Spin-Dependent Transport in a Two-Dimensional GaAs Electron System

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We have measured the low-temperature electron transport properties in a front-gated GaAs/Al_{0.33}Ga_{0.67}As heterostructure. Collapse of spin-splitting and an enhanced Lande $g$-factor at both Landau level filling factors $\nu = 3$ and $\nu = 1$ were observed. Our experimental results show direct evidence that the electron-electron interactions are stronger at $\nu = 3$ than those at $\nu = 1$ over approximately the same perpendicular magnetic field range. Moreover, we observed an enhancement of the magnetoresistivity of a two-dimensional electron system with an increasing parallel magnetic field. Using a simple model, we suggest that the increase of the magnetoresistivity is due to spin but the model over-estimates the Lande $g$-factor in our system.

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I. Introduction

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\textsuperscript{[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 $B$.

Applying an in-plane magnetic field $B_k$ parallel to a 2DEG is a powerful tool for studying spin-dependent electron transport since such a $B_k$ only couples to the electrons’ spin. The first tilted magnetic field experiment on a 2DEG revealed an enhancement of the $g$-factor\textsuperscript{[2]}. Recently there has been a great deal of interest in 2D systems in a parallel magnetic field\textsuperscript{[3]}. It was suggested that the observed strong magnetoresistance in high parallel magnetic fields is a manifestation of the spin alignment of the free carriers. It is generally believed that increasing $B_k$ enhances the Zeeman energy, pushing the band bottom of spin-antiparallel electrons towards the Fermi energy, pulling the band bottom of spin-parallel electrons away from the Fermi energy, and increasing the magnetoresistance of a 2D electron system.

Recently the role of spin in electron transport in a 2D system has been attracting a great deal of interest. In this paper, we review our experimental results on spin-dependent transport in a perpendicular magnetic field and in a parallel magnetic field\textsuperscript{[4]}. The structure of this paper is...
organised as follows. Section II describes spin-dependent transport in a perpendicular magnetic field and activation studies at Landau level filling factors $\varrho = 3$ and $\varrho = 1$. Section III presents spin-dependent transport in a 2D GaAs electron gas in a parallel magnetic field. In Section IV we summarise our experimental results, together with some conclusions.

II. Spin-dependent transport in a $B \perp$ field

It is now well established that the energy gap $\xi$ at a Landau level filling factor $\varrho$ can be determined from the exponential temperature dependence of the magnetoresistivity $\frac{1}{2} \xi \frac{1}{4} \exp (\varrho \frac{k_B}{2} T)$, where $k_B$ is the Boltzman constant and $T$ is the temperature, respectively. This approach is valid in both the integer and fractional quantum Hall regimes [5-7]. At $\varrho = 1$, $\xi$ is simply the “spin gap” which has the form [8]

$$\xi = j g^2 \frac{j}{B} + E_{\text{ex}} = j g^2 j \frac{j}{B}$$

where $E_{\text{ex}}$ is the many-body exchange energy which lifts the $j g^2 j$-factor from its bare value ($j g^2 j = 0.44$) to its enhanced value $j g^2 j$. $\frac{j}{B}$ is the Bohr magneton and $B$ is the applied magnetic field. This spin gap approach is also valid for other odd-number filling factors, for example, $\varrho = 3$.

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 $n$ is $3.3 \times 10^{15}$ m$^{-2}$ with a mobility of 30 m$^2$/Vs, without illumination. All measurements were performed in a top-loading $^3$He cryostat using standard four-terminal ac-phase sensitive techniques.

