Quantum corrections to the conductance of *n*-GaAs films in a strong magnetic field

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The conductance of doped n-GaAs films is studied experimentally as a function of magnetic field and temperature in strong magnetic fields right up to the quantum limit ($\hbar\omega_c = E_F$). The Hall conductance G_{xy} is virtually independent of temperature T until the transverse conductance G_{xx} is quite large compared with e^2/h. In strong fields, when G_{xx} becomes comparable to e^2/h, G_{xy} starts to depend on T. The difference between the conductances G_{xx} at the two temperatures 4.2 and 0.35 K depends only weakly on the magnetic field H over a wide range of magnetic fields, while the conductances G_{xx} themselves vary strongly. The results can be explained by quantum corrections to the conductance as a result of the electron-electron interaction in the diffusion channel. The possibility of quantization of the Hall conductance as a result of the electron-electron interaction is discussed. © *1998 American Institute of Physics.* [S0021-3640(98)00803-2]

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As is well known, quantum interference effects change the temperature dependence of the conductance of disordered metallic systems. According to the theoretical models, in the case of weak spin-spin and spin-orbit scatterings, the change in the conductance of the normal two-dimensional metallic system in a zero magnetic field as the temperature changes from T_0 to T is given by[1,2]

$$\delta G = \frac{e^2}{2\pi^2\hbar}\left\{ [p+1-\lambda_0-2\lambda_{\pm 1}-(p-1)\beta(T)]\ln\frac{T}{T_0}-\ln\frac{\ln T_c/T_0}{\ln T_c/T}\right\}. \tag{1}$$

Here p is the exponent of the temperature dependence of the reciprocal of the phase interruption time $1/\tau_\varphi \propto T^p$, T_c is a constant of the order of the Fermi energy E_F divided by the Boltzmann constant k_B, and $\beta(T)$ is a function of $\ln(T_c/T)$, whose values are presented in Ref. 1. The first term p in brackets on the right-hand side of expression (1) is due to single-electron interference (weak localization) and the remaining terms are due to quantum effects in the electron-electron interaction. The second, third, and fourth terms are due to interaction in the diffusion channel. The second term is due to the interaction of an electron and a hole with total spin $j=0$, the third term is due to the interaction of an electron and hole with total spin $j=1$ and projection of the total spin $m=0$, and the fourth term is due to the interaction of an electron and hole with total spin $j=1$ and spin projection $m=\pm 1$. In addition, the interaction constants are $\lambda_0=\lambda_{\pm}$. The fifth term is the Maki–Thompson correction. The last term in braces is due to interaction in the Cooper channel. The first and second terms in expression (1) decrease and the remaining terms increase the conductance with decreasing temperature. A magnetic field H suppresses weak localization and the Maki–Thompson corrections in the case $H>H_{\varphi}=\hbar c/4eD\tau_{\varphi}$ (D is the electron diffusion coefficient), it suppresses the correction due to interaction in the Cooper channel in the case $H>H_{\text{int}}=\pi c k_B T/2eD$, and in the case $H>H_s=\pi k_B T/g\mu_B$ (g is the Landé factor, and μ_B is the Bohr magneton), as a result of the effect on the spin variables, it also suppresses the correction due to the direct interaction in the diffusion channel with the total spin of electron and hole $j=1$ and $m=\pm 1$. With the exception of the Maki–Thompson correction, the electron-electron interaction does not affect the Hall conductance: $\delta G_{xy}=0$. We note that in transitional regions in terms of the magnetic field the corrections to the conductance are not logarithmic.

The results presented above were obtained for the case $\omega_c\tau\ll 1$ (ω_c is the cyclotron frequency and τ is the electron relaxation time). In strong magnetic fields $\omega_c\tau\gg 1$, the only remaining corrections are due to the electron-electron interaction in the diffusion channel and they were studied theoretically in Refs. 3–5. The authors found that near maxima of G_{xx} the results are identical to the results of Ref. 6, initially obtained for the case $\omega_c\tau\ll 1$. Specifically, $\delta G_{xy}=0$. Later, the results of Ref. 6 for δG_{xx} were somewhat altered.[7] Apparently, similar changes must also be introduced for the case of strong magnetic fields, but this was not done. Quantum corrections in a strong field were studied experimentally, as far as I know, only in the GaAs/AlGaAs heterostructures.[8] It was found that at its maxima the conductance G_{xx} varies logarithmically. However, no data on the behavior of G_{xy} are given in this work.

