Direct Measurements of the Spin Gap in the Two-Dimensional Electron Gas of AlGaAs-GaAs Heterojunctions

V. T. Dolgopolov, A. A. Shashkin, and A. V. Aristov
Institute of Solid State Physics, Chernogolovka, 142432 Moscow District, Russia

D. Schmerek and W. Hansen
Institut für Angewandte Physik, Universität Hamburg, Jungiusstrasse 11, D-20355 Hamburg, Germany

J. P. Kotthaus
Ludwig-Maximilians-Universität, Geschwister-Scholl-Platz 1, D-80539 München, Germany

M. Holland
Department of Electronics and Electrical Engineering, University of Glasgow, Glasgow G12 8QQ, United Kingdom
(Received 24 February 1997)

Using magnetocapacitance data, we directly determine the chemical potential jump at low temperatures of about 25 mK when the filling factor traverses the spin gap at $\nu = 1$ and the cyclotron gap at $\nu = 2$. The chemical potential jump for the cyclotron gap is found to increase proportionally to the magnetic field with a slope that is determined by an effective mass $0.071m_0$. The data yield a spin gap that also increases *proportionally* with magnetic field and is described by an enhanced Landé factor $g \approx 5.2$. This result has not been explained by existing theoretical models. [S0031-9007(97)03709-5]

PACS numbers: 73.40.Kp, 73.20.Dx

It is well known from early magnetotransport studies of Ref. [1] that in a two-dimensional electron system (2DES) the spin gap is much larger than the single-particle Zeeman energy. The strong enhancement of the gap has been associated with electron-electron interaction effects [2–4] and is often described in terms of an effective "exchange-enhanced" Landé factor. In GaAs effective Landé factors are found that are roughly an order of magnitude larger than the bulk value $|g| = 0.44$. According to the conventional theory [2], the effective Landé factor g should depend on the magnetic field as $g \propto B^{-1/2}$. Following this model Smith *et al.* [5] indeed described relatively low-magnetic-field data from Ref. [6], making allowance for considerable overlap of the Landau levels and the finite thickness of the 2DES.

More recently it has been shown that taking account of spin-spin correlations gives rise to a reduction of the spin gap that arises from formation of so-called Skyrmions [7,8]—large distortions of the spin field including many flipped spins. These are expected to be important as long as the Zeeman energy is small compared to the Coulomb exchange energy, i.e., in the weak-magnetic-field limit. The Skyrmion concept has been tested using different experimental techniques like NMR and transport measurements in tilted magnetic fields and under pressure [9–11]. Still, the information about the spin gap, which largely comes from activation energy measurements in odd-integer quantum Hall states, remains restricted and controversial (e.g., [6,10,11]). As a matter of fact, results of such experiments should be treated with care because they yield a "mobility gap" which can, owing to disorder, be very different from the gap in the spectrum. Thus, for determining gaps in the spectrum more direct experimental methods are desirable.

In the present paper we directly measure the spin gap in a 2DES by a capacitance technique on samples with field electrodes for controlling the electron density. The energy gap is deduced from the gate voltage dependence of the electron density in the 2DES. Up to a magnetic field of 16 T we find that the spin gap value is *proportional* to the magnetic field with good accuracy and corresponds to $g \approx 5.2$. This result cannot be explained by either the model of exchange-enhanced g factor or the Skyrmion theory.

We use AlGaAs-GaAs single-heterojunction samples with a metallic gate on the crystal surface that contain a highly doped (4×10^{18} cm^{-3} Si) layer with thickness 200 Å in the bulk of GaAs. This layer remains well conducting even at very low temperatures and serves as a back electrode. The inset of Fig. 1 displays a sketch of the bottom of the conduction band in our structure at a positive bias V_g applied to the front gate with respect to the back contact. The 2DES is field-effect induced in a way that is similar to Si metal-oxide-semiconductor field-effect transistors (MOSFET's). A blocking barrier between the gate and the 2DES is formed by a short-period GaAs-AlAs superlattice capped by a thin GaAs layer; this barrier is checked to be not transparent for electrons over the range of V_g used in the experiment. A wide but shallow tunnel barrier between the back electrode and the 2DES is created by the weak residual p doping of the GaAs layer. Electron transfer across this tunnel barrier establishes equilibrium between back contact and 2DES.