Figure 1 shows an activation plot of $\ln \frac{1}{2} \xi (\varrho = 1)$ as a function of $1 = T$ at various $B$. From the straight line fits shown in Fig. 1, we can measure $\xi$ at different carrier densities, and figure 2 shows such results. It is evident that $\xi$ shows a linear dependence on $B$ (and hence $\varrho$), as demonstrated by the straight line fit through the full squares. According to Eq. 1, we know that the exchange energy $E_{\text{ex}}$ 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 line fit shown in the solid line, we estimate $j g^2 j$ to be 3.11 and the critical magnetic field $B_{C}$ is 1.25 T at which $\xi$ collapses to zero. The intercept of -1.31 K on the y-axis is ascribed to disorder broadening at $\varrho = 1$ in our case. All our experimental results are consistent with the work by Kim et al. [8], in which InAs was inserted into the centre of the GaAs quantum well. In our system, at low $B$ the data (labeled as open squares) shows a 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 the $B_{C}$ determined from the line fit.

In the previous work of Kim et al. [8], due to the moderate disorder within the InAs/GaAs systems, the minimum of $\frac{1}{2} \xi$ at $\varrho = 3$ is not well resolved. Our GaAs system is of higher quality and we are able to study the spin-gap at $\varrho = 3$. Figure 3 shows $\ln \frac{1}{2} \xi (\varrho = 3)$ as a function of $1 = T$ at various $B$. The spin gaps at $\varrho = 3$ are determined from the straight line fits shown in Fig. 3. The measured spin gap $\xi$ 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 $j g^2 j$ to be 4.05. It is evident that the data at $\varrho = 3$ is similar to that at $\varrho = 1$: both the collapse of spin-splitting and the enhanced $j g^2 j$ over the bare value are observed. The measured $j g^2 j = 4.05$ is larger than $j g^2 j = 3.11$, showing direct evidence that the many-body interactions are stronger at $\varrho = 3$ than those at $\varrho = 1$. The fact that the magnitudes of the critical field $B_{C}$ of 0.8 and an interception of
-0.8 K at $\theta = 3$ are both smaller than those at $\theta = 1$ also shows that the effective disorder at $\theta = 1$ is larger than that at $\theta = 3$ over approximately the same measurement range $4T \cdot B \cdot 6T$.

**FIG. 1.** The logarithm of $\frac{1}{2} \rho_{xx}(\theta = 1)$ versus the inverse of temperature $1/T$ at different gate voltages (and hence magnetic fields $B$). From top to bottom: $B = 3.938$, 4.262, 4.65, 5.076, 5.592, and 6.032 T. The slopes of the straight line fits $\xi_1$ are shown in figure 2.

**FIG. 2.** The experimentally determined $\xi_1$ at various magnetic fields $B$. The straight line fit is discussed in the text. The dotted line is the bare Zeeman energy assuming $jg_0j = 0.44$.

**FIG. 3.** The logarithm of $\frac{1}{2} \rho_{xx}(\theta = 3)$ versus the inverse of temperature $1/T$ at different gate voltages (and hence magnetic fields $B$). From top to bottom: $B = 3.443$, 3.818, 4.064, 4.667, 5.263 and 5.860 T. The slopes of the straight line fits $\xi_1$ are shown in figure 4.

**FIG. 4.** The experimentally determined $\xi_3$ at various magnetic fields $B$. The straight line fit is discussed in the text. The dotted line is the bare Zeeman energy assuming $jg_0j = 0.44$. 
III. Spin-dependent transport in a $B_k$ field

We now turn our attention to in-plane magnetic field measurements. To check for an out-of-plane magnetic field component, we measure the Hall voltage. From this we know that the sample was aligned to better than $0.1\pm$ using an *in situ* rotating insert. Figure 5(a) shows the four-terminal resistivity $\frac{1}{2} \rho_x$ as a function of the in-plane magnetic field at five different carrier densities. It is evident that with increasing $B_k$, the resistivity increases. At the lowest carrier density $n = 8 \times 10^{14}$ m$^{-2}$, the magnetoresistivity shows saturation at a high $B_k \approx 12$ T.

