Chemical potential and *g*-factor of a 2D electron gas in a strong magnetic field

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A comparison of measurements of the oscillations of the chemical potential and of the magnetoresistance of a GaAs-$Al_xGa_{1-x}As$ heterojunction in strong magnetic fields yields the value of the effective *g*-factor of the 2D electron gas.

Raymond *et al.*[1] have reported observing a giant spin splitting of the Landau levels of a 2D electron gas in a GaAs-$Al_{0.3}Ga_{0.7}As$ heterojunction in strong magnetic fields (the effective *g*-factor ranged up to 20). That conclusion was based on an analysis of the results of measurements of the oscillations in the magnetoresistance ρ_{xx}

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under the assumption that at a constant electron density N_s the values $H_n^{\pm}$ of the magnetic field at which the chemical potential μ intersects the spin-split Landau sublevels $\varepsilon_n^{\pm}$ (and at which maxima are observed in ρ_{xx}) are determined by the condition $\mu(H_n^{\pm}) = \mu(0)$.

Our own measurements of the behavior of the chemical potential $\mu(H)$ and the magnetoresistance $\rho_{xx}(H)$ of the 2D electron gas at a GaAs-Al$_x$Ga$_{1-x}$As heterojunction do not confirm that suggestion. They yield a considerably smaller effective g-factor ($\lesssim 3.5$–4).

The method by which the oscillations in the chemical potential are measured is based on a determination of the change in the charge on a measurement capacitor consisting of the test sample and a bronze electrode.[2] The construction of the instrument was similar to that described in Ref. 3. To reduce the noise, we placed the measurement capacitor and the coaxial cable leading to the electrometer in a hermetically sealed-stainless tube filled with gaseous helium ($p \approx 200$ Torr at $T = 300$ K). The sample was a plate with dimensions of 6×8.5 mm, with current-carrying and potential leads soldered to the corners for the magnetoresistance measurements. The carrier mobility was 41×10^3 cm^2/(V·s), and the carrier density was found from the period of the oscillations in the magnetoresistance to be $N_s = 3.22 \times 10^{11}$ cm^{-2}. Most of the measurements were carried out at a temperature $T = 1.45$ K in magnetic fields up to 150 kOe, produced by a superconducting solenoid. In the field range 150–180 kOe, the magnetoresistance was recorded in a water-cooled Bitter magnet. All the measurements were carried out at the International Laboratory of Strong Magnetic Fields and Low Temperatures (Wroclaw, Polish People's Republic).

The results of the measurements of the oscillations in the chemical potential are shown at the top in Fig. 1. The sloping solid lines labeled $n = 0,1,...$ show the Landau levels $\epsilon_n = (n + 1/2)\hbar\omega_c$ calculated for[4] $m^* = 0.0675 m_0$. Since only the increment in the chemical potential, $\Delta\mu(H)$, was recorded in these experiments, the position of the measurements along the energy scale was chosen from the condition $\mu(H \to 0) = \pi\hbar^2 N_s/m^*$ [this value of $\mu(0)$ is shown by the dotted line].

A recording of the oscillations in the magnetoresistance $\rho_{xx}(H)$ is shown at the bottom in Fig. 1. We see that there is a large spin splitting of Landau levels $n = 0$ and 1, while the splitting of the $n = 2$ level is very slight (leading to merely a broadening of the corresponding ρ_{xx} maximum), and there is essentially no splitting at all for levels $n \geqslant 3$. A comparison of the $\rho_{xx}(H)$ and $\mu(H)$ curves shows that while the positions of the $\rho_{xx}(H_n)$ maxima at $n \geqslant 2$ correspond to the condition $\mu(H_n) = \mu(0)$, this condition clearly does not hold for the spin-split Landau levels $n = 0$ and 1. The behavior $\mu(H)$ in fields above 30 kOe differs markedly from that proposed in Ref. 1. The difference, however, is a consequence not of a violation of the condition $N_s = \text{const}$ but of the circumstance that the condition $\mu(H_n^{\pm}) = \mu(0)$ does not hold at all. Specifically, if the spin-split Landau sublevels $n^{\pm}$ do not overlap, the maximum of $\rho_{xx}(H_n^{\pm})$ should be observed when the corresponding Landau sublevel is half-filled. Since each sublevel holds eH/ch electrons, this condition gives us $H_n^{\pm} = chN_s/e(2n + 1 \pm 1/2)$. The values of $H_n^{\pm}$ calculated for $n = 0$ and 1 are shown in the lower part of Fig. 1 by the vertical bars. Their positions agree well with

