Parabolic Magnetoresistance from the Interaction Effect in a Two-Dimensional Electron Gas

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A negative magnetoresistance proportional to B^2 is found in the two-dimensional electron gas of GaAs-$Al_xGa_{1-x}As$ heterostructures. It is explained by the conductivity correction due to the electron interaction effect in disordered two-dimensional systems. The high-field electron lifetime, estimated both from the interaction effect and from the Shubnikov–de Haas oscillations, is much shorter than the zero-field lifetime, demonstrating the predominance of long-range potential fluctuations in high-mobility GaAs-$Al_xGa_{1-x}As$ samples.

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Two types of logarithmic corrections have been predicted for the electrical conductivity in disordered two-dimensional (2D) systems. The localization correction[1] results from the properties of a single electron in a random potential and leads to a negative magnetoresistance[2,3] in the weak magnetic field limit, $\omega_c\tau_0 \ll 1$, where ω_c is the cyclotron frequency given by $\omega_c = eB/m^*$ and τ_0 is the transport scattering time at $B=0$. This correction is suppressed at fields higher than the critical field given by $B_1 = \hbar/4eD\tau_0$, where D is the electron diffusion constant. The second correction is due to the enhanced Coulomb interaction between diffusively moving electrons[4,5] and is predicted to be present even when $\omega_c\tau_0 \gg 1$[6,7] and to lead to a negative magnetoresistance in this regime.[6] The interaction effect is affected by the Zeeman splitting and, consequently, a positive magnetoresistance[8] is expected in the regime when the magnetic field is above the critical field given by $B_2 = k_B T/g\mu_B$, where g is the conduction-electron g factor and μ_B is the Bohr magneton. The localization correction is sufficiently well understood[9-16] that the negative magnetoresistance, due to localization, has been used extensively to measure the inelastic scattering time. The interaction correction, on the other hand, is not so well understood and a consistent picture of the various effects in parallel and perpendicular fields has yet to emerge.[5,11,16] In Si metal-oxide-semiconductor field-effect transistors,[11] the screening length of the Coulomb interaction is short and the interaction effect is small. In contrast, the screening length in the GaAs heterostructure is longer and the interaction effect is important in the weak-field limit.[16] Paalanen, Tsui, and Gossard[17] also observed a logarithmic correction in the T dependence of the quantum oscillations of the diagonal conductivity and demonstrated the persistency of the interaction effect even to the quantum limit $\hbar\omega_c \simeq E_F$.

In a high-mobility 2D electron system, the high-field limit $\omega_c\tau_0 > 1$ can be reached at sufficiently low B that the condition $\omega_c \gg k_B T/\hbar$ for observing the Shubnikov–de Haas (SdH) quantum oscillations is not fulfilled even at relatively low T. We report in this Letter our studies of the magnetotransport properties of such a high-mobility 2D electron gas in this so-called classically strong-field regime. We find a negative magnetoresistance, which is proportional to B^2 and which has a logarithmic temperature dependence. Our sample parameters indicate that the localization effect is totally suppressed in this field regime ($B_1 < 2\times10^{-4}$ T), but the Zeeman splitting is not yet effective ($B_2 > 3$ T above 1 K temperature). We are able to fit our data with the predictions of the interaction theory[6,7] and determine the interaction coefficient $(1-F)$ and the cutoff temperature, $T_0 = \hbar/k_B\tau$, from their temperature dependence. We find an unexpectedly large T_0 suggesting that the relevant electron lifetime τ in the high-field regime is much shorter than τ_0. We attribute this short τ to the inhomogeneous Landau-level broadening by the dominance of long-range potential fluctuations in our high-mobility sample.

Our sample is a modulation-doped GaAs-$Al_xGa_{1-x}As$ heterostructure grown by molecular-beam epitaxy on Cr-doped GaAs substrate. The layered heterostructure consists of 1 μm undoped GaAs, 370 Å of undoped $Al_xGa_{1-x}As$, and 400 Å of Si-doped (2×10^{18} cm^3) $Al_xGa_{1-x}As$. By using a backgate bias, we are able to vary the electron density continuously between $n_s = 1.17\times10^{11}/cm^2$ and $n_s = 1.64\times10^{11}/cm^2$. Concomitantly, the mobility changes from $\mu = 0.65\times10^6$ cm^2/V s to 1.12×10^6 cm^2/V s.

