Exchange enhancement of the Landau-level separation for two-dimensional electrons in $GaAs/Ga_{1-x}Al_xAs$ heterojunctions

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Exchange enhancement of the Landau-level separation of up to 30% has been observed in three high mobility $GaAs/Ga_{1-x}Al_xAs$ single heterojunctions. Analysis of the amplitude of Shubnikov–de Haas oscillations as a function of temperature and magnetic field has allowed measurement of this enhancement at filling factors as high as $\nu=100$.

I. INTRODUCTION

The low level of disorder attainable in the two-dimensional electron gas (2DEG) in $GaAs/Ga_{1-x}Al_xAs$ heterojunctions leads to the occurrence of some striking electron-electron interaction effects. The application of a magnetic field perpendicular to the plane of the 2DEG further accentuates these effects, and has led, for example, to the observation of a g factor enhanced to more than 15 times its bare value.[1,2] Ultimately the interaction causes condensation of the 2DEG into the quantum fluid ground state responsible for the fractional quantum Hall effect,[3] and perhaps Wigner crystallization.[4]

g-factor enhancements have been treated theoretically by Ando and Uemura[5] and were first observed in single $GaAs/Ga_{1-x}Al_xAs$ heterojunctions by studies of spin split Shubnikov–de Haas oscillations ($g^*=2.6$ compared with a bare value of $g=0.44$),[6] and by making tilted field measurements ($g^*=4.5$).[7] More recent tilted field measurements have found exchanged enhancement of the g factor to $g^*=0.83$ at filling factors (ν) as high as 17,[1] while thermal activation measurements of the spin split magnetoresistance minima at $\nu=1$ and 3 yields values between 5.3 and 7.3.[1,2] The stronger enhancements seen in activation measurements are a result of the Landau levels being well separated in these experiments; in tilted field measurements there must be overlap between adjacent levels, hence a reduced population difference and a smaller enhancement. Further differences in the size of the enhancement are due to differences in sample disorder. An analogous enhancement of the Landau-level splitting to about 125% of its bare value (the cyclotron energy) has also been seen in the activated magnetoresistance at $\nu=2$ between 0.8 and 5.4 T. Both spin splitting and Landau-level enhancements constitute a measurement of the large wave-vector limit of the elementary excitations of the system.[8] At $\nu=1$ and 3 these are spin waves, and at $\upsilon=2$ they are magnetic excitons. The relatively poor quantitative agreement between the theory of Kallin and Halperin[8] and experiment is a result of disorder: experiments measure the energy gap between adjacent regions of extended states, which is always smaller than the energy between adjacent maxima in the density of states, and is reduced as the level of disorder increases. In contrast, the excitations considered by Kallin and Halperin[8] in the absence of disorder add to the separation of the peaks in the density of states. In this paper we utilize a technique which directly measures the exchange enhanced energy separation between adjacent peaks in the density of states, and allows observation of the enhancement at filling factors as high as $\nu=100$.

II. EXPERIMENTAL TECHNIQUE

We have found the separation between Landau levels by measuring the magnetic-field dependence of the amplitude of Shubnikov–de Haas oscillations as a function of electron temperature to obtain the single-particle coherence time, or quantum lifetime (τ_q). The quantum lifetime measures the time between scattering events, and so differs from the momentum relaxation time (τ) which is weighted by a factor which depends on the angle of scattering. In modulation-doped heterojunctions such as those in the present investigation, the quantum lifetime has been found to be between 4 and 60 times smaller than the momentum relaxation time found from the Drude conductivity,[9–13] depending on the amount of disorder in the sample. This contrasts with the situation for silicon metal-oxide-semiconductor field-effect transistors (MOSFET's) where the two times are approximately equal,[14] and is a reflection of the different scattering mechanisms in the two systems. In a heterojunction the ionized donors, which are the dominant source of scattering at low temperatures,[10,15] are spatially separated from the 2DEG leading to long-range, small-angle scattering.[13]

Ando[16] and Isihara and Smrcka[17] have calculated the broadening of Landau levels self-consistently and derived the following expression for the amplitude of the Shubnikov–de Haas oscillations at intermediate magnetic fields ($\omega_c\tau_q<2$):

$$\Delta\sigma_{xx}=\frac{ne^2\tau}{m^*}\frac{1}{1+(\omega_c\tau)^2}\left[\frac{4(\omega_c\tau)^2}{1+(\omega_c\tau)^2}\exp\left[-\frac{\pi}{\omega_c\tau}\right]\right]. \quad (1)$$

TABLE I. Sample details and results. The sixth column gives the enhancement of the Landau-level separation as discussed in the text. The last column shows the field at which the data deviates from the predicted behavior (see Fig. 2).

