Spin-dependent transport in a dilute two-dimensional GaAs electron gas in an in-plane magnetic field

Chi-Te Liang [a,1], Charles G. Smith [b], Michelle Y. Simmons [c], Gil-Ho Kim [d], David A. Ritchie, Michael Pepper [b]

[a] *Department of Physics, National Taiwan University, Taipei 106, Taiwan*
[b] *Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, United Kingdom*
[c] *School of Physics, University of New South Wales, Sydney 2052, Australia*
[d] *Department of Electronic and Electrical Engineering, Sungkyunkwan University, Suwon 440-746, Korea*

Abstract

We report low-temperature magnetoresistivity measurements of a high-quality gated two-dimensional electron gas (2DEG). In the dilute electron density limit, we show evidence for spin polarisation in an in-plane magnetic field. Using a simple model, we estimate the Landé g-factor in this dilute 2DEG to be about 3.32. This enhanced Landé g-factor compared with that of a bulk GaAs 2D electron system (0.44) is ascribed to electron-electron interaction effects at ultra-low electron densities and the fact that over the whole measurement range r_s does not vary significantly.

Key words: Spin; Electron-electron interactions; Spin polarisation

Recently there has been a great deal of interest in transport in dilute 2D (two-dimensional) systems[1–4]. In these studies, there are strong carrier-carrier interactions within the 2D systems. In an in-plane magnet field, the 2D system shows strong magnetoresistance which is believed to be a manifestation of the spin alignment of the free carriers[3,5]. The suppression of the "metallic state" with increasing in-plane magnetic field has now become important in trying to understand the underlying physics of the "metallic-like conductivity" in two dimensions.

In this paper, we report low-temperature magnetoresistivity measurements of a dilute 2D GaAs electron gas (2DEG) in which carrier-carrier interactions are much weaker compared with those in a GaAs hole gas[3] and in a Si electron gas[4]. We shall show evidence for spin polarisation in an in-plane magnetic field. Using a simple model, we estimate the Landé g-factor in this dilute 2DEG to be about 3.32. The enhanced value of the Landé g-factor in this dilute limit compared with that of a bulk 2DEG (0.44) is ascribed to electron-electron interactions and the fact that over the whole measurement range r_s does not vary significantly($3.7 \leq r_s \leq 4.7$).

The measurements were performed on a gated Hall bar made from GaAs/$Al_{0.33}Ga_{0.67}As$ heterostructure. At $V_g = 0$, the carrier concentration of the 2DEG was 1.53×10^{11} cm^{-2} with a mobility of 4×10^6 cm^2/Vs after brief illumination by a red light emitting diode. The depth of the 2DEG is 300 nm for our device. Experiments were performed in a top-loading ^{3}He cryostat at $T = 300$ mK and the four-terminal magnetoresistivity was measured with standard phase-sensitive techniques. The in-plane magnetic field $B_\parallel$ is applied parallel to the source-drain current.

Figure 1 shows the four-terminal magnetoresistivity ρ_{xx} as a function of in-plane magnetic field $B_\parallel$ at various carrier densities n_s. Let us consider the uppermost curve. We see that ρ_{xx} shows a $B_\parallel^2$ dependence for $B_\parallel < 5$ T and shows a weaker $B_\parallel^2$ dependence for

[1] Corresponding author. Present address: Department of Physics, National Taiwan University, Taipei 106, Taiwan E-mail: ctliang@phys.ntu.edu.tw

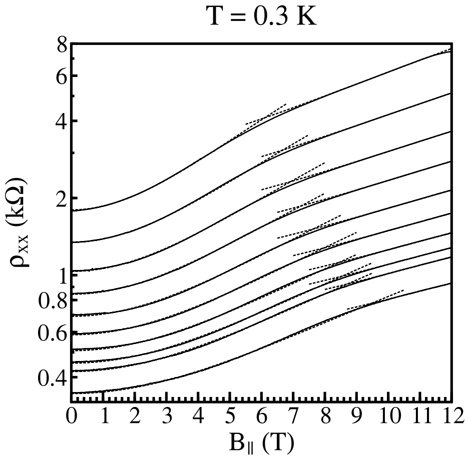

Fig. 1. $\rho_{xx}(B_\parallel)$ for various carrier densities. From top to bottom: $n_s = 1.379, 1.481, 1.591, 1.688, 1.780, 1.884, 1.967, 2.036, 2.076$ and $2.226 \times 10^{10}\text{cm}^{-2}$, respectively. Two parabolic fits for $B_\parallel < 5$ T and $B_\parallel > 9$ T for various n_s are shown in dotted lines.