Figure 1 shows the normalized magnetoresistance for $n_s = 1.17\times10^{11}/cm^2$ at $T = 1.04$, 3.17, and 9.8 K in high perpendicular fields, $\omega_c\tau_0 > 1$. At each of the three temperatures, we find a negative magnetoresistance, which is proportional to B^2. At 1.04 K, this parabolic dependence on B is observed up to ~ 0.2 T, corresponding to $\omega_c\tau_0 \approx 12$, above which the SdH oscillations appear. Notice that the SdH oscillations start at an unexpectedly high field.

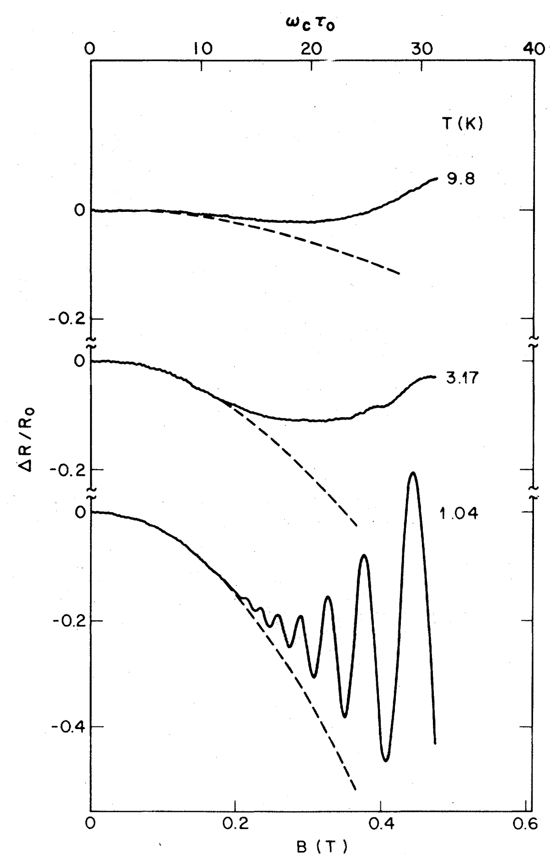

FIG. 1. The normalized magnetoresistance $\Delta R/R_0$ as a function of perpendicular B for $n_s = 1.17\times10^{11}/cm^2$ at three different temperatures. The broken lines represent the best fit of Eq. (3) to the data with $1-F = 0.27$ and $T_0 = 15.5$ K.

The observed negative magnetoresistance can be explained by the interaction corrections to the conductivity. Houghton, Senna, and Ying[6] and Girvin, Jonson, and Lee[7] predicted that the correction to the diagonal conductivity is independent of B and is given by

$$\Delta\sigma_{xx} = (e^2/2\pi^2\hbar)(1-F)\ln(T/T_0), \quad (1)$$

where $k_BT_0 \simeq \hbar/\tau$ and τ is the electron lifetime, which at high fields may be different from τ_0. The Hartree factor F is an angular average over the statically screened Coulomb interaction,

$$F = \int_0^{2\pi} \frac{d\theta}{2\pi} \frac{1}{1+(2k_F/K)\sin\theta/2}, \quad (2)$$

where K is the screening constant.[18] The above theory[6] predicts no correction for the Hall conductivity, i.e., $\Delta\sigma_{xy} = 0$. The magnetoresistance, ΔR, obtained by inverting the conductivity matrix, is given by[6]

$$\Delta R/R_0^2 \simeq (-e^2/2\pi^2\hbar)[1-(\omega_c\tau_0)^2] \times(1-F)\ln(T/T_0), \quad (3)$$

where R_0 is the sheet resistance per square of the 2D electron gas at $B = 0$. Equation (3) predicts a negative magnetoresistance proportional to B^2. The broken lines in Fig. 1 are calculated from Eq. (3), with use of the values of F and T_0 determined from the temperature dependence of the data illustrated in Fig. 2.

