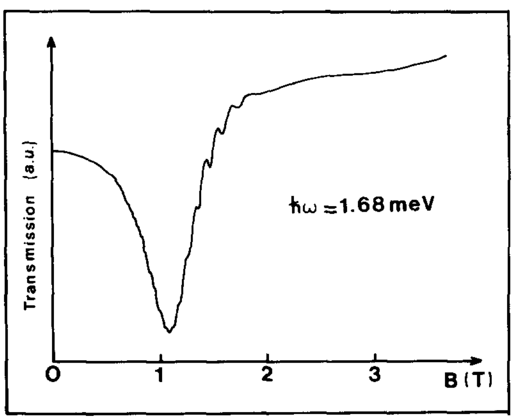

Fig.1 : typical transmission spectrum at 1.6 K in sample S'.

of the population of the Landau levels as they cross the Fermi level E_F. They are characteristic of the quasi-discrete density of states in a TDEG which arises from the complete quantization in such systems under strong magnetic fields. Figure 2 presents a plot of the reciprocal magnetic fields at which the quantum oscillations minima occur as a function of the Landau level index N, before and after exposure to light (K_r^+ laser, λ = 6764 Å). These oscillations are periodic in B^{-1} and clearly reverse their phase at the resonance, as predicted by Ando's calculations [3]. The period is a measure of the electron density n_s, namely $n_s = 2eh^{-1}\ (\Delta 1/B)^{-1}$. The values deduced for n_s are $7.5 \times 10^{11} cm^{-2}$ and $9.3 \times 10^{11} cm^{-2}$ before and after light exposure, respectively. The effect of light is persistent, the observed 25% enhancement of the carrier concentration remaining several hours after the light has been switched off. As already pointed out [2], this effect is likely to be due to deep electron traps in the $Al_xGa_{1-x}As$ layer. Indeed, a persistent photo conductivity effect exists in bulk $Al_xGa_{1-x}As$ [6]. When photo-excited, part of these trapped electrons transfer to the GaAs side, increasing the carrier density.

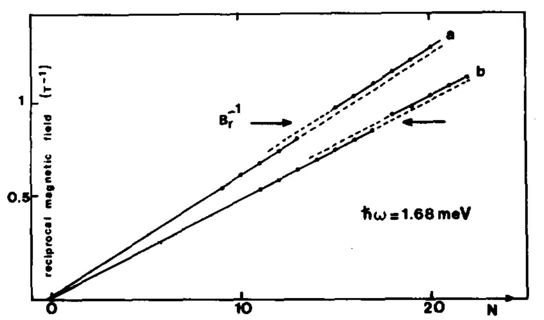

Fig.2 : plot of the reciprocal magnetic fields of the oscillations minima vs the Landau level index before (a) and after (b) light exposure.

The overall shape of the CR line is in fact reasonably fitted by the usual Lorentzian shape $1/\ \{1+(\omega-\omega_c)^2\tau^2\}$ where $\hbar\omega$ is the photon energy, $\omega_c = eB/m_c^*$ the cyclotron frequency and $\hbar/\tau$ the level broadening. This is not surprising since, as a function of the photon energy, the CR line should be essentially the convolution of the initial and final Landau levels densities of states. The exact shape-elliptic, gaussian or any [7] - of these distributions is not expected to affect the "Lorentzian-like" shape of their convolution. Therefore the CR line obtained by sweeping the magnetic field instead of the photon energy should also look like a Lorentzian. This classical description [8] yields an electron mass $m_c^* = 0.073 \pm .001\ m_o$, namely $m_c^* = 1.1\ m_e^*$ where $m_e^* = 0.0665\ m_o$ is the electron bandedge mass in bulk GaAs. From the values of m_c^* and n_s - which is also obtained from additional Shubnikov-de Haas measurements -, by using the variational method of Stern and Howard [10], we deduce the subband energy E_1 measured from the bottom of the GaAs conduction band at the interface, and the Fermi energy E_F in this electronic subband ; namely E_1 = 90 meV and E_F = 24 meV for sample S' before light exposure. The increase in the TDEG cyclotron mass as compared to the bulk mass seems entirely explained by the non-parabolicity of the GaAs conduction band at an energy $E_F + E_1$ = 114 meV.

Moreover, the CR linewidth gives some information on the Landau level broadening in the TDEG. For an isotropic three dimensional electron gas with a constant scattering time τ, the classical description of the CR gives $B_r/\Delta B_{1/2} = \omega\tau$, where B_r is the magnetic field at the resonance and $\Delta B_{1/2}$ the half width at the half amplitude of the CR line. For a TDEG, the assumption of a field independent relaxation time is not justified, and it is clear in Fig.3, which presents a plot of $\Delta B_{1/2}$ vs $B_r^{1/2}$ for sample S_3, that the CR linewidth increases with the photon energy or B_r.

