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Exchange-enhanced Landé g-factor, effective disorder and collapse of spin-splitting in a two-dimensional GaAs electron system

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Abstract

We have measured the low-temperature transport properties of front-gated GaAs/$Al_{0.33}Ga_{0.67}As$ heterostructures. Collapse of spin-splitting and an enhanced Landé $|g|$-factor at Landau level filling factors both $v = 3$ and 1 are observed. Our experimental results show direct evidence that the electron–electron interactions are stronger at $v = 3$ than those at $v = 1$ over approximately the same perpendicular magnetic field range. © 2002 Elsevier Science B.V. All rights reserved.

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A two-dimensional electron gas (2DEG) formed at the interface of a modulation doped GaAs/AlGaAs heterostructure has been an intensive subject of studies for more than two decades. When a large magnetic field is applied perpendicular to the plane of a low-disordered 2DEG, the 2DEG exhibits the integer quantum Hall effect [1] at liquid helium temperatures. The picture of extended states at the Landau level centres and localised states between Landau levels provides a simple description of the quantum Hall effect in a strong perpendicular magnetic field.

It is now well established that the energy gap Δ_v at a Landau level filling factor v can be determined from the exponential temperature dependence of magnetoresistivity $\rho_{xx} \approx \exp(-\Delta_v/2k_B T)$, where k_B is the Boltzman constant and T is the temperature. This approach is valid in both the integer and fractional quantum Hall regimes [2–4]. At $v = 1$, Δ_1 is simply the " spin gap" which has the form [3,5,6]

$$\Delta_1 = |g_0|\mu_B B + E_{ex} = |g^*|\mu_B B, \qquad (1)$$

where E_{ex} is the many-body exchange energy which lifts the $|g|$-factor from its bare value ($|g_0| = 0.44$) to its enhanced value $|g^*|$, μ_B is the Bohr magneton and B is the applied perpendicular magnetic field, respectively. This spin gap approach is also valid for other odd-number filling factors, for example, $v = 3$.

Previous $|g|$-factor measurements were mostly undertaken on un-gated samples [5,9,10]. In this case, measurements on the $|g|$-factors determined from $\Delta(B)$ need to be performed at *various* v for a *fixed* carrier density. Recently, we have shown that by

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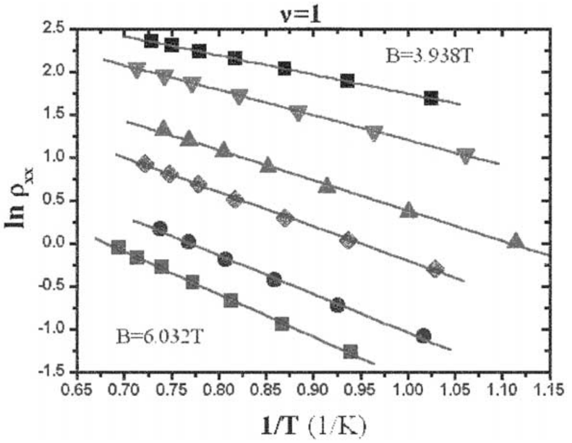

Fig. 1. The logarithm of $\rho_{xx}(\nu=1)$ versus the inverse of temperature $1/T$ at different gate voltages (and hence magnetic fields B). From top to top: $B = 3.938, 4.262, 4.65, 5.076, 5.592$, and 6.032 T. The slopes of the straight-line fits Δ_1 are shown in Fig. 2.

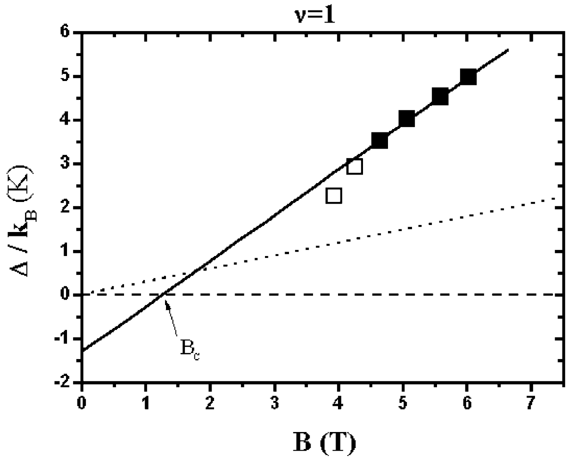

Fig. 2. The experimentally determined Δ_1/k_B at various magnetic fields B. The straight-line fit is discussed in the text. The dotted line is the bare Zeeman energy assuming $|g_0| = 0.44$. The spin gap Δ_1 collapses to zero at a finite B_c.