Sample (spacer, l)	n (10^{11} cm^{-2})	μ (10^6 cm^2/V s)	τ (ps)	τ_q (ps)	Enhancement (%)	Deviation field (T)
1	1.26	2.44	94.5	2.4	30	
(800 Å)	1.77	3.04	118	2.6	30	0.26
2	2.05	1.34	51.9	1.7	30	0.36
(400 Å)	2.75	1.11	43.0	1.8	30	0.33
	2.98	1.13	43.8	3.2	30	0.28
3	3.71	1.16	44.9	1.9	15	0.62
(200 Å)	4.01	1.24	48.0	2.5	10	0.62
	4.40	1.36	52.7	3.8	10	0.52

This expression was derived assuming short-range scattering, applicable to silicon MOSFET's, so no distinction between τ and τ_q was necessary. Coleridge, Stoner, and Fletcher[11] pointed out that for heterojunctions this distinction is required, and have shown that in the intermediate magnetic-field regime a simplified expression for $\Delta\rho_{xx}$ is obtained:

$$\Delta\rho_{xx}=4\rho_0\frac{\chi}{\sinh\chi}\exp\left[-\frac{\pi}{\omega_c\tau_q}\right], \qquad (2)$$

where the $\chi/\sinh\chi$ term (with $\chi=2\pi^2kT/\hbar\omega_c$) accounts for the effect of finite temperature and ρ_0 is given by $\rho_0=m^*/ne^2\tau$. Furthermore, this expression is shown by Coleridge, Stoner, and Fletcher[11] to be valid for long-range scattering (as is the case of $GaAs/Ga_{1-x}Al_xAs$ heterojunctions) over a wide range of magnetic fields.

We have measured τ_q for the 2DEG in three $GaAs/Ga_{0.67}Al_{0.33}As$ single heterojunctions grown by molecular-beam epitaxy at Philips Research Laboratories, Redhill, United Kingdom, the details of which are given in Table I. These low disorder samples (with mobilities in the range 0.67×10^6 to 3×10^6cm^2/V s) were grown with undoped $Ga_{1-x}Al_xAs$ spacer layer thicknesses of 800, 400, and 200 Å providing sheet electron concentrations from 1.26×10^{11} to 4.40×10^{11} cm^{-2}. Excitation currents between 10 and 50 nA were used; no change in the results was obtained using lower currents, indicating that there was no significant electron heating under these conditions. The electron concentration in each sample was increased by brief illumination with a red LED to induce persistent photoexcitation. Temperature measurements in the range 0.3 to 4.2 K were made using germanium resistance thermometry, while a ruthenium oxide resistance thermometer with a negligibly small magnetoresistance was used to stablize the temperature as the magnetic field was slowly swept.

III. ANALYSIS OF MAGNETORESISTANCE OSCILLATIONS

The magnetoresistance of a 2DEG is not only governed by Eq. (2); there are also contributions from electron-electron interactions and weak localization[18] (Fig. 1). Weak localization is suppressed at magnetic fields where the magnetic length $(\hbar/eB)^{1/2}$ is smaller than the electronic mean free path.[19] This occurs at very low fields (10 mT for our samples), so it does not contribute to the magnetoresistance once the Shubnikov–de Haas oscillations appear. Choi, Tsui, and Palmateer[20] have studied the contribution of electron-electron interactions to the magnetoresistance of a 2DEG and has shown that it is additive. The purely oscillatory component of the magnetoresistance can then be found by subtracting the midpoint of the oscillations from the data. Figure 2 shows the results of a typical analysis using this approach, where $\Delta\rho_{xx}\sinh\chi/(4\chi)$ is plotted against $1/B$ on a semilog scale (a Dingle plot). The data lie on a straight line with a slope of $-\pi m^*/e\tau_q$ and an intercept of ρ_0. Since the effects of weak localization and electron-electron interactions have been removed, ρ_0 is not the same as the zero-field resistivity, but it is found to be constant for constant electron concentration. Other methods for extraction of the oscillatory component of the magnetoresistance have been used previously;[10–13] the present approach is theoretically justified and simple. The value of τ given in Table I is obtained from the zero-field resistance and therefore contains all the contributions to the