Figure 2 shows the temperature dependence of the negative magnetoresistance at two different magnetic fields and at two different n_s. In order to remove the field dependence, we have divided ΔR by $R_0^2[1-(\omega_c\tau_0)^2]$. For both densities we find a logarithmic temperature dependence as predicted by Eq. (3). Furthermore, the results at different magnetic fields agree within our resolution and confirm the magnetic field dependence shown in Fig. 1. From the solid lines in Fig. 2 we obtain $1-F = 0.27$ and $T_0 = 15.5$ K for $n_s = 1.17\times10^{11}/cm^2$ and 0.28 and 9.8 K for $n_s = 1.64\times10^{11}/cm^2$. We also measured the Hall resistance and observed no T dependence within our resolution, consistent with the prediction of Houghton, Senna, and Ying.

The values of $1-F$ compare favorably with the theoretical predictions of 0.34 and 0.37 from Eq. (2) for $n_s = 1.17\times10^{11}/cm^2$ and $n_s = 1.64\times10^{11}/cm^2$,

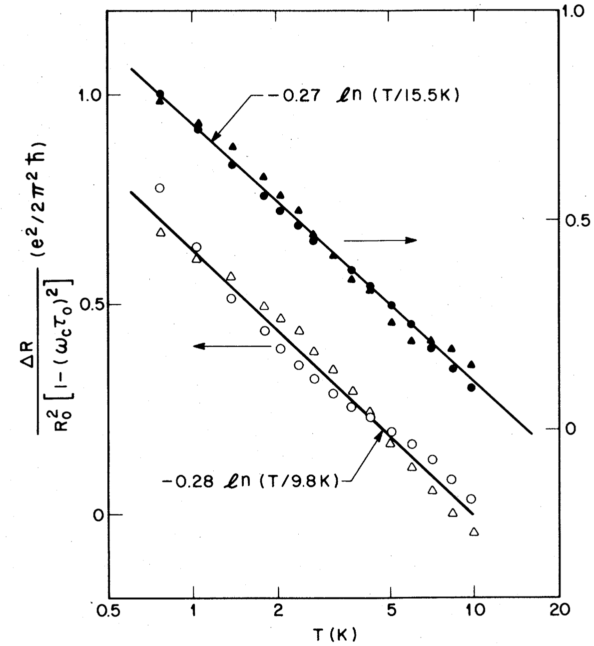

FIG. 2. The temperature dependence of the magnetoresistance $\Delta R = R(B) - R(0)$ at $B = 0.10$ T (circles) and $B = 0.21$ T (triangles). Data represented by solid symbols are from $n_s = 1.17\times10^{11}/\mathrm{cm}^2$ and those by open symbols are from $n_s = 1.64\times10^{11}/\mathrm{cm}^2$.

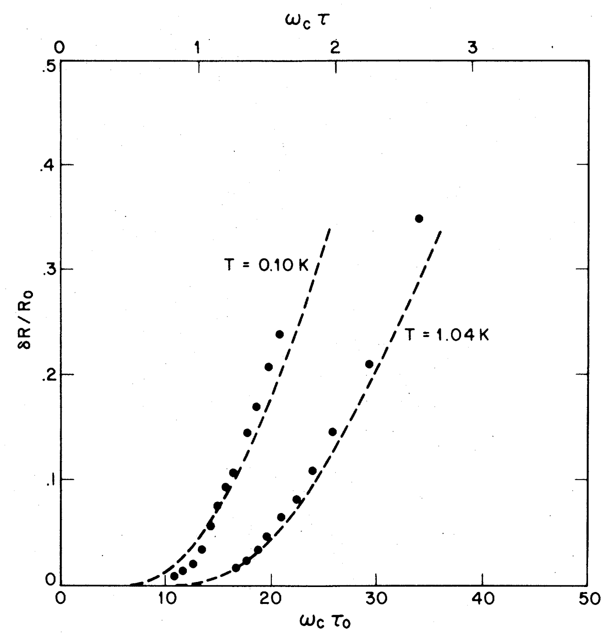

FIG. 3. The amplitude of the SdH oscillations as a function of magnetic field $\omega_c\tau_0 = \mu B$ for $n_s = 1.17\times10^{11}/\mathrm{cm}^2$. The dashed curves are fits of Eq. (4) to our data with $\tau = 0.077\tau_0$. The upper scale reads $\omega_c\tau$.