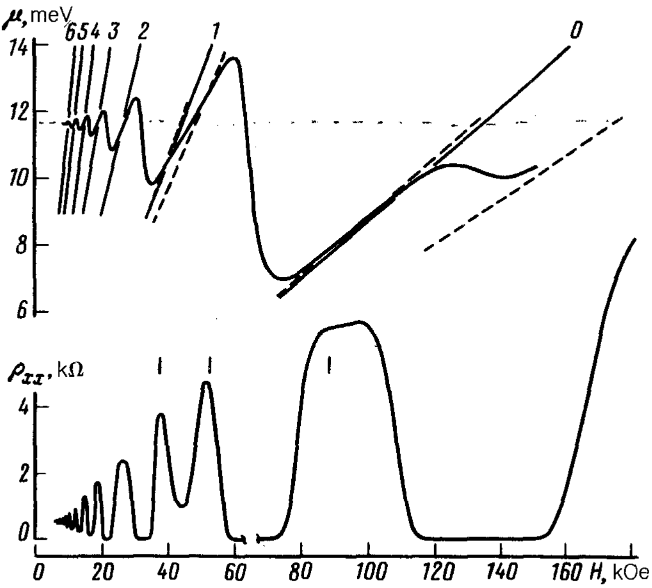

FIG. 1. The chemical potential (upper curve) and the magnetoresistance (lower curve) of the 2D electron gas at a GaAs-Al$_x$Ga$_{1-x}$As heterojunction versus the magnetic field at $T = 1.45$ K. To the right of the break in the $\rho_{xx}(H)$ curve, the sensitivity has been reduced by a factor of two.

the measured maxima of $\rho_{xx}(H)$; there are some slight shifts, apparently because of a slight overlap of neighboring Landau sublevels. If, on the other hand, the spin splitting is considerably smaller than the width of a Landau level, then the maximum of $\rho_{xx}(H_n)$ should be observed when an odd number of sublevels are filled, i.e., in the case $H_n = chN_s/e(2n+1)$. This condition is equivalent to the condition $\mu(H_n) = \mu(0)$.

The magnitude of the spin splitting thus cannot be determined on the sole basis of the $\rho_{xx}(H)$ dependence. We also need to know the $\mu(H)$ dependence. The dashed lines in the upper part of Fig. 1 show the Landau sublevels $0^{\pm}$ and $1^{\pm}$ determined from a comparison of the $\mu(H)$ and $\rho_{xx}(H)$ dependences. We see that the sublevels are positioned asymmetrically with respect to the original Landau level: The shift of the upper sublevel is considerably smaller than that of the lower sublevel. For the upper sublevel, the effective g-factor is $g \approx 0.5$–0.6, while for the lower sublevel it is $g \approx 3.5$–4. This asymmetry agrees qualitatively with the predictions of Refs. 5 and 6, which incorporate the exchange interaction in the 2D electron gas. In contrast with the results of Ref. 1, the experimental value of the g-factor does not exceed the theoretical estimate of its maximum possible value (≈ 10).

We note in conclusion that in measuring the dependence $\mu(H)$ we observed hysteresis effects in the magnetic-field regions corresponding to $\rho_{xx}(H) = 0$. These effects were similar to those which have been observed in inversion layers at a silicon surface.[7] The hysteresis increased so rapidly with decreasing temperature that at $T = 1.45$ K we were forced to carry out the measurements of $\mu(H)$ in these regions point by point, periodically turning off the field sweep. In contrast with Ref. 7, we observed nothing in the way of a significant decrease in the capacitance of the measurement capacitor in these regions. The reason for the hysteresis is a Hall effect involving weakly damped eddy currents induced in the 2D electron gas upon a change in the magnetic field.

[1] A. Raymond, J. L. Robert, C. Bousquet *et al.*, Solid State Commun. **55**, 271 (1985).

[2] V. I. Nizhankovskiĭ, V. G. Mokerov, B. K. Medvedev, and Yu. V. Shaldin, Zh. Eksp. Teor. Fiz. **90**, 1326 (1986) [Sov. Phys. JETP **63**, 776 (1986)].

[3] N. E. Alekseevskiĭ and V. I. Nizhankovskiĭ, Zh. Eksp. Teor. Fiz. **88**, 1771 (1985) [Sov. Phys. JETP **61**, 1051 (1985)].

[4] K. Muro, S. Mori, S. Narita *et al.*, Surf. Sci. **142**, 394 (1984).

[5] T. Ando and Y. Uemura, J. Phys. Soc. Jpn. **37**, 1044 (1974).

[6] Y. Uemura, J. Appl. Phys. Sup. 2, Part 2, 17 (1974).

[7] V. M. Pudalov, S. G. Semenchinsky, and V. S. Edelman, Solid State Commun. **51**, 713 (1984).

[8] R. K. Goodall, R. J. Higgins, and J. P. Harrang, Phys. Rev. **B31**, 6597 (1985).

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