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

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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.

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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 ($3.7 \leqslant r_s \leqslant 4.7$).

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/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 $T = 300$ mK and the four-terminal magnetoresistivity ρ_{xx} was measured with standard phase-sensitive techniques. The in-plane magnetic field $B_{\|}$ is applied parallel to the source-drain current.

Fig. 1 shows ρ_{xx} as a function of in-plane magnetic field $B_{\|}$ at various carrier densities n_s. Let us consider the uppermost curve. We see that ρ_{xx} shows a $B_{\|}^2$ dependence for $B_{\|} < 5$ T and shows a weaker $B_{\|}^2$ dependence for $B_{\|} > 9$ T, as shown by the two dotted lines. We ascribe the increase in ρ_{xx} at low $B_{\|}$ to gradual spin alignment of the 2DEG [2,4]. It is worth mentioning that in both previous work [2,3], ρ_{xx}

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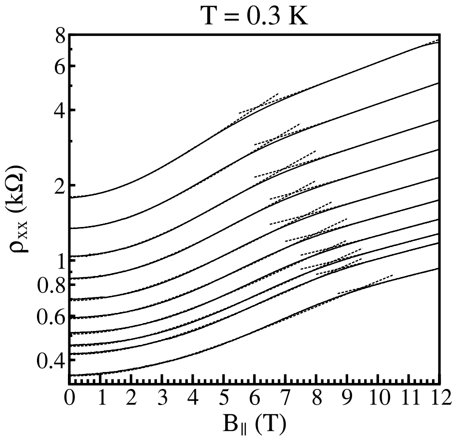

Fig. 1. $\rho_{xx}(B_{||})$ for various carrier densities. From top to bottom: $n_s = 1.379, 1.481, 1.591, 1.688, 1.780, 1.884, 1.967, 2.036, 2.076$ and 2.226×10^{10} cm^{-2}, respectively. Two parabolic fits for $B_{||} < 5$ T and $B_{||} > 9$ T for various n_s are shown in dotted lines.

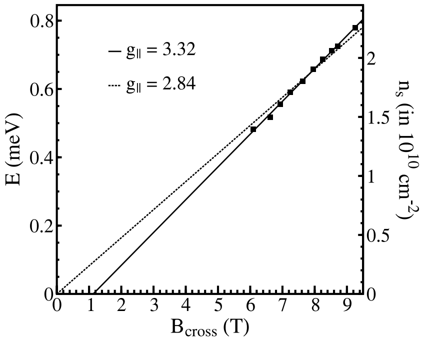

Fig. 2. Local Fermi energy E and the corresponding 2D carrier density n_s at various measured crossing field B_{cross}. The straight line fit through the origin is shown in the dotted line. The best linear fit is shown in the solid line.

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 [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_{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 ≈ 10% higher than the measured value at B_{cross}. Thus, we believe there is an error of 10% in estimating the g-factor in our system.

Fig. 2 shows B_{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 $E = \frac{1}{2} g \mu_{\text{B}} B_{||}$, 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 [3]. 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. It is worth mentioning that theoreical 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 ≈ 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 ≈ 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 diulte 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 $B_{||}^2$ 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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