In the previous work of Yoon *et al.* [3], a strong magnetoresistance with increasing $B_k$ was observed. In our system, only a small increase of $\frac{1}{2} \rho_x$ is seen up to $B_k = 15$ T. This is probably due to the weaker carrier-carrier interactions in our GaAs electron gas compared with those in a dilute 2D hole gas [3]. Typically in a 2D GaAs electron system, with only one subband populated, the carrier density, but not the Fermi energy is fixed when $B_k$ is varied. In our system, there are spin-parallel and spin-antiparallel electrons of equal densities at zero magnetic field. Therefore our 2D GaAs electron system can be regarded as *two* subbands with the same energy at $B_k = 0$. While the total electron density is fixed, the density of spin-antiparallel electrons *must decrease* whereas the density of spin-parallel electrons *must increase* with increasing $B_k$: this is why a strong parallel magnetic field can fully spin-polarise a 2D electron system. Thus pinning of the Fermi energy is the simplest but realistic picture. Now we use a simple model to quantify our experimental results. As mentioned earlier, applying $B_k$ results in a shift in the spin-antiparallel 2D conduction band edge, thereby effectively reducing the density of spin-antiparallel electrons. Therefore one can consider that applying $B_k$ at a fixed $V_g$ is equivalent to decreasing $V_g$ in a zero magnetic field. Now the measured $\frac{1}{2} \rho_x(B_k)$ at a fixed gate voltage could be considered as $\frac{1}{2} \rho_x(B = 0)$ and regarded as a function of $V_g$. In this case, we can convert the measured $\frac{1}{2} \rho_x(B = 0)$ to an energy scale. At $B = 0$ applying a negative gate voltage reduces the local
Fermi energy $E$, giving rise to an increase in $\frac{1}{2}x_x$. Thus a larger $\frac{1}{2}x_x(B = 0)$ corresponds to a smaller local Fermi energy $E$. From the relation $\frac{1}{2}x_x(B = 0) = \frac{1}{4}E - 0.42$, we are able to convert the measured $\frac{1}{2}x_x(B_k)$ to an energy scale, as shown in Fig. 5 (b). Good linear fits are found over a large range 6 T $\leq B_k \leq 15$ T. Assuming that this is due to the Zeeman term $gB_k$, from the slope we estimate the $g$ factor to be -2.42, -1.86, -1.32 and -1.00 ($j_g = 2.42$, $j_g = 1.86$, $j_g = 1.32$ and $j_g = 1.00$) for $n = 3.28 \times 10^{15}$ m$^{-2}$, $n = 2.57 \times 10^{15}$ m$^{-2}$, $n = 1.78 \times 10^{15}$ m$^{-2}$, and $n = 1.02 \times 10^{15}$ m$^{-2}$, respectively.

The estimated $j_g$ is larger than the bare the Lande $j_g$ factor (0.44) in bulk GaAs. We note that in previous measurements on quantum dots [9] and one-dimensional channels [10], the Lande $j_g$ factors are indeed found to be $\frac{1}{4}0.4$ in both cases. Therefore we believe that our simple model over-estimates the $g$ factor in our system. Thus spin-splitting may not be the sole mechanism for the increase of $\frac{1}{2}x_x$ in a high $B_k$; there might be an enhancement of elastic scattering with increasing $B_k$. However our simple model, in principle, shows an energy dependence linear in $B_k$ which can be ascribed to a spin effect in a high parallel magnetic field.

IV. Conclusions

In conclusion, we have measured the low-temperature transport properties of a 2D GaAs electron system. In a perpendicular magnetic field, we observe collapse of spin-splitting and the $j_g$-factors enhanced over its bare value in bulk GaAs at both $\vartheta = 3$ and $\vartheta = 1$. We have also shown that the effective disorder at $\vartheta = 1$ is larger than that at $\vartheta = 3$. Parallel magnetic field measurements show an enhancement of the magnetoresistivity. Using a simple model, we suggest that the increase of magnetoresistivity is due to the Zeeman effect. However, this simplified model over-estimates the Lande $j_g$-factor in our system.

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