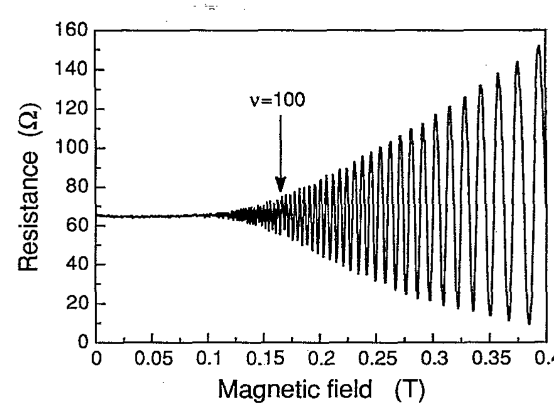

FIG. 1. Typical Shubnikov–de Haas oscillations for sample 3 at $n=4\times10^{11}$ cm^{-2} and $T=0.3$ K. The nonoscillatory contributions to the magnetoresistance can be seen in the gradual rise of the midpoint of the oscillations. Oscillations are visible for $\nu>130$.

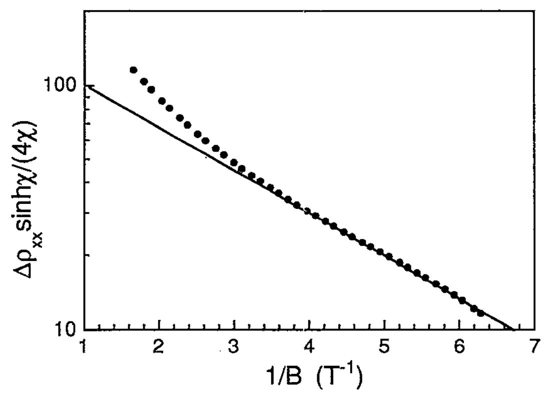

FIG. 2. Plot of $\Delta\rho_{xx}\sinh\chi/(4\chi)$ vs $1/B$ for sample 2 at $n=2.05\times10^{11}$ cm^{-2} and $T=0.5$ K (unenhanced data). A possible explanation for the deviation at high field is discussed in the text.

scattering. It is therefore not directly comparable to τ_q even when the effects of long-range scattering are taken into account.

IV. DISCUSSION

When a bare Landau-level separation of $\hbar\omega_c$ (where $\omega_c=eB/m^*$ and $m^*=0.068m_0$, m_0 being the free-electron mass) was used in the analysis the quantum lifetime obtained was found to increase with temperature between 0.3 and 1.3 K (Fig. 3). In measurements taken at 2.2 and 4.2 K there are fewer oscillations, and they appear at higher fields where Eq. (2) is no longer valid. Measurements were therefore performed well below the temperature at which the zero-field resistance is significantly increased by acoustic phonon scattering, so the quantum lifetime is expected to be independent of temperature. Indeed, even if phonons were making a significant contribution to scattering, the quantum lifetime would *decrease*, not increase, with temperature. This anomalous increase in the quantum lifetime with temperature can be eliminated by using an exchange enhanced Landau-level separation. To illustrate this, an examination of the temperature dependence of the oscillatory conductivity in the regime where $2\pi^2kT/\hbar\omega_c>1$ shows that Eq. (2) may be written in the following form:

$$\Delta\rho_{xx}\approx 8\rho_0\chi\exp\left[-(T+T_D)\frac{2\pi^2k}{\hbar\omega_c}\right], \tag{3}$$

where T_D, the Dingle temperature, is given by $T_D=\hbar/2\pi k\tau_q$. Using too low a value for the Landau-level separation (where there is enhancement) in (3) will lead to an error in the contribution of the temperature to $\Delta\rho_{xx}$. This is then seen as a temperature-dependent T_D. Only when the correct enhancement is used will the temperature contribution be properly accounted for making τ_q independent of temperature. Typically an enhancement of 30% (±5%) is required, though this decreases at higher electron concentrations due to increased scattering in the narrow spacer layer sample, and to the onset of inter-subband scattering as the second subband becomes occupied (see Table I).

