Spin gap in the two-dimensional electron system of GaAs/$Al_xGa_{1-x}As$ single heterojunctions in weak magnetic fields

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We study the interaction-enhanced spin gaps in the two-dimensional electron gas confined in GaAs/AlGaAs single heterojunctions subjected to weak magnetic fields. The values are obtained from the chemical potential jumps measured by magnetocapacitance. The gap increase with parallel magnetic field indicates that the lowest-lying charged excitations are accompanied with a single spin flip at the odd-integer filling factor $\nu=1$ and $\nu=3$, in disagreement with the concept of skyrmions.

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I. INTRODUCTION

Much interest has been attracted recently by possible formation of the spin textures in two-dimensional (2D) electron systems in perpendicular magnetic fields. The spin gap in a 2D electron system is expected to be enhanced compared to the single-particle Zeeman energy due to electron-electron interactions.[1,2] Within the concept of exchange-enhanced gaps, the gap enhancement is given by the exchange energy of a single spin-flip excitation.[1] However, in the limit of low single-particle Zeeman energies (particularly, at weak magnetic fields) and of weak electron-electron interactions, the skyrmion—the spin texture characterized by many flipped spins—is predicted to become for filling factor $\nu=1$ the lowest-energy charge-carrying excitation.[2] This corresponds to a reduction of the exchange-enhanced gap.

Possible formation of the skyrmions remains controversial so far although much work has been done on this (see, e.g., Refs. 3–10). Strongly enhanced values of the spin gap in the 2D electron system in GaAs/AlGaAs heterostructures were found by measurements of the activation energy for the longitudinal resistivity minimum at filling factor $\nu=1$, 3, and 5.[3–5] It was argued in Ref. 4 that introducing a parallel component of the magnetic field allows determination of the spin of the lowest-lying charged excitations by the increase in the activation energy with parallel field. The experimental results indicated that the excitations at $\nu=1$ are accompanied with seven electron spin flips, while at $\nu=3$ and 5 only a single spin flips.[4,10] This is consistent, in principle, with the predictions of the skyrmion approach. However, one should be careful in interpreting results of activation energy measurements because they yield a mobility gap which may be different from the gap in the spectrum. The latter can be determined directly by measurements of the chemical potential jump across the gap based on magnetocapacitance spectroscopy.[11,12]

In this paper, we report the first measurements of the chemical potential jump across the many-body enhanced spin gap at $\nu=1$ and 3 in the 2D electron system in GaAs/AlGaAs single heterojunctions in weak magnetic fields using a magnetocapacitance technique. We find that the increase of the gap with parallel component of the magnetic field corresponds to a single spin flip for both $\nu=1$ and $\nu=3$, which does not support formation of the skyrmions in the range of magnetic fields studied, down to $B_\perp \approx 2$ T. This finding is in contrast to the results of indirect transport measurements[4] on very similar samples in the same range of magnetic fields. Concerning the observed slightly sublinear dependence of the spin gap on perpendicular magnetic field, we suggest that its origin can be related to the Landau level mixing due to electron-electron interactions.

The remainder of the paper is organized as follows. Thermodynamic measurement technique and samples are described in Sec. II. Details of the data analysis and experimental results on the behavior of the spin gap with magnetic field are given in Sec. III. The obtained results are discussed and compared to those of transport measurements in Sec. IV. The main results are summarized in the conclusion.