measuring the activation energies $\Delta_1(B)$ in a gated sample in which InAs was inserted into the centre of the GaAs well [6], one can determine the effective $|g|$-factor $|g^*|$ while maintaining the Landau level filling factor $\nu = 1$ [6–8]. In this paper, we present magnetoresistivity measurements on a gated GaAs 2DEG. An enhanced g-factor due to many-body exchange interactions is observed at both ν=3 and 1. The measured $|g^*_{\nu=3}| = 4.05$ is larger than $|g^*_{\nu=1}| = 3.11$, showing direct evidence that many-body interactions are stronger at $\nu = 3$ than those at $\nu = 1$ over approximately the same magnetic field range $4\ \mathrm{T} \leqslant B \leqslant 6\ \mathrm{T}$. Moreover, we observe collapse of spin-splitting in which the spin gap Δ approaches 0 at a critical magnetic field B_c. The fact that the magnitudes of the critical field $B_c \approx 0.8$ T and an interception $\Delta(B)$ of -0.8 K at $\nu = 3$ are both smaller than those at $\nu = 1$ also shows that the effective disorder at $\nu = 1$ is larger than that at $\nu = 3$.

The front-gated Hall bar used in this work was made from GaAs/Al$_{0.33}$Ga$_{0.67}$As heterostructures. At $V_g = 0$ V, the carrier density of the 2DEG is $3.3 \times 10^{15}\ \mathrm{m}^{-2}$ with a mobility of $30\ \mathrm{m}^2\ \mathrm{V}^{-1}\mathrm{s}^{-1}$, without illumination. Measurements were performed in a top-loading ^{3}He cryostat using standard four-terminal AC phase sensitive techniques.

Fig. 1 shows an activation plot $\ln \rho_{xx}(\nu = 1)$ as a function of $1/T$ at various B. From the straight-line fits shown in Fig. 1, we can measure Δ_1 at different carrier densities, and Fig. 2 shows such results. It is evident that Δ_1 shows a linear dependence of B (and hence n_s), as demonstrated by the straight-line fit through the full squares. According to Eq. (1), we know that the exchange energy E_{ex} is approximately linear in B in our system. The measured spin gap is also enhanced over the single-particle Zeeman energy which is shown in the dotted line. From the linear fit shown in the solid line, we estimate $|g^*|$ to be 3.11 and a critical magnetic field B_c of 1.25 T in which Δ_1 collapses to zero. An interception of -1.31 K at the y-axis is ascribed to disorder broadening at $\nu = 1$ in our case. All our experimental results are consistent with the work by Kim et al. [6], in which InAs was inserted into the centre of the GaAs quantum well. In our system, at low B the data (labelled as open squares) shows slight deviation from the straight-line fit. This is due to increasing disorder broadening at a low carrier density (and hence B). The deviation labelled as open squares also suggests that the actual critical field is higher than B_c determined from the linear fit.

In the previous work of Kim et al. [6], due to the moderate disorder within the InAs/GaAs systems, the minimum in ρ_{xx} at $\nu = 3$ is not well resolved. Our GaAs system is of higher quality and we are able to study the spin gap at $\nu = 3$. Fig. 3 shows $\ln \rho_{xx}(\nu = 3)$ as a function of $1/T$ at various B. The spin gaps at ν=3 are determined from the straight-line fits shown in

