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Electron-spin resonance in the two-dimensional electron gas of GaAs-$Al_xGa_{1-x}As$ heterostructures

M. Dobers and K. v. Klitzing
Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, Postfach 80 06 65, D-7000 Stuttgart 80, Federal Republic of Germany

G. Weimann
Forschungsinstitut der Deutschen Bundespost beim Fernmeldetechnischen Zentralamt, Postfach 5000, D-6100 Darmstadt, Federal Republic of Germany

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Electron-spin resonance affects the magnetoresistivity of GaAs-$Al_xGa_{1-x}As$ heterostructures. With microwave frequencies of up to 70 GHz we studied systematically the spin splitting of the Landau levels in magnetic fields up to 14.5 T. The resonances within a certain Landau level are only observed at magnetic field values where the Fermi level is located between the corresponding spin levels. The spin splitting of a Landau level is an exact quadratic function of the magnetic field and its extrapolation to zero magnetic field leads to vanishing spin splitting. The g factors depend on the magnetic field and the Landau level index as follows: $g(B,N)=g_0-c(N+\frac{1}{2})B$, where g_0 and c are sample-dependent constants.

I. INTRODUCTION

The properties of a two-dimensional electron gas (2D EG) are of particular interest, especially in the case of an applied magnetic field perpendicular to the plane of the 2D EG, when the energy spectrum of the electrons is totally quantized.[1] Already without magnetic field the motion of the electrons perpendicular to the 2D EG is quantized into the so-called electric subbands. With an applied magnetic field every electric subband splits into a series of Landau levels, which again split into two energy levels with opposite spins, so that the energy dispersion of the lowest subband of a 2D EG in a perpendicular magnetic field in a one-valley system is (see also Fig. 3)

$$E_{N\pm}=E_0+(N+\tfrac{1}{2})\frac{\hbar e}{m^*}B\pm\tfrac{1}{2}g\mu_B B \ , \qquad (1)$$

where E_0 denotes the energy of the lowest electric subband, N the Landau level index ($N=0,1,2,\ldots$), μ_B the Bohr magneton, and B the magnetic field. The plus and minus signs refer to spin up and spin down, respectively. The two band-structure parameters in this energy dispersion are m^* and g, the effective mass and the g factor, respectively.

For the investigation of the effective mass, cyclotron resonance is a widely used method.[2] On the contrary, electric-spin resonance (ESR), situated in the millimeter- and centimeter-wave region, has up to now been neglected because of the experimental difficulties. Nobody has been able to apply conventional ESR techniques to two-dimensional conduction electrons. In fact, however, the magnetoresistivity is affected by ESR. This indirect method uses the heterostructure itself as a detector for ESR and is often sensitive enough to study systematically the magnetic field dependence of the g factor in the different Landau levels.

Another experimental approach to the spin splitting of the Landau levels is the analysis of the magnetoquantum oscillations.[3,4] However, these transport measurements are strongly influenced by many-electron interaction and the resulting g factors can be strongly enhanced by exchange interaction.[5] The only methods to determine the bare g factors based on the one-electron energy levels are resonant optical experiments,[6] about which we want to report.

II. EXPERIMENTS

Out of a variety of different samples showing principly the same results we take two as examples. Sample 1, a normal heterostructure, consists of 4 μm of undoped GaAs on top of a semi-insulating GaAs substrate, a spacer of 33 nm of $Al_{0.35}Ga_{0.65}As$, 33 nm of Si-doped $Al_{0.35}Ga_{0.65}As$, and 25 nm of GaAs. Sample 2, a single side doped quantum well, consists of 4 μm of undoped GaAs on top of a semi-insulating GaAs substrate, a superlattice of 6×10.4 nm $Al_{0.35}Ga_{0.65}As$, and 5×3.4 nm GaAs, 15 nm GaAs, a spacer of 15.5 nm of $Al_{0.35}Ga_{0.65}As$, 39 nm of Si-doped $Al_{0.35}Ga_{0.65}As$, and 25 nm of undoped GaAs.

The two-dimensional carrier densities are $N_s=2.3\times10^{11}$ cm^{-2} (sample 1) and $N_s=3.3\times10^{11}$ cm^{-2} (sample 2), the mobilities are 1 000 000 cm^2/Vs (sample 1) and 300 000 cm^2/Vs (sample 2). The samples had standard Hall bar geometry, and were located inside an oversized waveguide in front of a movable short, immersed in liquid helium.

In magnetic fields perpendicular to the plane of the 2D EG the magnetoresistivity ρ_{xx} was measured by standard lock-in detection, typically utilizing frequencies of the order of 10 Hz. Changes of the sample resistivity due to the chopped microwave radiation (1 kHz) were detected using a second lock-in amplifier. In magnetic fields up to

14.5 T we used various microwave sources (klystrons and backward-wave oscillators) to cover the frequency range up to 70 GHz. The output power lay between a few mW and several hundred mW.