II. EXPERIMENTAL TECHNIQUE

Measurements were made in an Oxford dilution refrigerator with a base temperature of ≈30 mK on remotely doped GaAs/AlGaAs single heterojunctions (with a low temperature mobility $\approx 2\times10^6$ cm^2 V^{-1} s^{-1} at electron density 1×10^{11} cm^{-2}) having the Hall bar geometry with area 5

$\times 10^4$ μm^2. A metallic gate was deposited onto the surface of the sample, which allowed variation of the electron density by applying a dc bias between the gate and the 2D electrons. To populate the 2D electron system, the sample was illuminated with an infrared light-emitting diode; after the electron density saturated, the diode was switched off. The gate voltage was modulated with a small ac voltage of 4 mV at frequencies in the range 0.5–11 Hz, and both the imaginary and real components of the current were measured using a current-voltage converter and a lock-in amplifier. Smallness of the real current component as well as proportionality of the imaginary current component to the excitation frequency ensure that we reach the low-frequency limit and the measured magnetocapacitance is not distorted by lateral transport effects. A dip in the magnetocapacitance at integer filling factor is directly related to a jump of the chemical potential across a corresponding gap in the spectrum of the 2D electron system:[11]

$$\frac{1}{C} = \frac{1}{C_0} + \frac{1}{Ae^2 dn_s/d\mu}, \tag{1}$$

where C_0 is the geometric capacitance between the gate and the 2D electrons, A is the sample area, and the derivative $dn_s/d\mu$ of the electron density over the chemical potential is thermodynamic density of states. The chemical potential jump is determined by integrating the magnetocapacitance over the dip in the low-temperature limit where the magnetocapacitance saturates and becomes independent of temperature[13] (see Fig. 1). Additional experiments were performed on three-electrode samples of GaAs/AlGaAs single heterojunctions in which the 2D electron system is field effect induced in a way similar to silicon metal-oxide-semiconductor field-effect transistors. It is separated from the front gate by a blocking barrier and from the back electrode by a wide but shallow tunnel barrier. The sample design allows the suppression of lateral transport effects, so the range of strong perpendicular magnetic fields becomes easily accessible (for more details, see Ref. 12).

III. RESULTS

Typical magnetocapacitance traces in the low temperature limit at different electron densities and tilt angles of the magnetic field as well as the temperature dependence of the magnetocapacitance are displayed in Fig. 1 near $\nu=1$ and 3. Narrow minima in the magnetocapacitance at integer filling factor are separated by broad maxima, the oscillation pattern reflecting the behavior of the thermodynamic density of states in quantizing magnetic fields. As the magnetic field is increased, the maximum $C(B)$ increases and approaches in the high-field limit the geometric capacitance C_0. We have verified that the obtained C_0 corresponds to the value calculated using Eq. (1) from the zero-field capacitance and the density of states $m/\pi\hbar^2$ (where $m=0.067m_e$ and m_e is the free electron mass). Note that the so-called negative compressibility effect manifests itself in our samples as a local maximum in $C(B)$ above C_0 that is observed in fields $B_\perp > 2$ T at the edge of the dip in the magnetocapacitance for

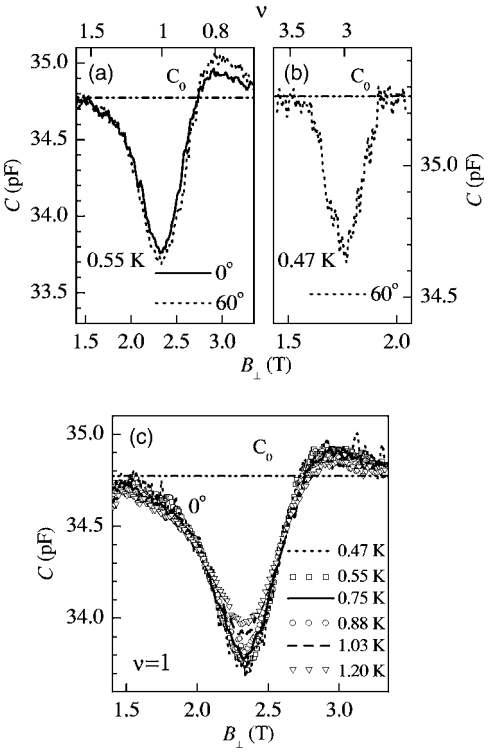

FIG. 1. Magnetocapacitance traces in the low-temperature limit at different tilt angles for $n_s=5.7\times10^{10}$ cm^{-2} (a) and $n_s=1.28\times10^{11}$ cm^{-2} (b) and the temperature dependence of the magnetocapacitance at $n_s=5.7\times10^{10}$ cm^{-2} (c). Also shown by a dash-dotted line is the geometric capacitance C_0.