0031-9007/97/79(4)/729(4)$10.00

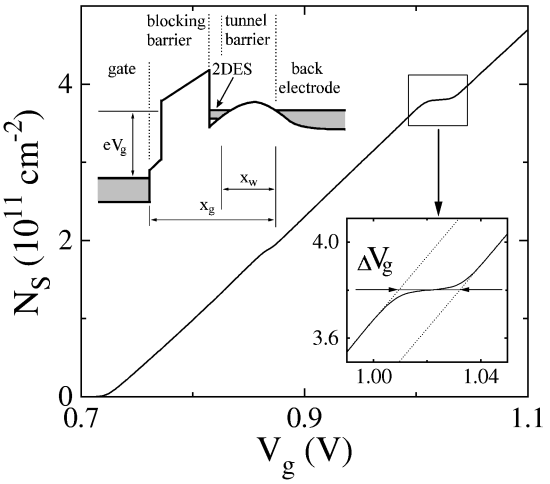

FIG. 1. Electron density in the 2DES as a function of gate voltage in a magnetic field $B = 8$ T. A blowup of the $\nu = 2$ plateau region shows the way to determine the plateau width. A sketch of the band diagram of the device is displayed in the inset.

The experimental method employed here to determine the spin gap is based on the measurements of the electron density N_s of a 2DES in a quantizing magnetic field as a function of gate voltage. In Fig. 1, we depict corresponding data that are determined from our capacitance measurements as described below. At gate voltages $V_g = 0.87$ V and $V_g = 1.02$ V plateaulike structures are discernible that reflect the reduced density of states in the spin and cyclotron gaps, respectively: when the Fermi level μ lies in a gap of the energy spectrum, the 2DES does not screen an incremental electric field so that a plateau arises in the dependence $N_s(V_g)$. The plateau width is obtained by linear extrapolation of the density dependence as shown in the second inset of Fig. 1. If the density of states in the center of the Landau levels is sufficiently high, the extrapolated straight lines to a good approximation reflect the geometrical capacitance given by the distance between the front gate and the 2DES. If the back contact and the 2DES remain in equilibrium, the plateau width directly reflects the jump of the chemical potential between the centers of adjacent Landau levels,

$$\Delta V_g = \frac{x_g}{x_w}\,\frac{\Delta\mu}{e}\,, \tag{1}$$

where the quantities x_g, x_w are shown in the inset of Fig. 1.

From simple electrostatic considerations it follows [12,13]

$$dN_s = dV_g\,\frac{x_g}{x_w}\,\frac{C_{\rm low} - C_{\rm high}}{Ae}\,, \tag{2}$$

where $C_{\rm low}$ and $C_{\rm high} = \kappa A/x_g$ are low and high frequency limits of the device capacitance as measured between the back electrode and the gate, and A is the sample area. The dimensions x_g and x_w are determined by the spatial electron charge distributions in the 2DES and the back electrode. In particular, they are not identical to the growth parameters of the epitaxial layers. Therefore, we determine x_g and x_w from calibration experiments as described below. Once the values of x_g and x_w are known the dependence $N_s(V_g)$ is calculated from the measured capacitance $C_{\rm low}(V_g)$ by integrating Eq. (2) [14].

The capacitance $C_{\rm high}(V_g)$ is determined from a fit of the frequency dependence of the real and imaginary current components at filling factor $\nu \approx 1$ [12,13] for a number of magnetic fields from 7 to 16 T [15]. The obtained points including the values of the capacitance at V_g below the threshold voltage for the generation of the 2DES are interpolated well by a straight line [13]. The other calibration is made in a similar way to that used in Ref. [14]. The gate voltage dependence of x_w is obtained from the magnetocapacitance oscillations at a low magnetic field of $\sim$1 T. Assuming that x_w does not change rapidly over the gate voltage region ΔV_{LL} in which one Landau level is filled, we deduce x_w from the integral form of the relation (2).

We have performed measurements on three different samples with the gate areas 9200 μm^2 for one of them and 870 μm^2 for the others. We work in the frequency range 100 Hz to 10 kHz at magnetic fields up to 16 T and temperatures $\gtrsim$25 mK. The amplitude of the ac modulation of V_g does not exceed 1 mV and corresponds to the linear regime of response. To measure the ac current through the sample we employ a standard lock-in technique with a self-made low-noise I-V converter. The results obtained on all samples are similar.