Although quantum corrections to the conductance in 2D films placed in a strong magnetic field have not been studied theoretically, it can be expected that the result in this case will be identical to the results for weak magnetic fields, $\omega_c\tau\ll 1$. The first objective of the present work is to study experimentally the magnetic field and temperature dependences of the conductances G_{xx} and G_{xy} of 2D films of doped n-GaAs in strong magnetic fields right up to the quantum limit ($\hbar\omega_c=E_F$, where E_F is the Fermi energy) and to compare the experimental results with the theory of quantum corrections due to electron-electron interaction.

In Ref. 9, quantization of G_{xx} and, correspondingly, the appearance of minima of G_{xy} at temperatures less than 1 K were found in experimental samples in the quantum limit $\hbar\omega_c>E_F$, while at $T=4.2$ K G_{xy} and G_{xx} are monotonic functions of the magnetic field.[9] Quantization of G_{xy} arises for G_{xx} comparable to e^2/h, when second-order localization corrections can be substantial (the magnetic field suppresses first-order corrections). The second objective of this work is to determine which is the more significant under these conditions: electron-electron interaction or localization effects.

The measurements were performed on samples prepared by molecular-beam epitaxy. A 0.1 μm thick layer of undoped GaAs was deposited on a semi-insulating GaAs (100) substrate at temperature $T=410$ °C. The following were deposited next: an epitaxial layer of undoped GaAs (0.6 μm), a GaAs/AlAs$\times 20$ periodic structure with GaAs

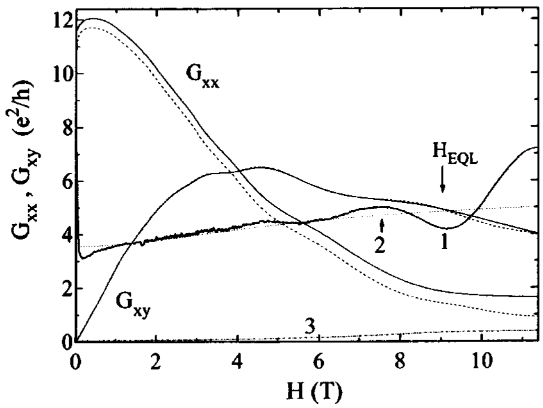

FIG. 1. Hall G_{xy} and transverse G_{xx} (on a square) conductances versus magnetic field at two temperatures. The solid curves are for $T=4.2$ and the dashed curves for $T=0.35$ K. Curve *1*—$\delta G_{xx}(H)$ (difference of the curves $G_{xx}(H)$ at $T=4.2$ K and at $T=0.35$ K), multiplied by 10. Curve *2*—$\delta G_{xx}(H)\cdot 10$, calculated according to Eq. (2) with the constants λ_0 and $\lambda_{\pm}$ obtained by fitting the temperature dependences of G_{xx} in Fig. 2. Curve *3*—$\delta G_{xx}(H)\cdot 10$ due to second-order localization corrections.

thicknesses equal to 10 monolayers and AlAs thicknesses equal to 5 monolayers, an undoped GaAs layer (1 μm), a layer of silicon-doped n-GaAs (0.1 μm) with a prescribed donor density of 1.5 and 3×10^{17} cm^{-3} for samples 2 and 3, respectively, and once again a layer of undoped GaAs (1 μm). Samples 0.18 mm wide and 3 mm long with legs for measurements of the longitudinal and transverse stresses in and transverse to the planes of the samples were etched from disks. The measurements were performed with a 30 Hz ac current in a magnetic field up to 11.5 T in the temperature range 0.3–4.2 K. The main measurements were performed in a field oriented perpendicular to the plane of the sample.

The volume electron densities n in a strongly doped layer were determined according to the periods of the Shubnikov–de Haas oscillations of the transverse resistance R_{xx}. They equal 1.8 and 2.5×10^{17} cm^{-3} for samples 2 and 3. The electron densities N_s per unit film area and the mobilities $\mu=2400$ and 2500 cm^2/V$\cdot$s were found from the resistance in a zero magnetic field and the Hall constant. The values obtained for the mobilities are close to the mobilities in single crystals with close densities n.[10] The mean free path lengths, equal to approximately 0.03 μm, as determined from the mobilities, are much less than the film thicknesses d. Dividing n by N_s, we determined the ‘‘effective’’ film thicknesses to be 0.07 and 0.083 μm. They are somewhat less than the thicknesses of the doped layers because of the decrease in the electron density near the boundaries. To show in addition that the electron spectrum in the films is three-dimensional, the resistance of sample 2 was measured in a magnetic field parallel to the film plane but once again perpendicular to the current. It was virtually identical to the resistance in a perpendicular field (the positions of the visible maxima and minima of the Shubnikov–de Haas oscillations were also identical).