We have also analyzed the same data at fixed field as a function of temperature to extract the effective mass from the $\sinh\chi/(4\chi)$ temperature-dependence term. This is the conventional way of obtaining the effective mass from Shubnikov–de Haas oscillations. Since m^* appears in the equation only as part of the Landau-level separation (and in the prefactor ρ_0 which is not susceptible to interpretation because of the effects discussed above), an enhancement in the Landau-level separation should show up in this analysis as a reduction in m^* (by 25% in most cases), and this is indeed the case. Figure 4 shows the result of such an analysis for sample 2 at $n=2.98\times10^{10}$ cm^{-2} measured in a magnetic field of 0.21 T. The solid line, which is a fit to the theoretical expression that yields $m^*=0.052\pm0.003$ m_0, is clearly in very good agreement with the experimental data points (shown as filled circles in Fig. 4). For comparison the fit to the theoretical expression with m^* constrained to 0.068 m_0 (broken line) is

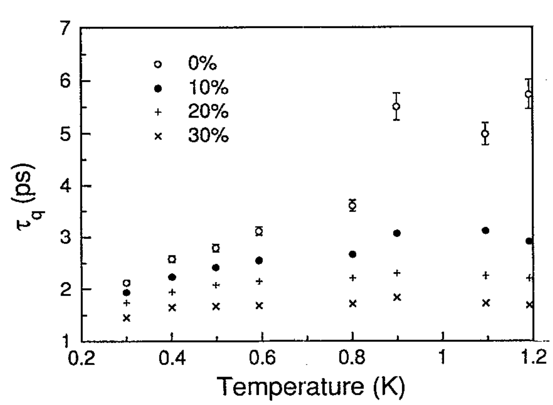

FIG. 3. The temperature dependence of τ_q using the enhanced Landau-level separation, and separations enhanced by 10%, 20%, and 30%. For this sample (2 at $n=2.05\times10^{11}$ cm^{-2}) an enhancement of about 30% restores the expected temperature independence.

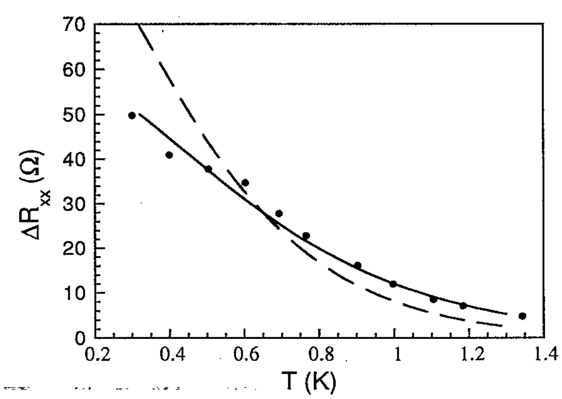

FIG. 4. Temperature dependence of the amplitude of the Shubnikov–de Haas oscillations measured in a magnetic field of 0.21 T for sample 2 at $n=2.98\times10^{11}$ cm^{-2}. Experimental data points are shown as filled circles. Also shown is the fit to the theoretical expression (solid line), which yields $m^*=0.052\pm0.003m_0$, and a curve with m^* constrained to $0.068m_0$ for comparison (broken line).

also shown. The additional information obtained from this analysis is the magnetic-field dependence of m^*. In the field range for which the Dingle plots are linear there is a slight increase ($\pm$ 5% deviation from the average value) in m^* with field. This does not alter the linearity of the Dingle plots significantly, and consequently it does not change the central conclusion of this report that τ_q measured using an analysis with $\hbar\omega_c$ equal to the cyclotron energy yields an anomalous temperature dependence which is removed by adopting an exchange enhanced Landau-level separation (or equivalently a reduced effective mass). It should be noted that previous studies of Shubnikov–de Haas oscillations used heterojunctions with mobilities some ten times smaller[10,11] than those in the present study. It is therefore not surprising that exchange effects manifest themselves much more strongly in our samples. Furthermore, because the technique we have used in these experiments directly measures the separation between peaks in the density of states, and not the separation between regions of extended states as in previous activation measurements,[2] it remains sensitive to exchange enhancement even at low fields.