$\nu=1$. Experimentally, it is easier to analyze $C(B)$ traces: being independent of $B_\perp$, the geometric capacitance C_0 practically does not depend on the parallel component of the magnetic field but increases with n_s as the 2D electrons are forced closer to the interface. As explained above, the chemical potential jump at integer $\nu=\nu_0$ is determined by the area of the dip in the magnetocapacitance:

$$\Delta = \frac{Ae^3\nu_0}{hcC_0}\int_{\text{dip}} \frac{C_0 - C}{C} dB_\perp, \tag{2}$$

where the integration over $B_\perp$ is equivalent to the one over n_s provided the minimum is narrow. The criterion of narrow minima is met in our experiment. Indeed, the formula (2) gives values of Δ that are underestimated approximately by $(\delta B/B)^2$, where $\delta B/B$ is the relative half-width of the nearly symmetric minimum. This contribution is less than 4% even in the lowest magnetic fields $B_\perp$ used in the experiment. More importantly, it does not depend on parallel component of the magnetic field [Fig. 1(a)] and, therefore, the data analysis made below is valid.

In magnetic fields $B_\perp \lesssim 2$ T, where the magnetocapacitance does not reach C_0, the value C_0 in the integrand of Eq. (2) is replaced by a step function C_{ref} that is defined by two reference levels corresponding to the C values at $\nu=\nu_0+1/2$ and $\nu=\nu_0-1/2$. The so-determined Δ is smaller than the level splitting by the level width whose contribution is obtained by substituting $(C_0-C_{\text{ref}})B_0^2/CB_\perp^2$ (where B_0

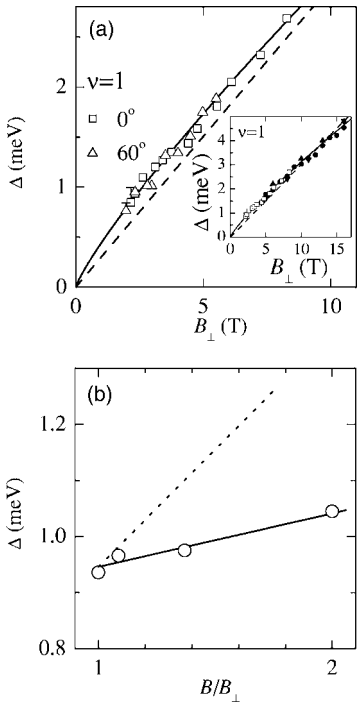

FIG. 2. (a) Chemical potential jump across the spin gap at $\nu=1$ as a function of perpendicular component of the magnetic field excluding the term that is responsible for the increase of the gap with parallel field. The level width contribution is indicated by systematic error bars; see text. The solid line is a power-law fit with exponent $\alpha \approx 0.85$, and the dashed line corresponds to $g=5.2$. The data in perpendicular magnetic fields are compared in the inset with those of Ref. 12 obtained on three-electrode samples (solid symbols). (b) Change of the $\nu=1$ spin gap with $B_\parallel$ at fixed $B_\perp=2.35$ T. The solid line corresponds to an effective g factor $g \approx 0.7$. The dashed line depicts the slope expected from Ref. 4.

$=hcn_s/e\nu_0$) for the integrand in Eq. (2) and integrating between the magnetic fields $B_1=hcn_s/e(\nu_0+1/2)$ and $B_2=hcn_s/e(\nu_0-1/2)$. It is clear that in the range of $B_\perp$ mentioned above, the accuracy of the measurement method becomes worse with decreasing $B_\perp$ due to increasing level broadening/overlap.

