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

C.-T. Liang[1], Tsai-Yu Huang[1], Yu-Ming Cheng[1], Chao Han Pao[1], Chun-Cheng Lee[1],
Gil-Ho Kim[2], and J. Y. Leem[3]

[1]*Department of Physics, National Taiwan University, Taipei, Taiwan 106, R.O.C.*
[2]*Telecommunication Basic Research Laboratory, ETRI, Yusong P.O. Box 106, Taejon 305-600, Korea*
[3]*Materials Evaluation Centre, KRISS, P.O. Box 102, Taejon 305-600, Korea*

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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 [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 $B_\parallel$ parallel to a 2DEG is a powerful tool for studying spin-dependent electron transport since such a $B_\parallel$ only couples to the electrons' spin. The first tilted magnetic field experiment on a 2DEG revealed an enhancement of the g-factor [2]. Recently there has been a great deal of interest in 2D systems in a parallel magnetic field [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 $B_\parallel$ 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 [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 $º = 3$ and $º = 1$. 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 $B_?$ field

It is now well established that the energy gap $¢_º$ at a Landau level filling factor $º$ can be determined from the exponential temperature dependence of the magnetoresistivity $½_{xx}$ ¼ $\exp(¡¢_º=2k_BT)$, 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 $º = 1$, $¢_1$ is simply the "spin gap" which has the form [8]

$$¢_1 = jg_0j{}^1{}_B B + E_{ex} = jg^¤j{}^1{}_B B; \tag{1}$$

where E_{ex} is the many-body exchange energy which lifts the jgj-factor from its bare value ($jg_0j = 0:44$) to its enhanced value $jg^¤j$, ${}^1{}_B$ 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, $º = 3$.

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 $3.3 £ 10^{15}$ 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$½_{xx}(º = 1)$ as a function of $1=T$ at various B. From the straight line fits shown in Fig. 1, we can measure $¢_1$ at different carrier densities, and figure 2 shows such results. It is evident that $¢_1$ shows a linear dependence on 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 $jg^¤j$ to be 3.11 and the critical magnetic field B_c is 1.25 T at which $¢_1$ collapses to zero. The intercept of -1.31 K on the y-axis is ascribed to disorder broadening at $º = 1$ 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 sqaures also suggests that the actual critical field is higher than the B_c determined from the linear fit.

In the previous work of Kim *et al.* [8], due to the moderate disorder within the InAs/GaAs systems, the minimum of $½_{xx}$ at $º = 3$ is not well resolved. Our GaAs system is of higher quality and we are able to study the spin-gap at $º = 3$. Figure 3 shows ln$½_{xx}(º = 3)$ as a function of $1=T$ at various B. The spin gaps at $º = 3$ are determined from the straight line fits shown in Fig. 3. The measured spin gap $¢_3$ 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 $jg^¤j$ to be 4.05. It is evident that the data at $º = 3$ is similar to that at $º = 1$: both the collapse of spin-splitting and the enhanced $jg^¤j$ over the bare value are observed. The measured $jg^¤_{º=3}j = 4.05$ is larger than $jg^¤_{º=1}j = 3.11$, showing direct evidence that the many-body interactions are stronger at $º = 3$ than those at $º = 1$. The fact that the magnitudes of the critical field B_C ¼ 0.8 and an interception of

-0.8K at ° = 3 are both smaller than those at ° = 1 also shows that the effective disorder at ° = 1 is larger than that at ° = 3 over approximately the same measurement range 4T · B · 6T.

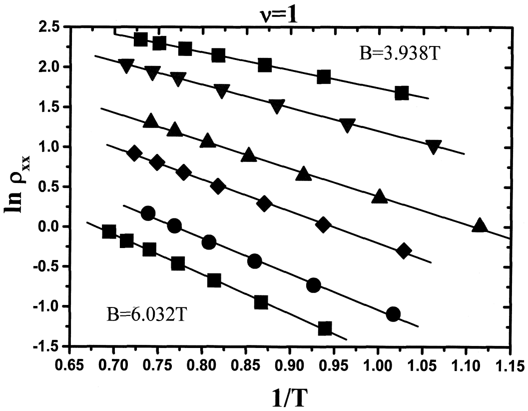


FIG. 1. The logarithm of ½xx(° = 1) versus the inverse of temperature 1=T at different gate voltages (and hence magnetic fields B). From top to bottom: B = 3.938, 4.262, 4.65, 5.076, 5.592, and 6.032 T. The slopes of the straight line fits ¢ 1 are shown in figure 2.

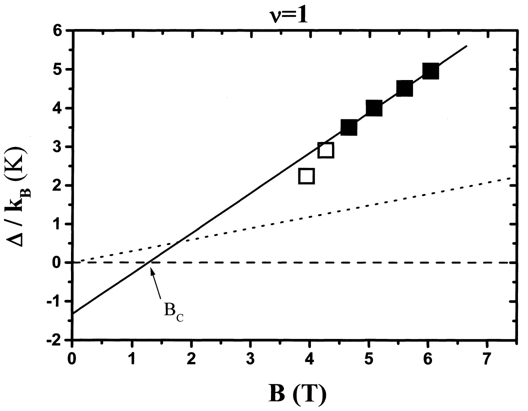


FIG. 2. The experimentally determined ¢ 1 at various magnetic fields B. The straight line fit is discussed in the text. The dotted line is the bare Zeeman energy assuming jg0j = 0:44.