Typical experimental dependences $N_s(V_g)$ are presented in Figs. 1 and 2. Up to 1 K all the experimental data have been checked to be temperature independent.

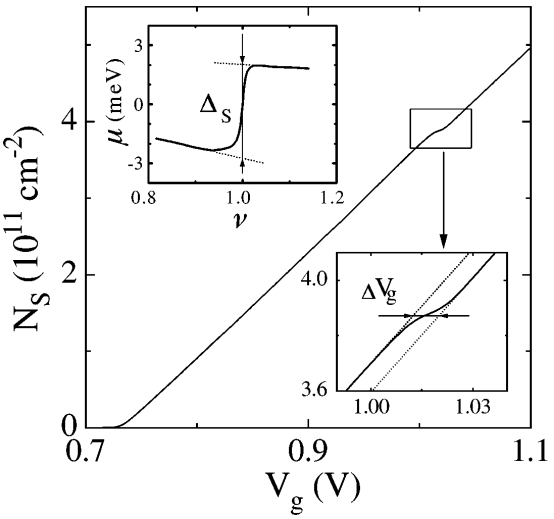

FIG. 2. Dependence of the electron density on gate voltage at $B = 16$ T. The plateau region for $\nu = 1$ is blown up. The inset shows the corresponding chemical potential jump calculated from the thermodynamic density of states.

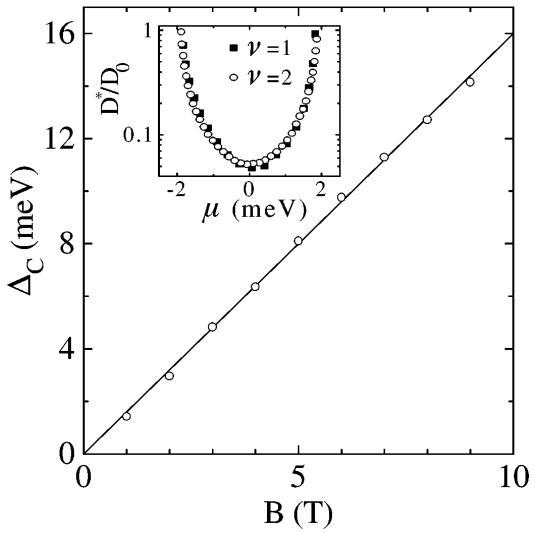

FIG. 3. Change of the cyclotron gap at $\nu = 2$ with magnetic field. The behaviors of the thermodynamic density of states in the spin gap at $B = 16$ T and cyclotron gap at $B = 3$ T are compared in the inset.

Deviation of the N_s value in the middle of the plateau at integer filling factor from the calculated degeneracy of the Landau levels reflects the calibration procedure accuracy. The chemical potential jumps presented in Figs. 3 and 4 are determined by means of Eq. (1) from the plateau widths in $N_s(V_g)$ data such as those in Figs. 1 and 2.

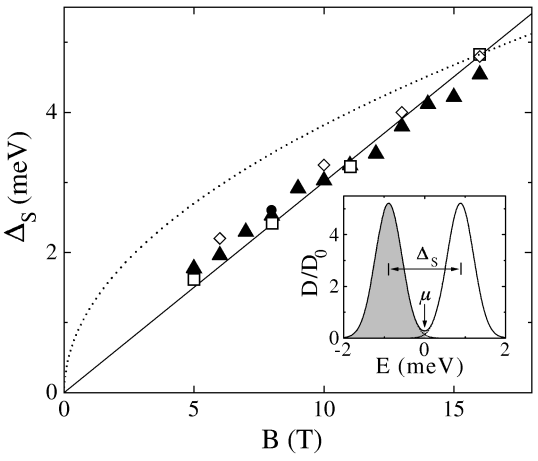

FIG. 4. Behavior of the spin gap at $\nu = 1$ with changing magnetic field. The values of spin gap are obtained from the plateau width (triangles), the conversion of the thermodynamic density of states (diamonds), and the comparison of the thermodynamic densities of states in the cyclotron and spin gaps (squares). Also shown is the spin gap value (dot) taken from optical studies [18]. The solid line corresponds to the effective Landé factor $g \approx 5.2$. The dotted line is a square-root dependence drawn for comparison through the maximum-field point, which is expected from a simple theory, ignoring a numerical factor. The inset displays the profile of the density of states for the spin sublevels at $\nu = 1$ in a magnetic field of 5 T.