Figure 1 displays the transverse G_{xx} (on a square) and Hall G_{xy} conductances versus the magnetic field for sample 2 at temperatures $T=0.35$ and 4.2 K. The conductances

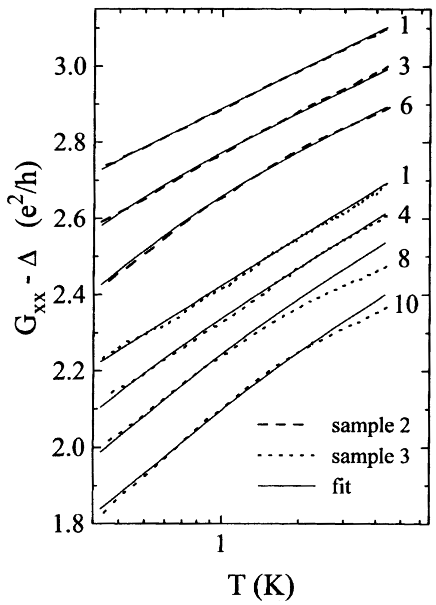

FIG. 2. Temperature dependences of the dissipative conductance G_{xx} in different magnetic fields, indicated by the numbers near the curves. For convenience, all curves except the bottom curve are shifted downwards. The shifts Δ for different curves are (top to bottom) 8.37, 4.89, 1.16, 18.7, 18.13, 2.08, and 0.

were determined by converting from the transverse resistance R_{xx} on a square and the Hall resistance R_{xy}. The transverse conductance G_{xx} at first increases somewhat in weak fields and then decreases by approximately a factor of 10. At $T=4.2$ K G_{xx} is everywhere greater than its value at $T=0.35$ K. The curves $G_{xy}(H)$ are virtually identical, with the exception of the strongest magnetic fields in which G_{xx} is comparable to e^2/h. The difference $\delta G_{xx}=G_{xx}(4.2)-G_{xx}(0.35)$ at first decreases rapidly and then increases slowly. In strong fields δG_{xx} starts to oscillate, while $G_{xy}(H)$ becomes temperature-dependent. The oscillations of $G_{xx}(H)$ and $G_{xy}(H)$ at low temperatures are observed on these samples in the magnetic field range 10–23 T.[9] The temperature dependences $G_{xx}(T)$ for both samples in different magnetic fields are presented in Fig. 2. In weaker fields they are close to logarithmic and in stronger fields they differ appreciably from log T.

The increase of $G_{xx}(H)$ and decrease of δG_{xx} in a weak field are due mainly to the suppression of weak localization. Quantum corrections in this region of magnetic fields were studied in Ref. 11 on samples similar to ours. The small increase in δG_{xx} in fields greater than 1 T and the deviation of the temperature dependences from a logarithmic dependence can be attributed to the effect of a magnetic field on the corrections to the conductance that are due to the electron-electron interaction in the diffusion channel with $j=1$ and $m=\pm 1$. The difference between conductances in a magnetic field at two temperatures T and T_0 in this case should be[2]

$$\delta G_{xx}(H)=\frac{e^2}{2\pi^2\hbar}\left[(1-\lambda_0-2\lambda_{\pm1})\ln\frac{T}{T_0}+2\lambda_{\pm1}\int_0^\infty\frac{\partial^2}{\partial\omega^2}\left(\frac{\omega}{\exp\hbar\omega/k_BT-1}\right)\right.$$
$$\left.\times\ln\left|1-\frac{\omega_s^2}{\omega^2}\right|d\omega\right], \qquad (2)$$