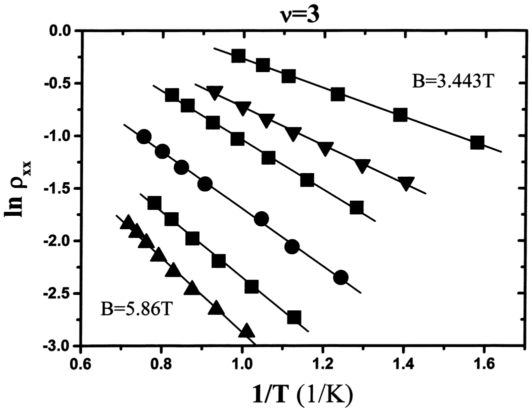


FIG. 3. The logarithm of ½xx(° = 3) versus the inverse of temperature 1=T at different gate voltages (and hence magnetic fields B). From top to bottom: B = 3.443, 3.818, 4.064, 4.667, 5.263 and 5.860 T. The slopes of the straight line fits ¢ 1 are shown in figure 4.

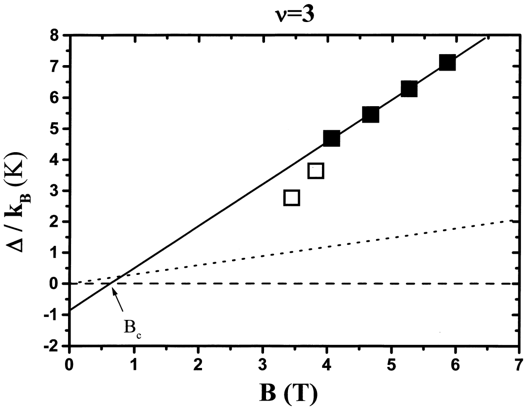
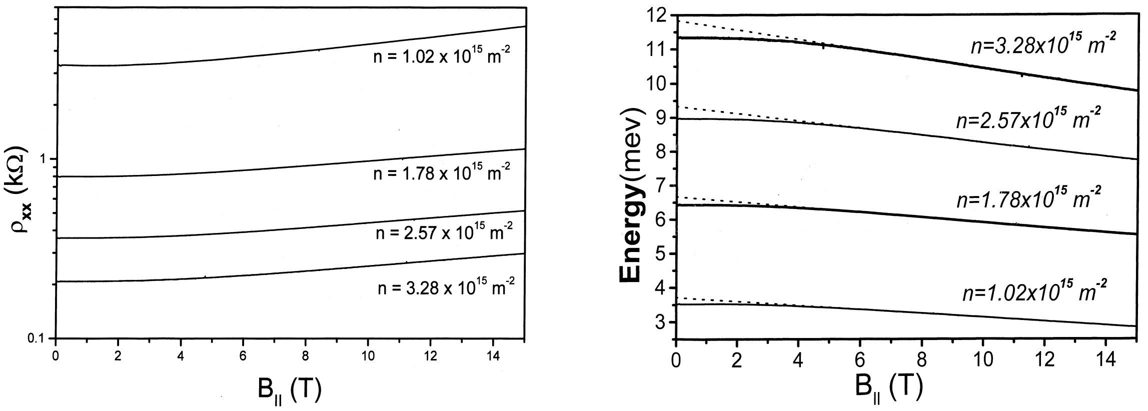


FIG. 4. The experimentally determined ¢ 3 at various magnetic fields B. The straight line fit is discussed in the text. The dotted line is the bare Zeeman energy assuming jg0j = 0:44.



(a) (b)

FIG. 5. (a) Four-terminal resistivity $½_{xx}$ as a function of B_k at five different carrier densities. (b) Estimated local Fermi energy E as a function of B_k. The linear fits at high fields 6 T · B_k · 15 T are discussed in the text.

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 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 $n = 8{:}16 £ 10^{14}$ m$^{i\ 2}$, the magnetoresistivity shows saturation at a high B_k ¼ 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 $½_{xx}$ 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 $½_{xx}(B_k)$ at a fixed gate voltage could be considered as $½_{xx}(B = 0)$ and regarded as a function of V_g. In this case, we can convert the measured $½_{xx}(B = 0)$ to an energy scale. At $B = 0$ applying a negative gate voltage reduces the local

Fermi energy E, giving rise to an increase in $½_{xx}$. Thus a larger $½_{xx}(B = 0)$ corresponds to a smaller local Fermi energy E. From the relation $½_{xx}(B = 0)$ ¼ $E^{i\ 0:42}$, we are able to convert the measured $½_{xx}(B_k)$ to an energy scale, as shown in Fig. 5 (b). Good linear fits are found over a large range 6 T · B_k · 15 T. Assuming that this is due to the Zeeman term $g^1{}_B B_k$, from the slope we estimate the g factor to be -2.42, -1.86, -1.32 and -1.00 (jgj = 2.42, jgj = 1.86, jgj = 1.32 and jgj = 1.00) for n = 3.28 £ 10^{15} m$^{i\ 2}$, n = 2.57 £ 10^{15} m$^{i\ 2}$, n = 1.78 £ 10^{15} m$^{i\ 2}$, and n = 1.02 £ 10^{15} m$^{i\ 2}$, respectively.

The estimated jgj is larger than the bare the Lande jgj factor (0.44) in bulk GaAs. We note that in previous measurements on quantum dots [9] and one-dimensional channels [10], the Lande jgj factors are indeed found to be ¼ $0:4$ 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 $½_{xx}$ 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. Conculsions

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 jgj-factors enhanced over its bare value in bulk GaAs at both $º = 3$ and $º = 1$. We have also shown that the effective disorder at $º = 1$ is larger than that at $º = 3$. 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 jgj-factor in our system.

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