A typical trace of ρ_{xx} and its change with respect to microwave-radiation $\Delta\rho_{xx}$ is shown in Fig. 1. The solid line represents the change in ρ_{xx}, whereas ρ_{xx} itself is represented by the dashed line for comparison. $\Delta\rho_{xx}$ consists of a broad spectrum that reflects the periodicity of the Shubnikov–de Haas oscillations. A careful analysis shows that this spectrum is due to a nonresonant heating of the sample,[7–9] and it is related to the derivative of the magnetoresistivity with respect to the temperature. On top of this broad spectrum there is a sharp resonant structure, in this case at $B \approx 11.5$ T which is related to electron-spin resonance. The magnetic field position of this peak shifts with the microwave frequency. Doing a series of such experiments with different microwave frequencies one can analyze the magnetic-field dependence of the spin splitting of the Landau levels.

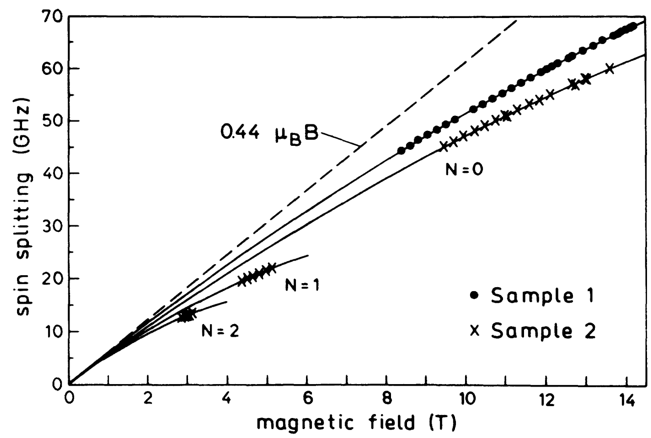

FIG. 2. Measured spin splittings of the lowest Landau level (sample 1) and the three lowest Landau levels (sample 2). The dashed line corresponds to the bulk-GaAs spin splitting $\Delta E = 0.44\mu_B B$. The solid lines are least-square fits to the experimental data (cf. text).

III. RESULTS AND DISCUSSION

The spin splittings of the two samples are given in Fig. 2. Because the electron-wave functions extend only slightly into the $Al_xGa_{1-x}As$, the measured spin splittings are compared to the bulk-GaAs spin splitting (dashed line) corresponding to the linear magnetic field dependence $\Delta E_{\rm bulk} = 0.44\mu_B B$. Due to the fact that the Fermi level lies only within a certain magnetic field range inside a particular Landau level, the measured splittings for each Landau level cover only a restricted magnetic-field window around odd filling factors $i = N_s h/(eB)$.

Nevertheless, distinct from former investigations[10] the measurements cover a rather broad magnetic-field range. Because of this one can clearly see that the spin splittings of the Landau levels in GaAs heterostructures do not vary linearly with respect to the magnetic field. The magnetic-field dependence is, on the contrary, exactly given by quadratic polynomials for each Landau level. The solid lines in Fig. 2 represent least-squares fits to three-parametric quadratic polynomials. For sample 1 the fit leads to the following analytic expression for the spin splitting in the lowest Landau level:

$$\Delta E = 0.3\ \text{GHz} + 0.42\mu_B B - (0.077\ \text{GHz})\frac{B^2}{1\ \text{T}^2}\ . \qquad (2)$$

The quadratic extrapolation to zero magnetic field leads to a vanishingly small spin splitting of the Landau level, which is within the scattering of the data equal to zero. In the case of sample 2 the experimental results in the lowest and the first Landau level show a similar quadratic magnetic field dependence. For the results in the $N=2$ Landau level one cannot determine this quadratic behavior unequivocally because in the small magnetic-field window there are only a few measured points. Nevertheless the whole data set of sample 2 shown in Fig. 1 including the measurements in the second Landau level can be described by the following analytic expression which in Fig. 2 is again represented by the solid lines:

$$\Delta E = 0.15\ \text{GHz} + 0.40\mu_B B - [0.165(N+\tfrac{1}{2})\ \text{GHz}]\frac{B^2}{1\ \text{T}^2}\ . \qquad (3)$$

The data can be described by a negligible zero-magnetic-field splitting and by a common linear term, both being independent of the Landau level. A dependence of the Landau level only arises from the quadratic term.

From our measurements we derive the following magnetic-field and Landau-level dependence of the g factor, defined by $g \equiv \Delta E/(\mu_B B)$:

$$g(B,N) = g_0 - c(N+\tfrac{1}{2})B\ , \qquad (4)$$

where g_0 and c are constants depending on the actual heterostructure.[11] From Eqs. (2) and (3) these can be calculated: $g_0 = 0.42$, $c = 0.0111\ \text{T}^{-1}$ for sample 1 and $g_0 = 0.40$, $c = 0.0115\ \text{T}^{-1}$ for sample 2.

