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Spin-dependent transport in a two-dimensional GaAs electron gas in a parallel magnetic field

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Abstract

We report low-temperature magnetoresistivity measurements of high-quality gated two-dimensional (2D) electron systems. 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 two-dimensional electron gas to be about 3.32. The 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. © 2002 Elsevier Science B.V. All rights reserved.

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In a low-dimensional electron system [1], applying an in-plane magnetic field $B_{\|}$ parallel to the plane of the electron gas has been proved to be a powerful technique to study spin-dependent electron transport. The first tilted magnetic field experiment on a two-dimensional electron gas (2DEG) revealed an enhancement of the g-factor [2]. In a one-dimensional (1D) electron system, it was first demonstrated by Wharam et al. [3] that a large $B_{\|}$ lifts the electron spin-degeneracy, causing consecutive spin-parallel (parallel to $B_{\|}$) and spin-antiparallel (anti-parallel to $B_{\|}$) conductance plateaux in multiples of e^2/h [4]. Using a source-drain bias technique [5], Patel et al. [4] measured the Landé g-factor in a one-dimensional (1D) constriction for the first time. Later this measurement was extended to the case of an ultra-high-quality 1D electron gas. When the 1D channel is wide, it is found that the measured Landé g-factor is $\approx$0.4, close to that of bulk GaAs. As the channel is progressively narrowed there is an enhancement of the Landé g-factor [6].

Recently there has been a great deal of interest in charge transport in dilute 2D systems [7–10]. In low carrier concentrations there is a significant drop in the resistance with decreasing temperature. It is also found that application of an in-plane magnetic field remove this increase and as the effect is not dependent on direction of field it seems most likely to be associated

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with spin [10,12,13]. A change in density of states could be expected to influence the screening properties of the dilute system as well as any possible interaction between them.

Previously we studied spin-dependent electron transport in a quasiballistic quantum wire [14]. It was found that at zero split-gate voltage when the quasiballistic wire is not electrostatically defined, the two-terminal conductance due to the bulk 2DEG shows monotonic decrease with increasing $B_{\|}$. In order to gain more insights into the effect of an $B_{\|}$ on 2DEG transport and exclude any contact resistance effect, we measure the four-terminal magnetoresistivity of a gated 2D electron system at various carrier densities. In this paper, we report low-temperature magnetoresistivity measurements of 2D GaAs electron gases in which carrier–carrier interactions are much weaker compared with those in a GaAs hole gas [10] and in a Si electron gas [11]. Our experimental results fall into two categories. In the dilute density limit, 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 over the whole measurement range r_s does not vary significantly.

The devices used in this work are two gated Hall bars made from GaAs/Al$_{0.33}$Ga$_{0.67}$As heterostructure. Sample A has a carrier density of 1.4×10^{15} m^{-2} with a mobility μ of 400 m^2 V s^{-1} at $V_g = 0$ after brief illumination with a red light-emitting diode. Sample B has a 2DEG carrier density of 3.3×10^{15} m^{-2} and a mobility of 30 m^2 V s^{-1} at $V_g = 0$ without illumination. 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 $B_{\|}$ is applied parallel to the source-drain current. To check for an out-of-plane magnetic field component, we measure the Hall voltage. From this we know that the sample was aligned better than 0.1° using an *in-situ* rotating insert.

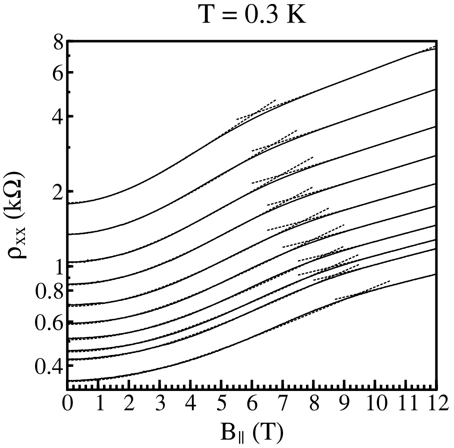

Fig. 1. $\rho_{xx}(B_{\|})$ for various carrier densities. From top to bottom: $n_s = 1.379$, 1.481, 1.591, 1.688, 1.780, 1.884, 1.967, 2.036, 2.076 and 2.226×10^{10} cm^{-2}, respectively. Two parabolic fits for $B_{\|} < 5$ T and $B_{\|} > 9$ T for various n_s are shown in dotted lines. The data is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