In Fig. 2(a), we show the chemical potential jump across the $\nu=1$ spin gap as a function of perpendicular component of the magnetic field. In the high-field limit the data are in good agreement with the results obtained on three-electrode samples [see the inset to Fig. 2(a)]. This indicates that the enhanced value of the gap is sample independent. As $B_\perp$ is decreased, the g factor $g=g_{\max}$ becomes yet more enhanced than its high-field value $g \approx 5.2$ (dashed line). This implies that in the weak-field region, the functional form of $\Delta(B_\perp)$ changes to a sublinear law. Particularly, the data for the gap can be described by a function $\Delta \propto B_\perp^\alpha$ with $\alpha \approx 0.85$ (solid line). Once the exponent α is close to unity, this sublinear fit is practically indistinguishable from the linear fit to the data in fields $B_\perp \gtrsim 5$ T.

In Fig. 2(b), we show the behavior of the spin gap at $\nu=1$ in a fixed field $B_\perp=2.35$ T as a function of parallel magnetic field. The gap increases linearly with total magnetic field B and is described by an effective g factor $g=g_{\min}$

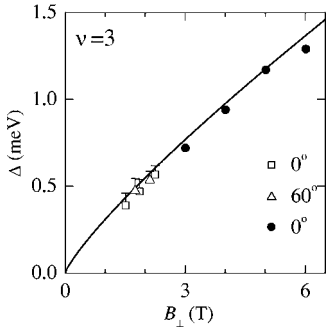

FIG. 3. The spin gap at $\nu=3$ vs. $B_\perp$ excluding the same term $g_{\min}\mu_B(B-B_\perp)$ as for the case of $\nu=1$ (open symbols) along with the data obtained on three-electrode samples (solid symbols). The level width contribution is shown by systematic error bars. The solid line is a power-law fit with exponent $\alpha \approx 0.85$.

≈ 0.7. Note that this value is considerably smaller than the effective g factor $g \approx 3.1$ [the dashed line in Fig. 2(b)] obtained by transport measurements on very similar samples in the same range of magnetic fields.[4] Moreover, the determined $g_{\min} \approx 0.7$ is confirmed by the data of Fig. 2(a), where we compare the results for the $\nu=1$ spin gap in perpendicular and tilted magnetic fields excluding the term $g_{\min}\mu_B(B-B_\perp)$ that describes the increase of the spin gap with $B_\parallel$. The data coincidence indicates that the value $g_{\min}$ does not practically change in the range of fields $B_\perp$ (or electron densities) studied. That stands to reason that due to weak dependence of the gap on parallel magnetic field, the accuracy of the method for determining $g_{\min}$ is not high (50% at worst for our case). Nevertheless, this is not crucial for our results and conclusions.

The chemical potential jump across the $\nu=3$ spin gap versus perpendicular component of the magnetic field is displayed in Fig. 3. The gap can also be described by a power-law dependence $B_\perp^\alpha$ with $\alpha \approx 0.85$, although its value is about 30% smaller than that at $\nu=1$. The same term $g_{\min}\mu_B(B-B_\perp)$ as for the case of $\nu=1$ has been subtracted from the value of the gap in tilted magnetic fields. As inferred from the coincidence of the data in perpendicular and tilted magnetic fields, there is no pronounced dependence of $g_{\min}$ on filling factor.

IV. DISCUSSION

It is tempting to compare the obtained $g_{\min} \approx 0.7$ with the "noninteracting" value $|g| \approx 0.44$, which is determined in spin resonance measurement,[14] as dictated by Kohn's theorem analog. However, for magnetotransport and magnetocapacitance experiments, it is the interaction-enhanced values of g that are relevant. Recently, it has been established in studies of weak-field Shubnikov–de Haas oscillations and parallel-field magnetotransport[15] that at low electron densities, the g factor is enhanced well above its value $|g|=0.44$ in bulk GaAs, being renormalized by electron-electron interactions. The g factor $g=g_{\min}$ determined in our experiment turns out to be concurrent with the interaction-renormalized g factor ($g=0.7$ at electron density 4×10^{10} cm^{-2}) obtained

in Ref. 15. We therefore arrive at a conclusion that the lowest-lying charged excitations are accompanied with a single spin flip at $\nu=1$ and 3.