It can be seen from Fig. 2 that our Dingle plots are linear over a large field range. There are, however, deviations from this behavior at high fields, which could have a variety of causes. Equation (1) [and thus also (2) and (3)] was derived for the intermediate field range where $\omega_c\tau_q<2$. Experiments have shown that (2) appears to be valid up to higher fields[11,13] above which the oscillations cease to be sinusoidal and higher-order corrections become necessary. Also the theory does not include localization effects, so this may result in the deviations seen in the data. Finally, at high fields spin splittings in the oscillations become resolved. In Ando's zero-temperature theory higher-order corrections are required below a critical T_D/ω_c. Thus at finite temperature, where T and T_D can be seen by expression (3) to have similar effects, the range of validity of (1)–(3) is given by a critical $(T+T_D)/\omega_c$. The critical field at which deviation occur is then linearly dependent on temperature, and T_D may be found from a plot of the deviation field against temperature. Figure 5 shows such a plot for sample 1 at its lowest concentration. Because the deviations seem to be weaker at low temperatures, and the high-temperature measurements have few well-resolved oscillations, there is only a narrow temperature range for which the relevant information can be extracted. However, there is a clear temperature dependence of the deviation field in this temperature range, suggesting that this is the mechanism for the deviation in this case. The quantum lifetime found from this data is 3.1($\pm$0.7) ps, compared with 2.4($\pm$0.2) ps found by analysis of the envelope of the Shubnikov–de Haas oscillations including the effect of enhancement. In contrast to the behavior at this electron concentration, the deviation fields at all other concentrations do not show any temperature dependence. In these cases, therefore, a critical $\omega_c\tau_q$ cannot be the mechanism which causes the high-field deviations. Notably the deviation field found in these cases decreases as the spacer layer increases. A possible explanation for this effect may be found by applying the percolation description of electron

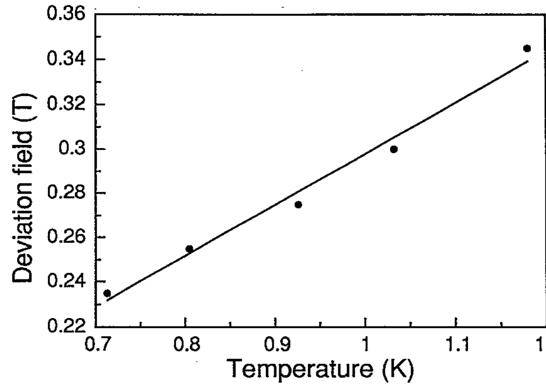

FIG. 5. The temperature dependence of the deviation field for sample 1 at $n=1.26\times10^{11}$ cm^{-2}. The predicted linear temperature dependence shown here is not seen at higher 2DEG electron concentrations.

motion in a disorder potential, in which the potential forms a random contour map and electrons' wave functions follow equipotentials. The characteristic distance between hills and valleys in such a "terrain" is governed by the spacer layer thickness, l. Although the impurity potential in the doped $Al_{1-x}Ga_xAs$ will reflect the average distance between the impurities, moving a distance l away from the $Al_{1-x}Ga_xAs$ has the effect of filtering out the more rapid spatial variations of the potential, and leaving only those variations which occur over distances greater than l. Thus provided the impurity atoms are separated from each other by an average distance ($\sim$100 Å in our samples) that is less than l, the potential seen by the 2DEG will have a characteristic length $\sim l$. This condition is satisfied in all our samples. One may expect a qualitative change in electron transport between the two cases where the cyclotron radius $l_c>l$ (low fields), when the electron samples many hills and valleys, and $l_c \ll l$, when the electron samples just part of one hill or valley.[21] Certainly one would expect a simple scattering theory to break down in the latter case, and this is a possible cause for the behavior we have seen. It should be noted that the deviation fields do not, in fact, correspond to cyclotron orbits that are the same size as the spacer layer thickness, but the ratio l_c/l is 3 at the lowest concentration and increases monotonically with electron concentration to 10 at the highest concentration. This behavior strongly suggests that screening plays an important role in the effect. There is also an increase in τ_q as the electron concentration in each sample is increased which is further evidence for screening and corroborates previous work.[9,12,22]

V. CONCLUSIONS

We have performed a systematic study of the quantum lifetime of two-dimensional electrons in three $GaAs/Ga_{1-x}Al_xAs$ heterojunctions. The temperature-dependence measurements provide startling new evidence for an exchange enhancement of the Landau-level separation of up to 30%, present even at fields below 0.2 T and filling factors of $v=100$. An analysis of the same data at fixed field and varying temperature corroborates these results. We find that the deviation of $\Delta\rho_{xx}$ from the behavior described by (2) is not a result of the critical $\omega_c\tau_q$ in most cases, and tentatively attribute it to a sample-dependent size effect. The authors note that a calculation by Smith, MacDonald, and Gumbs[23] finds significant exchange enhancement of the effective mass of 2DEG's even at high filling factors.

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