Fig. 1 shows the four-terminal magnetoresistivity ρ_{xx} as a function of in-plane magnetic field $B_{\|}$ at various carrier densities n_s. Let us consider the uppermost curve. It is evident 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 [10,11]. It is worth mentioning that in both previous work [10,11], 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 [10,11]. The physical origin of $B_{\|}^2$ at high $B_{\|}$ is believed to be due to the enhancement of electron scattering when the magnetic length is comparable to the thickness of the 2DEG [12]. This is supported by the fact that at $B_{\|} = 9$ T where ρ_{xx} starts showing a weak B^2 dependence, the corresponding magnetic length is ≈ 9 nm, in close agreement with a typical 2DEG thickness of 10 nm. To obtain quantitative information on this spin alignment effect, we use an empirical method similar to those reported [10,11], 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. Note that the magetoresistivity shows little temperature dependence between $T = 0.3$ K and 1 K, suggesting that the $B_{\|}^2$ dependence is a semi-classical effect.

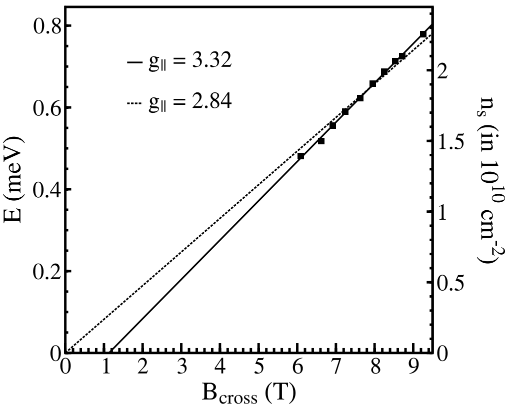

Fig. 2. Local Fermi energy E and the corresponding 2D carrier density n_s at various measured crossing field B_{cross}. The straight line fit through the origin is shown in the dotted line. The best linear fit is shown in the solid line.

Also within our experimental accuracy, we did not observe a “metal–insulator transition” [15] in our device.

Fig. 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 [10,11], we assume the slope of the E–B_{cross} diagram is given by the Zeeman energy $E = 1/2 g\mu_B B_{\|}$, 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 [11]. Note that both measured values are close 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 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 $\approx 20\%$. 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.

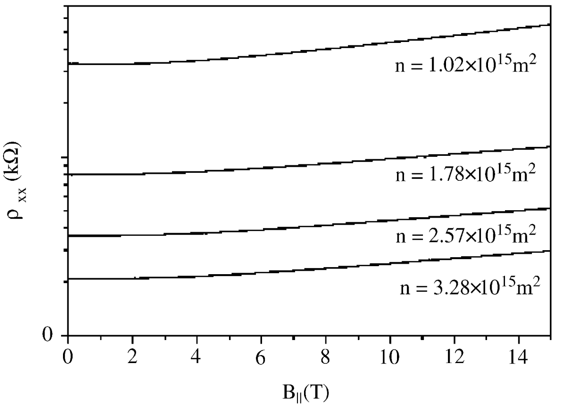

Fig. 3. Four-terminal resistivity ρ_{xx} as a function of $B_{\|}$ at four different carrier densities. The data is taken on Device B.

We now turn our attention to in-plane field measurements in the high carrier density limit. Fig. 3 shows the four-terminal resistivity ρ_{xx} as a function of in-plane magnetic field at four different carrier densities. It is evident that with increasing $B_{\|}$, the resistivity gradually increases. With the attainable magnetic field, we are not able to observe saturation of ρ_{xx} in a high parallel magnetic field. Thus, we cannot estimate the g-factor in our system. It would be interesting to measure the in-plane g-factor in the high-density limit in which electron–electron interactions are weak in the system.

In conclusion, we have measured gated 2D GaAs electron gases. In the dilute electron density limit, our experimental results show that the magnetoresistance exhibits a much weaker $B_{\|}^2$ 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. In the high density limit, parallel magnetic field measurements also show a gradual enhancement of the magnetoresistivity.

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