$B_\parallel > 9$ T, as shown by the two dotted lines. We ascribe the increase in ρ_{xx} at low $B_\parallel$ to gradual spin alignment of the 2DEG[3,5]. It is worth mentioning that in both previous work[3,4], ρ_{xx} shows an exponential B dependence in *both* low and high magnetic field regimes. We believe the fact that in our case ρ_{xx} shows a B^2 dependence is due to much weaker carrier-carrier interactions compared with those in previous studies[3,4]. To obtain quantitative information on this spin alignment effect, we use an empirical method similar to those reported [3,4], but using two parabolic fits, as shown in the two dotted lines in Fig. 1 for various n_s. The interception of two parabolic fits is defined as the "crossing field" B_{cross} for a certain 2D carrier density. As shown later, from $B_{cross}(n_s)$ we can estimate the g-factor in our system.

Figure 2 shows the crossing field B_{cross} as a function of both carrier concentration n_s and the corresponding local Fermi energy E. Following the previous work[3,4], we assume the slope of the $E - B_{cross}$ diagram is given by the Zeeman energy $E = \frac{1}{2} g \mu_B B_\parallel$, where μ_B is the Bohr magneton. In this case, a linear fit through the origin gives an estimated g-factor of 2.84. As shown in Fig. 2, the best linear fit yields a value of the g-factor of 3.32. This fit gives a negative interception at $B = 0$ which can be attributed to disorder broadening[4]. Note that both measured values are comparable to that measured in a clean 1D electron gas when there is a single 1D subband occupied[6]. Previously this enhancement of g-factor[6] is ascribed to electron-electron interactions at low carrier densities. We note that the dimensionaless parameter r_s, the ratio of the Coulomb interaction energy to the kinetic (Fermi) energy reflects the strength of electron-electron interactions in the system. In our system, r_s

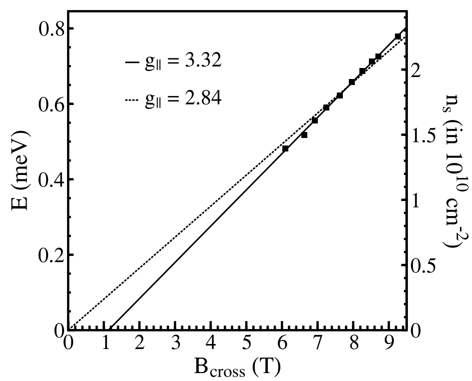

Fig. 2. Local Fermi energy E and the corresponding 2D carrier density n_s at various measured crossing field B_{cross}. The straight line fit through the origin is shown in the dotted line. The best linear fit is shown in the solid line.

is ≈ 4.7 at the lowest carrier density and decreases to 3.7 at the highest n_s. Therefore over the whole measurement range, r_s only decreases by an amount of $\approx$ 20 percent. In this case, we believe that the strength of electron-electron interactions does not vary significantly over the whole measurement range, thus giving rise to an approximately constant g-factor determined from the straight line fit shown in Fig. 2.

In conclusion, we have measured a dilute gated 2D GaAs electron gas. Our experimental results obtained in a much weaker interacting GaAs electron system show that the magnetoresistance exhibits a much weaker $B_\parallel^2$ dependence compared with those in a GaAs hole gas and in a Si electron system. Using an empirical method, we estimate the Landé g-factor to be 3.32 in this dilute GaAs 2DEG. This enhanced g-factor is ascribed to electron-electron interactions and the fact that over the whole measurement range r_s does not vary significantly.

Acknowledgements

This work was funded by the NSC, Taiwan. The work at Cambridge was supported by the Engineering and Physical Sciences Research Council (EPSRC), UK. C.T.L. thanks T. Chin for her support.

References

[1] D. Simonian *et al.*, Phys. Rev. Lett. **79,** 2304 (1997).

[2] M. Y. Simmons *et al.*, Phys. Rev. Lett. **80,** 1292 (1998).

[3] J. Yoon *et al.*, Phys. Rev. Lett. **84,** 4421 (2000).

[4] V. M. Pudalov *et al.*, Cond-mat/0004206 (2000).

[5] V.T. Dolgopolov and A. Gold, JETP Lett. **71**, 27 (2000).

[6] K. J. Thomas *et al.*, Phys. Rev. Lett. **77,** 135 (1996).