respectively.[18] However, they are smaller than the value 0.50 measured in the weak-field limit on low-mobility samples with comparable densities.[16] We believe that the screening approximation in Eq. (2) describes more accurately high-mobility samples than low-mobility samples. The electron lifetime τ obtained from our data through $\tau = \hbar/k_B T_0$ is unexpectedly short, namely $\tau \approx 0.020\tau_0$ for $n_s = 1.17\times10^{11}/\mathrm{cm}^2$ and $\tau \simeq 0.018\tau_0$ for $n_s = 1.64\times10^{11}/\mathrm{cm}^2$. We also determined the electron lifetime from the amplitude of the SdH oscillations observed at low T (Fig. 1). For short-range scatterers in the limit $\omega_c\tau \lesssim 1$, Ando[19] obtained the following expression for the oscillation amplitude:

$$\frac{\delta R}{R} \simeq \frac{\delta\sigma}{\sigma} \simeq \frac{2(\omega_c\tau)^2}{1+(\omega_c\tau)^2}\exp\left(\frac{-\pi}{\omega_c\tau}\right)\frac{x}{\sinh x}, \qquad (4)$$

where $x = 2\pi^2 k_B T/\hbar\omega_c$. We assume Eq. (4) to be valid here and use τ as a fitting parameter. In Fig. 3 we plot the amplitude of the SdH oscillations as a function of $\omega_c\tau$ at two different temperatures for $n_s = 1.17\times10^{11}/\mathrm{cm}^2$, and a rather good fit to the data is obtained with $\tau = 0.077\tau_0$. Similarly, $\tau = 0.055\tau_0$ gives a good fit of the data at $n_s = 1.64\times10^{11}/\mathrm{cm}^2$. These fits are obtained for $\omega_c\tau \leqslant 2$, which is somewhat above the range of $\omega_c\tau$ for Eq. (4) to be valid. In any case, taking into account the approximative nature of Eq. (4), we find both determinations of τ consistent, demonstrating convincingly that, in our high-mobility sample, τ in the high-field limit is much shorter than τ_0.

We attribute this apparent shortening of the electron lifetime to inhomogeneous broadening of the Landau levels by the dominance of long-range potential fluctuations in the high-mobility samples. The short-range scattering due to interface roughness is absent in epitaxially grown GaAs-$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ heterostructures. Residual impurities in the GaAs as well as the doping impurities selectively placed inside the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ can give rise to weak, long-range potential fluctuations, dominant in the high-mobility samples. In the case of long-range potential fluctuations, the broadening of the Landau levels is not related directly to τ_0.[19] The effective τ used to characterize the broadening can be much smaller than τ_0. In our sample at 1 K, the SdH oscillations vanish at $B \approx 0.2$ T. If we assume that the range Δr of the dominant potential fluctuation is given by the cyclotron diameter of electrons closest to E_F at $B \simeq 0.2$ T, we obtain $\Delta r \sim 1000$ Å. In the presence of such long-range potential fluctuations, the high-field transport in the quantum Hall regime (where the cyclotron radius is $\ll \Delta r$)

can be described by the classical percolation model.[20] Such a classical description has in fact been used to explain successfully the observation that the quantum Hall plateaus in high-mobility GaAs-Al_xGa_{1-x}As heterostructures approach perfectly sharp steps as T approaches zero.[17]

In conclusion, we have observed a large negative magnetoresistance, which is proportional to B^2 and has a logarithmic temperature dependence in a high-mobility 2D electron gas. This observation confirms the predictions of the theory on the interaction effect in disordered 2D systems by Houghton, Senna, and Ying[6] and Girvin, Jonson, and Lee.[7] It demonstrates convincingly that, in the absence of Zeeman splitting, the interaction effect in the particle-hole channel is indeed independent of magnetic field. We find good agreement between theory and experiment on the value of the interaction coefficient $(1-F)$ and attribute this success to the fact that the screening approximation is accurate in describing high-mobility samples. We also find that long-range potential fluctuations dominate the broadening of the Landau levels in our high-mobility sample. This dominance of long-range potential fluctuations underlies the classical percolation description of the quantum Hall effect in high-mobility GaAs-Al_xGa_{1-x}As heterostructures.

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$$f(F)=[4-3(2+F)F^{-1}\ln(1+F/2)].$$

$f(F)$ is 0.55 and 0.57 for the low- and high-density samples, respectively. These values are about a factor of 2 larger than the experimental values.

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