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‘Mobility gap’ of a spin-split GaAs two-dimensional electron gas

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Abstract

We have performed magnetotransport measurements of the electron g-factor in a two-dimensional GaAs electron gas. In order to obtain the spin gap Δ_s, we measure the spin-split longitudinal resistivity minimum which shows an activated behavior. From the spin gaps at different odd filling factors, we can obtain the effective g-factor which is greatly enhanced over its bare value (0.44) in GaAs. This enhancement is due to many-body electron–electron interactions. Our experimental results provide compelling evidence that conventional activation energy studies yield a ‘mobility gap’ which can be very different from the real spin gap in the energy spectrum.

Keywords: Spin splitting; g-Factor

1. Main text

A two-dimensional electron system (2DES) formed at the interface of a modulation doped GaAs/AlGaAs heterostructure [1] has been an intensive subject of studies for the last two decades. This interest is generated by the advancing progress in preparing high-quality semiconductor samples which open up new areas not only in fundamental physics but also in potential device applications [2]. In the presence of a strong perpendicular magnetic field B, the Landau quantization becomes important, resulting in discrete but highly degenerate Landau levels. The picture of extended states at the Landau level centers and localized states between Landau levels provides a simple description of the integer quantum Hall effect (IQHE) in a strong perpendicular magnetic field B.

In the IQHE, the spin splitting of each Landau level appeared to be much stronger than expected from just a bare Zeeman gap. Jank [3] first proposed that this enhancement is due to exchange interactions amongst the electrons, leading to the concept of an enhanced g-factor. The spin gap can be written as

$$\Delta_s = g_0\mu_B B + E_{ex} = g * \mu_B B, \tag{1}$$

where E_{ex} is the many-body exchange energy which lifts the g-factor from its bare value ($g_0 = 0.44$ in GaAs) to its enhanced value g^*. A standard method of determining the spin gap is to perform activation energy measurements at the minimum of the longitudinal resistivity $\rho_{xx} \sim \exp(-\Delta_s/2k_B T)$ [4–8], where k_B is the Boltzmann constant and T is the temperature, respectively. However, such a measurement is rather restricted and yields a ‘mobility gap’ which may be different from the real spin gap in the energy spectrum [9,10].

In the present work, we report the spin-dependent transport properties in a two-dimensional GaAs electron system. In the presence of a perpendicular magnetic field, the well-developed odd-integer filling factors $\nu = 3$, 5, 7, 9, and 11 can be observed in the longitudinal resistivity. From the spin gaps at the different odd-integer filling factors, we can obtain the effective g-factor for the GaAs 2DES. The measured g-factor is greatly enhanced over its bulk value (0.44) due to many-body electron–electron interactions.

Our sample used in this study is a GaAs/AlGaAs heterostructure grown by molecular beam epitaxy. The following layer sequence was grown on a GaAs (100) substrate: 2 μm GaAs buffer, 400 nm AlGaAs, 30 layers of AlAs/GaAs superlattices, 200 nm of AlGaAs with a Si concentration of 1.2×10^{17} cm^{-3}, 80 nm of AlGaAs,

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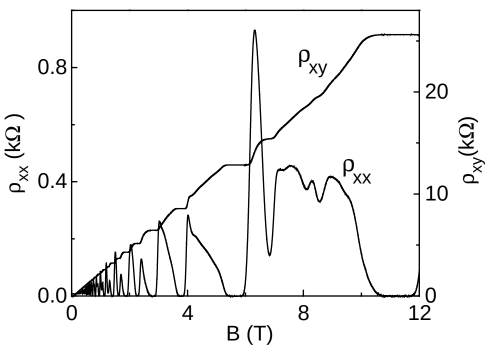

Fig. 1. The longitudinal (ρ_{xx}) and Hall (ρ_{xy}) resistivities as a function of the magnetic field B at $T=0.3$ K.

25.5 nm of GaAs, 80 nm of AlGaAs, 200 nm of AlGaAs with a Si concentration of 1.7×10^{17} cm^{-3}, and a 17 nm GaAs cap layer. The two-dimensional electron system was formed at the interface of GaAs and undoped AlGaAs. Magneto transport measurements were performed with a top-loading He^3 system with a superconductor magnet. A phase sensitive four-terminal ac lock-in technique was used with a driving current of 100 nA. The carrier concentration of the 2DEG is 3.19×10^{11} cm^{-2} without illumination, and the mobility is 2.39×10^{6} cm^2/Vs at 0.3 K.