While the results of indirect transport studies of the spin gap in the 2D electron system in GaAs have been interpreted as evidence for skyrmions,[4] our direct measurements of the spin gap in very similar samples question such an interpretation. The obtained experimental results do not support formation of the skyrmions in the range of magnetic fields studied, down to $B_\perp \approx 2$ T. As a matter of fact, the change of the spin gap with parallel magnetic field is consistent with the concept of exchange-enhanced gaps which includes single spin-flip excitations, the Zeeman energy contribution being determined by the interaction-renormalized g factor. Therefore, evidence for skyrmions should be sought in the region of yet lower Zeeman energies, using direct experimental methods.

We now discuss briefly the Landau level mixing as a possible candidate to explain the experimental dependence of the spin gap on perpendicular magnetic field. The gap enhancement is determined by the exchange energy estimated as $e^2/\kappa l$ (where l is the magnetic length), which yields a square-root magnetic field dependence of the gap if $g_{\max} \gg g_{\min}$. For our case the corrections to the exchange energy due to level overlap[16] are below 5% in magnetic fields $B_\perp$ about 2 T and, therefore, they cannot provide an appreciable increase of the power of the theoretical square-root dependence $\Delta(B_\perp)$.[12] We suggest that the Landau level mixing due to electron-electron interactions,[16–18] which gives rise to a more pronounced reduction of the gap in low magnetic fields, can be responsible for the observed dependence $\Delta(B_\perp)$.

Since mixing the Landau levels causes electron-hole symmetry breaking, its significance can easily be established in experiment. Evidence for the electron-hole symmetry breaking is given by the data for the magnetocapacitance which reveals the negative compressibility effect at $\nu=1$ (Fig. 1). This effect being linked to electron-electron interactions,[19,20] its asymmetry about $\nu=1$ should reflect the electron-hole asymmetry of many-body interactions in the lowest spin-split Landau level. As the magnetic field is increased, the experimental magnetocapacitance becomes more symmetric (see Fig. 4) and, hence, the electron-hole symmetry sets in. To this end, it is tempting to give such a qualitative account of the observed dependence of the spin gap on perpendicular magnetic field, at least, for the lowest filling factor. However, there exists a caveat that the exponent for $\Delta(B_\perp)$ can be expected to decrease with increasing magnetic field, which is not confirmed by the experimental data.

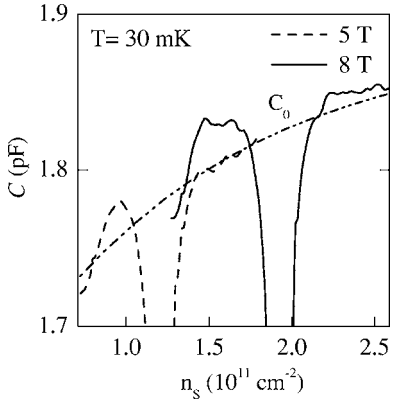

FIG. 4. Capacitance near $\nu=1$ as a function of electron density in three-electrode samples at different perpendicular magnetic fields. The geometric capacitance C_0 is indicated by the dash-dotted line.

V. CONCLUSION

In summary, we have performed measurements of the chemical potential jump across the $\nu=1$ and $\nu=3$ many-body enhanced spin gap in the 2D electron system of GaAs/AlGaAs single heterojunctions in weak magnetic fields. The increase of the gap with parallel magnetic field corresponds to a single spin flip for $\nu=1$ and 3 in the range of magnetic fields studied, down to $B_\perp \approx 2$ T. This finding is in disagreement with the concept of skyrmions and shows that evidence for skyrmions should be sought in the region of yet lower Zeeman energies and that results of indirect studies of the spin gap should be treated with care.

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