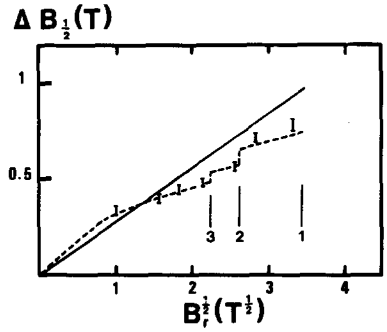

Fig.3 : plot of $\Delta B_{1/2}$ vs $B_r^{1/2}$. The solid line is the linear empirical law as described in the text. The dashed line is the theoretical values of $(m_c^*/\hbar e)(\Gamma_N + \Gamma_{N+1})/2$, deduced from the calculations of Ref.5. The arrows labelled 3,2,1 indicate the crossover of the corresponding Landau level with the Fermi level.

Ando and Uemura [5] have given a theory for the Landau levels broadening in a TDEG. In these calculations, the width Γ_N of the N^{th} Landau level should depend on the range δ of the scattering potential as well as on the value of N. But for short range scatterers with $\delta \ll \ell$ where $\ell = (\hbar/eB)^{1/2}$ is the radius of the ground Landau orbit, Γ_N is independant of N and given [5] by $\Gamma_N = \Gamma = (2\hbar^2 eB/\pi m_c^* \tau_o)^{1/2}$, where τ_o is the scattering time at B=0. Thus, if we assume that the CR linewidth reflects the Landau level width at the resonance field B_r, we expect, at least at low magnetic fields (large values of ℓ), a proportionality between $\Delta B_{1/2}$ and $B_r^{1/2}$, namely $\Delta B_{1/2} = \alpha\mu_o^{-1/2}\, B_r^{1/2}$, where $\mu_o = e\tau_o/m_c^*$ is the static mobility at B=0. In previous studies [2,4,9] such a linear law with $\alpha = 0.63 \pm 0.03$ was fitted to the data. The straight line drawn in Fig.3 shows this linear law, with the static mobility μ_o = 50 000 $cm^2V^{-1}s^{-1}$ and $\alpha = 0.63$.

Now, if we assume that the scattering is mainly coulombic, the range δ of the scattering potential should be the screening length in the TDEG [11], which does not depend on the electron density and whose value is δ = 50 Å in the case of GaAs [12]. The magnetic length is $\ell = (\hbar/eB)^{1/2}$ = 250/$B^{1/2}$ Å. Thus, for large magnetic fields, the approximation $\delta/\ell << 1$ is not justified. Ando and Uemura [5] have performed a numerical estimation of Γ_N vs δ/ℓ in the case of a gaussian potential. From Fig.3 of Ref.5, it can be seen that Γ_N is a decreasing function of δ/ℓ for $\delta/\ell < 1$ – which is always our case – and that the N dependence seems to saturate for N > 4. Thus we qualitatively expect that $\Delta B_{1/2}$ should be smaller than predicted from the linear law for the largest values of B_r. Furthermore, using δ = 50 Å and the data shown in Fig.3 of Ref.5, we can deduce, for each magnetic field, the theoretical values for $\Gamma_N + \Gamma_{N+1}$ with N determined by the condition that the Fermi level E_F lies between the N^{th} and the $N+1^{th}$ Landau level. Indeed, the width of the CR line should be proportional to the sum of the widths of the concerned adjacent Landau levels. Namely, the dashed line drawn in Fig.3 gives the theoretical values of $(m_c^*/\hbar e)(\Gamma_N+\Gamma_{N+1})/2$, which almost perfectly fit the data. The steps which appear when the low index Landau levels (N=3,2) are crossing the Fermi level are the reflect of the strong N dependence of Γ_N for the small N. Of course, in general more than two Landau levels are involved within a CR line so that, in a more sophisticated analysis, these steps should be smoothed. We wish to point out that no adjustable parameter enters in this calculation since the number as well as the nature of the long range scatterers are implicity involved in τ_o.

Finally, we have studied the temperature dependence of the CR linewidth. The results for samples S_1, S_2 and S_3, which were grown in the same conditions, are plotted in Fig.4. These data exhibit a low temperature plateau of $\Delta B_{1/2}^{-1}$ followed by a monotonic decrease in the phonon scattering regime, which is exactly the observed behaviour of the Hall mobilities [13]. Fig.4 also shows that $\Delta B_{1/2}^{-1}$ increases monotonically with the thickness d of the spacer layer of undoped $Al_xGa_{1-x}As$, as expected from the increasing spatial separation of the electrons from their parent donors, and as already reported for the Hall mobility [14].

In conclusion, our results indicate that the CR linewidth is related to the transport mobility in the whole range of temperatures (1.5 to 120 K) studied here ; till the system is not in the ultra quantum limit [15] (last Landau level N = 0 only partly occupied) the observed CR linewidths

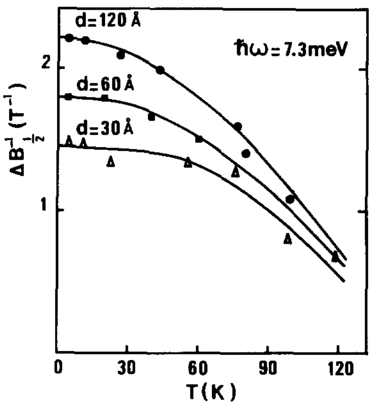

Fig.4 : Temperature dependence of $1/\Delta B_{1/2}$ for samples S_1,S_2,S_3.

are closely fitted by the one electron Ando and Uemura's theory of the Landau levels broadening.

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