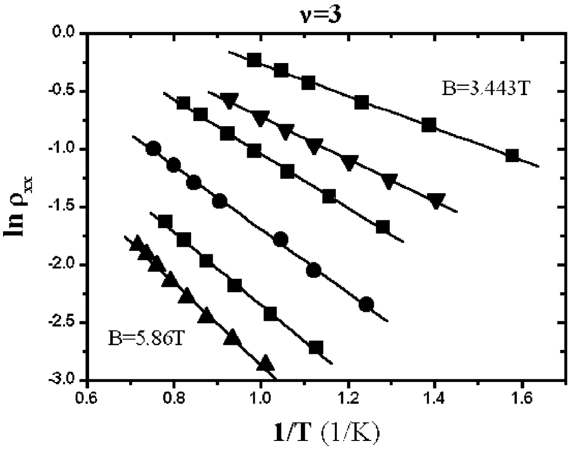

Fig. 3. The logarithm of $\rho_{xx}(\nu=3)$ versus the inverse of temperature $1/T$ at different gate voltages (and hence magnetic fields B). From top to top: $B = 3.443, 3.818, 4.064, 4.667, 5.263$, and 5.860 T. The slopes of the straight-line fits Δ_3 are shown in Fig. 4.

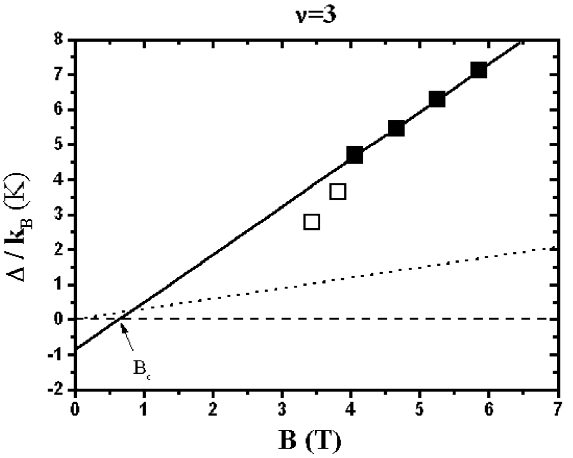

Fig. 4. The experimentally determined Δ_3/k_B at various magnetic fields B. The straight-line fit is discussed in the text. The dotted line is the bare Zeeman energy assuming $|g_0| = 0.44$. The spin gap Δ_3 collapses to zero at a finite B_c.

Fig. 4. The measured spin gap Δ_3 is also enhanced over the single-particle Zeeman energy, as clearly shown in Fig. 4. From the slope of the linear fit, we estimate the $|g^*|$ to be 4.05. It is evident that the data at $\nu=3$ is similar to that at $\nu = 1$: both collapse of spin-splitting and the enhanced $|g^*|$ over the bare value are observed. The measured $|g^*_{\nu=3}| = 4.05$ is larger than $|g^*_{\nu=1}| = 3.11$, showing direct evidence that many-body interactions are stronger at $\nu = 3$ than those at $\nu = 1$. The fact that the magnitudes of the critical field $B_c \approx 0.8$ T and an interception of -0.8 K at $\nu = 3$ are both smaller than those at $\nu = 1$ also shows that the effective disorder at $\nu = 1$ is larger than that at $\nu = 3$ over approximately the same measurement range $4\text{ T} \leqslant B \leqslant 6$ T. Recently, Fogler and Shklovskii [11] have shown that the exchange-enhanced interactions may be distroyed by disorder and lead to collaspe of spin-splitting at a critical filling factor ν_c. The fact that $|g^*_{\nu=3}| = 4.05$ is larger than $|g^*_{\nu=1}| = 3.11$ over the same magnetic field range is consistent with the theory of Fogler and Shklovskii.

In conclusion, we have measured the low-temperature magneto-transport properties of a gated two-dimensional GaAs electron gas. In our system, the measured effective Lande g-factor $|g^*_{\nu=3}| = 4.05$ is larger than $|g^*_{\nu=1}| = 3.11$, showing direct evidence that many-body interactions are stronger at $\nu = 3$ than those at $\nu = 1$ over approximately the same magnetic field range $4\text{ T} \leqslant B \leqslant 6$ T. We also observe collapse of spin-splitting in which the spin gap Δ approaches 0 at a critical magnetic field B_c. The fact that the magnitudes of the critical field $B_c \approx 0.8$ T and an interception $\Delta(B)$ of -0.8 K at $\nu = 3$ are both smaller than those at $\nu = 1$ also shows that the effective disorder at $\nu = 1$ is larger than that at $\nu = 3$. We suggest that disorder can reduce exchange-enhanced interactions as supported by the $|g^*|$ measurement performed at both $\nu = 3$ and 1.

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