In Fig. 3 the chemical potential jump for the cyclotron gap at $\nu = 2$ is depicted as a function of magnetic field. This linear dependence corresponds, taking account of the Zeeman splitting, to the effective mass value of $0.071m_0$ (m_0 is the free electron mass) which is close to the value of $0.070m_0$ found in cyclotron resonance studies on similar samples [16]. Assuming that the deviation of the data from the straight line in Fig. 3 is due to experimental uncertainty, we can evaluate the accuracy with which we determine the spin gap as presented below. In the range of chemical potential jumps from 1.7 to 14 meV our procedure provides better than 10% accuracy in determining gaps in the spectrum.

Figure 4 shows the behavior of the spin gap with changing magnetic field. The range of magnetic fields used is chosen so that the spin gap values fall within the above indicated energy interval. To our surprise, the data are best described by a *proportional* increase of the spin gap with magnetic field.

In Fig. 4 we compare the data derived with the help of the above-described procedure with results of two alternative methods for the determination of the chemical potential jump at filling factor $\nu = 1$. In the first method, that, e.g., has been applied in Ref. [14], we extract from the experimental data the dependence of the thermodynamic density of states on electron density [13] and then calculate the chemical potential as a function of filling factor. The corresponding result for $B = 16$ T is displayed in the inset of Fig. 2. Linear extrapolation of the dependence $\mu(\nu)$ at $\nu < 1$ and $\nu > 1$ as shown in the inset of Fig. 2 defines a jump of the chemical potential. We note that this method is less accurate. First, it requires for extrapolation a larger interval of filling factors. Second, the jump $\Delta\mu$ is much more sensitive to the value of x_g and, third, the actual extrapolation law is unknown [17]. In the second method we use an empirical procedure to determine the spin gap. Here the thermodynamic density of states $D^*(\mu)$ at $\nu \approx 1$ is compared to the one at $\nu \approx 2$ in different magnetic fields. If the fields are chosen so that the gaps are equal, the dependences $D^*(\mu)$ can be expected to coincide. An example is given in the inset of Fig. 3. As seen from Fig. 4, the data points obtained with the help of all three methods are close to a straight line corresponding to the constant Landé factor $g \approx 5.2$. Within experimental uncertainty this behavior cannot be described by a square-root dependence as indicated by the dashed line in Fig. 4.

The observed linear dependence of the spin gap on magnetic field is very similar to that found in activation energy studies [6]. According to Ref. [6], the activation energy for $\nu = 1$ changes approximately linearly with magnetic field over the range 1.2 to 8 T. The corresponding g factor is about 7, which is appreciably larger as compared to the value observed here. The difference is likely to be due to particularities of the activation energy

method because also at $\nu = 2$ the measured gap exceeds the cyclotron splitting $\hbar\omega_C$ by 40%. Since, in theory, the gap values obtained by the activation technique may, because of disorder, be only smaller than gaps in the spectrum, the actual origin of the discrepancy remains to be seen. We note that optical investigations yield values of the spin gap at filling factor $\nu = 1$ and of the cyclotron gap at $\nu = 2, 4$ (see Figs. 38–40 from Ref. [18]), which are consistent with our data (Fig. 4).

A simple estimate of the Coulomb exchange energy $e^2/\kappa l$ (l is the magnetic length) gives values that are about an order of magnitude larger than the experimentally determined spin gaps. Two physical mechanisms may lead to decreasing exchange energy: nonzero thickness of the 2DES and the disorder broadening of quantum levels. With the 2DES thickness and the level width as adjustable parameters, Smith *et al.* [5] succeed in describing the magnetic-field dependence of the spin gap found in Ref. [6]. In our case, knowing the density of states we easily find the width and overlap of quantum levels [13]. The behavior of the density of states $D(E)$ at $\nu = 1$ for the lowest magnetic field used is shown in the inset of Fig. 4. One can see that the corrections to the exchange energy due to level overlap do not exceed 1% at $B \geq 5$ T. As far as the finite thickness of the 2DES is concerned, it gives rise to a considerable decrease in the exchange energy at high magnetic fields, while in the low-field limit its effect is negligible. Hence, this mechanism alone fails to provide an increase of the power of the theoretical square-root dependence $\Delta_S(B)$ [19]. Obviously, the approach [5] does not explain our experimental data at strong magnetic fields.