Fig. 1 shows the four-terminal measurements of the longitudinal (ρ_{xx}) and Hall (ρ_{xy}) resistivities at the temperature $T=0.3$ K. With increasing the magnetic field, we can observe the well-resolved spin splitting at odd-integer filling factor $\nu=1$, 3, 5, 7, 9, and 11 from the corresponding Hall plateaus in ρ_{xy}. In order to evaluate the energy gaps at each odd-integer filling factor, we measured the temperature dependence of ρ_{xx} at the minimum which shows an activated behavior, $\rho_{xx}\sim\exp(-\Delta_s/2k_BT)$. Fig. 2 shows an Arrhenius plot of ln ρ_{xx} as a function of $1/T$ at various odd-integer filling factors. From the straight line fits shown in Fig. 2, we can obtain the spin gaps which are between mobility edges at $\nu=3$, 5, 7, 9, and 11. From the Arrhenius plots, we can observe that the curve deviates from

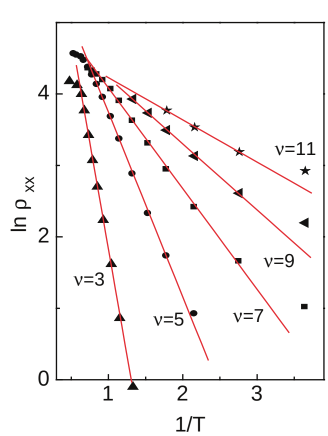

Fig. 2. Typical Arrhenius plots for $\nu=3$, 5, 7, 9, and 11.

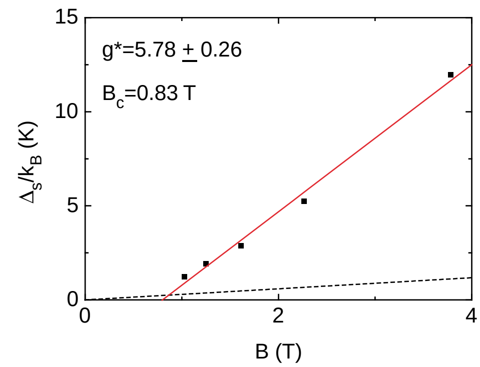

Fig. 3. The determined spin gaps Δ_s at various odd filling factors and hence magnetic fields. The dashed line shows the bare Zeeman splitting.

the straight line at high temperatures when ρ_{xx} minimum is poorly resolved and conduction is no longer activated. Fig. 3 shows the spin gaps at different magnetic fields which are proportional to $1/\nu$. It is evident that the spin gap shows a linear dependence of the magnetic field B. According to Eq. (1), we can obtain the effective g-factor as 5.78 ± 0.26 from the least-square fit of the spin gaps at various magnetic fields. The enhanced g-factor is almost 14 times greater than the bare Zeeman splitting which is shown in dashed line in Fig. 3. This enhancement is due to many-body electron–electron interactions.

In Fig. 3, we can see that the spin gap drops approximately linearly to zero at a critical field $B_c\sim0.83$ T, which is in sharp contrast to the work by Usher [6]. The disorder broadening Γ_s can be estimated from the critical magnetic field B_c, $\Gamma_s=h/2\pi\tau_s=g^*\mu_BB_c$. From this we obtain a quantum lifetime of $\tau_s=2.34$ ps, in qualitative agreement with the value 1.19 ps obtained from the Dingle plot which is shown in Fig. 4. For the low-field regime where $\Delta_s<\Gamma_s$, the many-body interactions are destroyed by disorder, and there is no spin-splitting for the magnetic field less than B_c. Therefore, our experimental results provide that conventional activation energy studies yield a mobility gap that can be very different from the real spin gap which is the energy between adjacent Landau levels in the zero disorder limit.

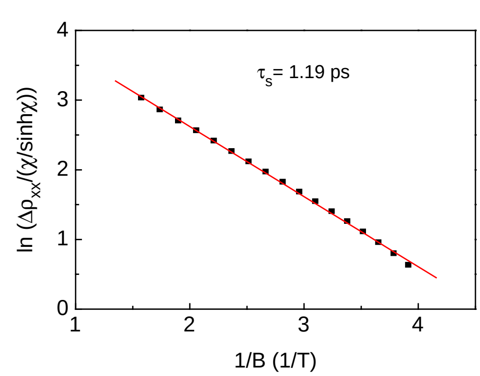

Fig. 4. Typical Dingle plot at $T=0.3$ K.

It is important to note that the activation energy studies indicate that an energy gap due to exchange energy increase linearly with the magnetic field. This can interpret that the effective g-factor is almost the same at all magnetic fields, and the spin gap $\Delta_s = g^* \mu_B B$. Although many previous studies [6–9] have reported such a linear increase, the simple theories of exchange energy suggest that the spin gap should increase like $B^{1/2}$. However, this square-root dependence holds only when there is just one Landau level occupied and the Coulomb energy ($E_c = e^2/4\pi\varepsilon_0\varepsilon_r l_B$) is small compared with the cyclotron energy, where $l_B = (h/2\pi eB)^{1/2}$ is the magnetic length [8]. From our experimental result, the Coulomb energy is larger than the cyclotron energy when the filling factor $\nu \geqq 3$. Therefore, the exchange energy should increase linearly with the magnetic filed at $\nu \geqq 3$ in our system.

In conclusion, we have studied the magneto transport properties in a GaAs two-dimensional electron gas. The enhanced g-factor of 5.86, which is almost 14 times greater than the bare value (0.44) in GaAs, is measured from activation experiments at Landau level occupancies $\nu = 3$, 5, 7, 9, and 11. This enhancement is due to many-body electron–electron interactions. We also observe the collapse of spin splitting in which the spin gap approaches to zero at a critical magnetic field B_c of 0.83 T. Our experimental results indicate that conventional activation energy studies yield a mobility gap which can be very different from the real spin gap in the zero disorder limit.

Acknowledgements

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