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

Chi-Te Liang\(^a,\,*\), Charles G. Smith\(^b\), Michelle Y. Simmons\(^c\), Gil-Ho Kim\(^d\), David A. Ritchie\(^b\), 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, South 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.

\( * \) Corresponding author. Fax: +886-2-23639984.
E-mail address: ctliang@phys.ntu.edu.tw (C.-T. Liang).

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Recently there has been a great deal of interest in transport in dilute two-dimensional (2D) systems [1–3]. 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 [2,4]. 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 [2] and in an Si electron gas [3]. 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 \( 1.53 \times 10^{11} \text{ cm}^{-2} \) with a mobility of \( 4 \times 10^6 \text{ cm}^2/\text{V s} \) after brief illumination by a red light emitting diode. The depth of the 2DEG is 300 nm for our device. Experiments were performed in an \(^3\)He cryostat at \( T = 300 \text{ mK} \) and the four-terminal magnetoresistivity \( \rho_{xx} \) was measured with standard phase-sensitive techniques. The in-plane magnetic field \( B_{\parallel} \) is applied parallel to the source-drain current.

Fig. 1 shows \( \rho_{xx} \) 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 \( \rho_{xx} \) shows a \( B_{\parallel}^2 \) dependence for \( B_{\parallel} < 5 \text{ T} \) and shows a weaker \( B_{\parallel}^2 \) dependence for \( B_{\parallel} > 9 \text{ T} \), as shown by the two dotted lines. We ascribe the increase in \( \rho_{xx} \) at low \( B_{\parallel} \) to gradual spin alignment of the 2DEG [2,4]. It is worth mentioning that in both previous work [2,3], \( \rho_{xx} \)
shows an exponential $B$ dependence in both low and high magnetic field regimes. We believe the fact that in our case $\rho_{xx}$ shows a $B^2$ dependence is due to much weaker carrier–carrier interactions compared with those in previous studies [2,3]. To obtain quantitative information on this spin alignment effect, we use an empirical method similar to those reported [2,3], 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” $B_{\text{cross}}$ for a certain 2D carrier density. As shown later, from $B_{\text{cross}}(n_s)$ we can estimate the $g$-factor in our system. We note that the resistance at the “crossing field” is $\approx 10\%$ higher than the measured value at $B_{\text{cross}}$. Thus, we believe there is an error of $10\%$ in estimating the $g$-factor in our system.

Fig. 2 shows $B_{\text{cross}}$ as a function of both carrier concentration $n_s$ and the corresponding local Fermi energy $E$. Following the previous work [2,3], we assume the slope of the $E - B_{\text{cross}}$ diagram is given by the Zeeman energy $E = \frac{1}{2} g \mu_B B_{\parallel}$, where $\mu_B$ 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 3.2. This fit gives a negative interception at $B = 0$ which can be attributed to disorder broadening [3]. We note that the dimensionless parameter $r_s$, the ratio of the Coulomb interaction energy to the kinetic (Fermi) energy reflects the strength of electron–electron interactions. It is worth mentioning that theoretical results show that with decreasing $n_s$ (and hence increasing $r_s$), the $g$-factor is expected to increase due to increasing electron–electron interactions [5]. In our system $r_s$ is $\approx 4.7$ 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 $\approx 20\%$. 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. We note that Tutuc and co-workers [6] recently reported that when $r_s$ decreases from 2.1 to 6.3, the $g$-factor decreases from 2.7 to 1.3 in a similar dilute GaAs electron gas.

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 $B_{\parallel}$ dependence compared with those in a GaAs hole gas and in an 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.

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References