According to a recent model [7,8], Skyrmion-caused modification of the excitation spectrum at odd-integer fillings results in a stronger change of Δ_S with magnetic field in the region of competition between the Zeeman and Coulomb energies. Measurements of the activation energy in tilted magnetic fields [10] indicate that the change of the spin gap attributed to Skyrmion effects is smaller than 10% if $g\mu_B B/(e^2/\kappa l) \geq 0.015$. Using this condition we estimate that in our experiment the Skyrmion effects can be neglected at $B \geq 5$ T.

In our opinion, the theory failure to explain the obtained experimental data is caused by the fact that the many-particle phenomena should be very sensitive to correlations of a disorder potential which is present in real systems. Thus, more theoretical work is needed taking into account disorder effects.

We are thankful to Dr. A. Wixforth, Dr. A. Lorke, and Dr. A. O. Govorov for fruitful discussions of the results. This work was supported in part by Volkswagen-Stiftung under Grant No. I/71162 and by the Programme "Nanostructures" from the Russian Ministry of Sciences. D. Sch. gratefully acknowledges support of the Graduiertenkolleg "Physik nanostrukturierter Festkörper" der Deutschen Forschungsgemeinschaft.

[1] F. F. Fang and P. J. Stiles, Phys. Rev. **174**, 823 (1968).
[2] T. Ando and Y. Uemura, J. Phys. Soc. Jpn. **37**, 1044 (1974).
[3] Yu. A. Bychkov, S. V. Iordanskii, and G. M. Eliashberg, JETP Lett. **33**, 143 (1981).
[4] C. Kallin and B. I. Halperin, Phys. Rev. B **30**, 5655 (1984).
[5] A. P. Smith, A. H. MacDonald, and G. Gumbs, Phys. Rev. B **45**, 8829 (1992).
[6] A. Usher, R. J. Nicholas, J. J. Harris, and C. T. Foxon, Phys. Rev. B **41**, 1129 (1990).
[7] S. L. Sondhi, A. Karlhede, S. A. Kivelson, and E. H. Rezayi, Phys. Rev. B **47**, 16 419 (1993).
[8] H. A. Fertig, L. Brey, R. Cote, and A. H. MacDonald, Phys. Rev. B **50**, 11 018 (1994).
[9] S. E. Barret, G. Dabbagh, L. N. Pfeiffer, K. W. West, and R. Tycko, Phys. Rev. Lett. **74**, 5112 (1995).
[10] A. Schmeller, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **75**, 4290 (1995).
[11] D. K. Maude, M. Potemski, J. C. Portal, M. Henini, L. Eaves, G. Hill, and M. A. Pate, Phys. Rev. Lett. **77**, 4604 (1996).
[12] R. C. Ashoori and R. H. Silsbee, Solid State Commun. **81**, 821 (1992); R. C. Ashoori, Ph.D. thesis, Cornell University, New York, 1992.
[13] V. T. Dolgopolov, A. A. Shashkin, A. V. Aristov, D. Schmerek, H. Drexler, W. Hansen, J. P. Kotthaus, and M. Holland, Phys. Low-Dimens. Semicond. Struct. **6**, 1 (1996).
[14] J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **50**, 1760 (1994).
[15] The real current component should vanish in both the low and high frequency limits. While the former is realized in the experiment, the latter is nearly reached within our frequency range as the ratio of the real and imaginary current components at the highest frequencies does not exceed 10% in fields 7 to 16 T.
[16] H. Drexler, W. Hansen, J. P. Kotthaus, M. Holland, and S. P. Beaumont, Semicond. Sci. Technol. **7**, 1008 (1992).
[17] To solve a similar problem with the chemical potential jump at fractional filling factors an additional fitting parameter (the width of Gaussian density distribution) was introduced in Ref. [14].
[18] I. V. Kukushkin and V. B. Timofeev, Adv. Phys. **45**, 147 (1996).
[19] With increasing N_s the absolute value of the bulk g factor decreases due to the modified penetration of the wave function into the blocking barrier [20]. We estimate that in our samples the bulk g factor changes from -0.42 to -0.39 in fields 5 to 16 T. The corresponding correction gives rise to a larger deviation of the theoretical dependence $\Delta_S(B)$ from the experimental one.
[20] E. L. Ivchenko and A. A. Kiselev, Sov. Phys. Semicond. **26**, 827 (1992).