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

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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 polarization 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 two-dimensional (2D) electron system (0.44) is ascribed to electron-electron interaction effects at ultralow electron densities and the fact that over the whole measurement range r_s does not vary significantly.

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In a two-dimensional electron gas (2DEG),¹ applying an in-plane magnetic field $B_{\parallel}$ parallel to the plane of the electron system has proved to be a powerful technique to study spin-dependent electron transport. In a tilted magnetic-field experiment on a two-dimensional (2D) Si electron gas, the g factor was found to be considerably larger than the bulk electron g factor.² Janak³ proposed that this enhanced g factor is due to exchange interactions among the electrons. In the following years a number of authors⁴⁻⁷ studied this interesting many-body effect. With the advent of the modulation doped GaAs/AlGaAs heterojunction,⁸ exchange-enhanced g factors were also observed in 2D GaAs electron gases.⁹⁻¹¹

Recently there has been a great deal of interest in transport in dilute 2D systems.¹²⁻¹⁶ In these studies, there are strong carrier-carrier interactions within the 2D systems. In an in-plane magnetic field, the 2D system shows strong magnetoresistance which is believed to be a manifestation of the spin alignment of the free carriers.^{15,17,18} 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 “metalliclike conductivity” in two dimensions.

Previously we studied spin-dependent electron transport in a quasiballistic quantum wire.¹⁹ 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 $B_{\parallel}$. In order to gain more insight into the effect of a $B_{\parallel}$ 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 a dilute 2D GaAs electron gas in which carrier-carrier interactions are much weaker compared with those in a GaAs hole gas¹⁵ and in a Si electron gas.¹⁶ We shall show evidence for spin polarization 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 a 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 $4 \times 10^6 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ 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 ³He cryostat at $T = 300 \text{ mK}$ 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. 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.

Figure 1 shows the four-terminal magnetoresistivity measurements ρ_{xx} and ρ_{xy} as a function of perpendicular magnetic field B at $V_g = 0 \text{ V}$. The minima in ρ_{xx} coincide with the quantum Hall plateaux, showing that the uniformity of the carrier density n_s in our wafer and the high quality of our gated 2DEG.

We now turn to our main experimental results. Figure 2 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 $B_{\parallel} < 5 \text{ T}$ and a weaker $B_{\parallel}^2$ dependence

FIG. 1. Four-terminal magnetoresistivity measurements $\rho_{xx}(B)$ and $\rho_{xy}(B)$ in a perpendicular magnetic field B at $V_g = 0 \text{ V}$.

FIG. 2. $\rho_{xx}(B_{||})$ 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 $2.226 \times 10^{10} \text{ cm}^{-2}$, respectively. Two parabolic fits for $B_{||} < 5 \text{ T}$ and $B_{||} > 9 \text{ T}$ for various n_s are shown by the dotted lines.

for $B_{||} > 9 \text{ T}$, as shown by the two dotted lines. It is easier to see the $B_{||}^2$ dependence in both the low- and high-field regime when we plot ρ_{xx} as a function of $B_{||}^2$, as shown in Fig. 3. We ascribe the increase in ρ_{xx} at low $B_{||}$ to gradual spin alignment of the 2DEG.^{15,17,18} It is worth mentioning that in both previous works,^{15,16} 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.^{15,16} To obtain quantitative information on this spin-alignment effect, we use an empirical method similar to those reported,^{15,16} but using two parabolic fits, as shown in the two dotted lines in Fig. 2 for various n_s . The interception of two parabolic fits is defined as the

FIG. 3. $\rho_{xx}(B_{||}^2)$ 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 linear fits for various n_s are shown by the dotted lines.

FIG. 4. Local Fermi energy E and the corresponding 2D carrier density n_s at various measured crossing fields B_{cross} . The straight-line fit through the origin is shown by the dotted line. The best linear fit is shown by the solid line.

“crossing field” B_{cross} for a certain 2D carrier density. We note that recently Tutuc and Shayegan performed similar magnetotransport measurements on a dilute GaAs electron system in a parallel magnetic field.²⁰ In their system, the magnetoresistivity shows an $\exp(B_{||}^2)$ dependence at low fields and an $\exp(B_{||})$ dependence at high fields. They showed that the onset of the $\exp(B_{||})$ dependence corresponds to full spin polarization in the 2D system.^{20,21} These results^{20,21} justify the validity of our empirical identification in which the crossover of $B_{||}^2$ dependence corresponds to full spin polarization of our dilute GaAs electron system. As shown later, from $B_{cross}(n_s)$ we can estimate the g factor in our system. Note that the magnetoresistivity shows little temperature dependence between $T = 0.3 \text{ K}$ and $T = 1 \text{ K}$, suggesting that the $B_{||}^2$ dependence is a semiclassical effect. Also within our experimental accuracy, we did not observe a “metal-insulator transition” (MIT) in our device. The reason for this is probably due to the rather weak “MIT behavior” in a 2D GaAs electron gas²² and the limited-measurement temperature range in our system.

Figure 4 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,^{15,16} we assume the slope of the E - B_{cross} diagram is given by the Zeeman energy $E = \frac{1}{2} g \mu_B B_{||}$, 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. 4, 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.¹⁶ Note that both measured values are comparable to that measured in a clean 1D electron gas when there is a single 1D subband occupied.²³ Previously this enhancement of g factor²³ is ascribed to electron-electron interactions at low carrier densities. 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 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. 4.

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.

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