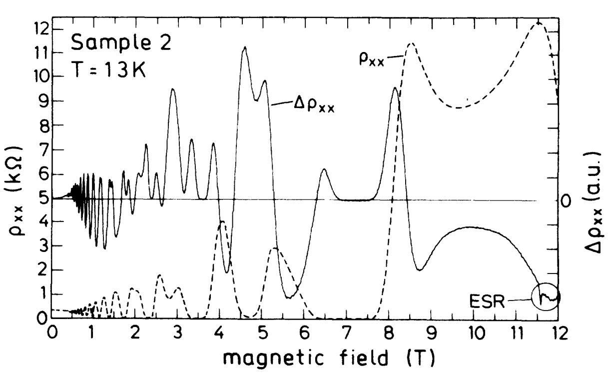

FIG. 1. Magnetoresistivity ρ_{xx} (dashed line) and its changes with respect to applied microwave radiation $\Delta\rho_{xx}$ (solid line). ESR occurs at $B \approx 11.5$ T.

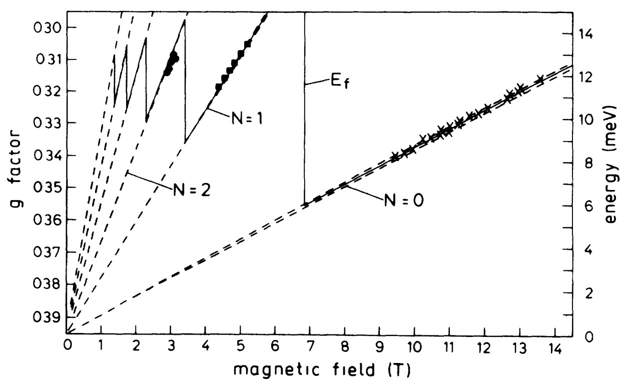

FIG. 3. g factors of sample 2 derived from the experimental data shown in Fig. 2 and the corresponding energy spectrum of the Landau levels with the Fermi level (dashed line) determined neglecting Landau-level broadening. For a better comparison the abscissa of the g factors is inverted.

The coefficient of the second term is the same as in the energy dispersion [Eq. (1)]. The spin splitting of a Landau level is thus determined by a g factor, which linearly decreases with increasing energy of the Landau level. The extrapolation of the Landau levels to zero magnetic field leads to the subband energy E_0; the corresponding extrapolation for the g factors of different Landau levels leads to g_0.

This proportionality is illustrated in Fig. 3, which shows the g factors of sample 2 derived from the results of Fig. 2. For a direct comparison these g factors are drawn with an inverted abscissa. Also depicted in Fig. 3 is the corresponding Landau-level fan chart including the Fermi energy, which is determined neglecting Landau-level broadening. The jumps of the Fermi energy resulting from the magnetic-field-dependent degeneracy of the Landau levels mark the ranges within which the spin splitting of a certain Landau level is measurable. One can clearly see that the g factor is a direct indication of the position of the Fermi level.

A complimentary analysis of transport experiments leads to enhanced g factors of up to 13 (Ref. 12) which is about thirty times bigger than in resonance experiments. This confirms the idea that the g-factor enhancement seen in transport experiments is due to many-electron interaction and does not affect the splitting of the Landau levels.

Theoretical considerations[13,14] have shown that the magnetic-field dependence of the g factors is in the case of GaAs-$Al_xGa_{1-x}As$ heterostructures mainly a consequence of the nonparabolicity of the GaAs conduction band. The good quantitative agreement of these calculations with our experimental results[13,14] shows again that the resonant experiments probe the one-electron energy levels and are not influenced by many-body interaction.

Contrary to the case of conventional ESR techniques one is not able to analyze the line shape of the resonance peaks because they are not pure absorption lines, but also reflect the conductivity mechanism, which is not understood in detail. The width of the resonant structure for all investigated samples is of the order of $\Delta B = 50$ mT, which yields a homogeneous width $\Gamma_{\rm ESR} = \frac{1}{2} g \mu_B \, \Delta B$ of the density of states of the spin levels of less than $\Gamma_{\rm ESR} = 1$ μV. This differs by orders of magnitude from the level width derived from the dc mobility μ. In special samples at very low filling factors the level width derived from cyclotron resonance $\Gamma_{\rm CR}$ can reach values as low as 10 μeV.[15,16] In our samples, however, $\Gamma_{\rm CR}$ also lies at least 2 orders of magnitude above $\Gamma_{\rm ESR}$, although determined at frequencies 100 times larger. Obviously the scattering mechanisms leading to level broadening seen in dc transport and cyclotron resonance experiments do not affect the spin of the scattered electrons. As a consequence, the dc mobility is only one parameter for the description of the scattering and thus for the quality of the sample; it does not say anything about the strength of spin scattering. This agrees with the fact that different samples with the same dc mobility may show great differences in the measurability of ESR.

IV. CONCLUSION

We have performed electron-spin resonance of the two-dimensional conduction electrons in GaAs-$Al_xGa_{1-x}As$ heterostructures by detecting the ESR-induced change of the magnetoresistivity. The spin splitting of the Nth Landau level $\Delta E = g \mu_B B$ is given by the magnetic-field-dependent g factor $g = g_0 - c(N + \frac{1}{2})B$, where g_0 and c are constant for a given sample. This g factor is not influenced by exchange interaction and it is shown to be a direct measure for the Fermi level.

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