where $\omega_s=g\mu_BH$. The experimental results cannot be fit adequately by expression (2), if it is assumed that $\lambda_0=\lambda_{\pm1}$ and the interaction constant for $j=0$ equals 1. For this reason, we fit the experimental curves choosing as the two independent adjustable parameters the coefficient a_1 of the logarithm and the coefficient a_2 of the integral in expression (2). The results for the temperature dependences are displayed in Fig. 2. The fitted curves describe the experimental results fairly well, with the exception of the curves in 8 and 10 T for sample 3 at temperatures above 2 K. These deviations could be due to the fact that the two-dimensionality condition $d\gg(D\hbar/k_BT)^{1/2}$ is not satisfied. The adjustable parameters are $a_1=0.45$ and $a_2=0.23$ for sample 2 and $a_1=0.57$ and $a_2=0.16$ for sample 3. If it is assumed that the interaction constant for $j=0$ equals 1, then $\lambda_0=0.32$ and $\lambda_{\pm1}=0.125$ for sample 2 and $\lambda_0=0.2$ and $\lambda_{\pm1}=0.1$ for sample 3. The dependences $\delta G_{xx}(H)$ calculated using the values obtained for the parameters a_1 and a_2 (curve *2* in Fig. 1) describe the experimental curves well in substantial magnetic field intervals (1–7 T for sample 2).

In fields of about 0.2 T small dips are observed in the curves $\delta G_{xx}(H)$. These dips cannot be due to the behavior of only a weak localization and interaction in the diffusion channel in a magnetic field. Apparently, they are due to the electron-electron interaction in the Cooper channel.

A magnetic field suppresses the first-order localization corrections to the conductance. However, since in strong magnetic fields δG_{xx} become comparable to G_{xx}, there arises the question of what role do localization corrections to the conductance in the next order play. According to the results obtained on the basis of the nonlinear σ model in a magnetic field (see the review in Ref. 12 and references cited therein),

$$\beta=\frac{d\ \ln G_{xx}}{d\ \ln L}=-\frac{2}{(2\pi G_{xx})^2}-\frac{6}{(2\pi G_{xx})^4}+O\left(\frac{1}{(2\pi G_{xx})^6}\right). \qquad (3)$$

For our values of G_{xx} (in units of e^2/h) only the first term on the right-hand side of the expression need be retained. Then, solving the equation we obtain

$$G_{xx}=\left(G_{xx,0}^2-\frac{1}{\pi^2}\ln L\right)^{1/2}\approx G_{xx,0}+\frac{p}{4\pi^2}\frac{1}{G_{xx,0}}\ln(T/T_0), \qquad (4)$$

where $L=(D\tau_\varphi)^{1/2}$. The magnetic field dependence of the quantity $\delta G_{xx}=G_{xx}-G_{xx,0}$ for this case is presented in Fig. 1 (curve *3*). The value of G_{xx} at $T=4.2$ K was taken as $G_{xx,0}$ and it is assumed that $p=1$, just as in a zero magnetic field.[1,11] The values of $\delta G_{xx}(H)$ computed in this manner are much smaller than the experimental values (see Fig. 1), i.e., the electron-electron interaction dominates.

Let us discuss the effect of the electron-electron interaction in films with G_{xx} and $G_{xy}>e^2/h$ at low temperatures. As temperature decreases, the dissipative conductance G_{xx} decreases as a result of the electron-electron interaction, while the Hall conductance G_{xy} does not change. It the dissipative conductance vanishes, then according to Laughlin's gauge arguments the Hall conductance should be quantized.[13] Therefore it can be expected that the electron-electron interaction, which decreases G_{xx}, ultimately will result in quantization of $G_{xy}=ie^2/h$. Since there are no distinguished values of i, G_{xy} will apparently approach one of the closest quantized values as temperature decreases, and transitional regions where G_{xy} is not quantized and correspondingly, G_{xx} approaches a constant value should exist. Such behavior of films was conjectured by Khmel'nitskiĭ on the basis of a single-electron analysis.[14] However, for $G_{xx}>e^2/h$ the temperature dependence of G_{xx} due to the interaction is stronger than the temperature dependence of G_{xx} due to single-electron effects. Therefore the quantization of G_{xy} should be due mainly to the electron-electron interaction. In this case, the quantization of G_{xy} and the decrease of G_{xx} should apparently be accompanied by the appearance of Coulomb gaps at the Fermi level.

In summary, the experimental results are described quite well by quantum corrections, due to electron-electron interaction in the diffusion channel, to the conductance, if it is assumed that either $\lambda_0\neq\lambda_{\pm 1}$ or the second term in brackets in expression (1) is different from 1. The quantization of the Hall conductance observed in Ref. 9 is apparently due to the electron-electron interaction.

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