PHYSICAL REVIEW B VOLUME 37, NUMBER 7 1 MARCH 1988

High-field magnetoconductivity of electrons on hydrogen

P. W. Adams and M. A. Paalanen
AT&T Bell Laboratories, Murray Hill, New Jersey 07974-2070
(Received 29 October 1987)

We have measured the diagonal magnetoconductivity of a dilute two-dimensional electron gas in the high-field limit ($\omega_c\tau_0 \gg 1$). We find good agreement with theory and comparable values for the zero-field and high-field scattering times, which is characteristic for short-range scattering potentials.

Electrons deposited on inert cryogenic surfaces (i.e., hydrogen, helium, neon) form a nondegenerate two-dimensional electron gas (2D EG).[1] The transport properties of these dilute systems are particularly interesting since one can usually neglect electron-electron interactions[2] when making comparisons with theory. In the present paper, measurements of the diagonal magnetoconductance of a 2D EG on solid hydrogen surfaces are reported in the regime in which $\omega_c\tau_0 \gg 1$ and $\hbar\omega_c \gtrsim kT$, where $\omega_c = eB/m_{el}$ is the cyclotron frequency and τ_0 is the zero-field scattering time.

In the experiments described below we have measured the conductivity σ_{xx} in a Corbino geometry. For small magnetic fields applied perpendicular to the surface of motion, the resistivity is

$$\sigma_{xx}^{-1}(B) = \sigma_0^{-1}(1+(\mu_0 B)^2) \ , \tag{1}$$

where $\mu_0 B = \omega_c\tau_0$, $\mu_0 = e\tau_0/m_{el}$, $\sigma_0 = n_0 e^2\tau_0/m_{el}$, and n_0 is the areal electron density. Equation (1) is easily derived from the drift velocity equations and is generally valid for $\mu_0 B = \omega_c\tau_0 \ll 1$. Quantum corrections to Eq. (1) become important when either $\mu_0 B \simeq 1$ or the electron cyclotron radius becomes comparable to the thermal wavelength ($\hbar\omega_c \simeq kT$). In general, σ_{xx}^{-1} will begin to vary more slowly than B^2 at high fields due to the fact that the classical cyclotron radius,

$$l_c \simeq \frac{m_{el}V}{eB} \approx \frac{(2m_{el}kT)^{1/2}}{eB} \ ,$$

cannot be smaller than the quantum Landau radius, $l_0 = (\hbar/eB)^{1/2}$. In the extreme high-field limit, i.e., $\mu_0 B \gg 1$, $\hbar\omega_c \gg kT$, the electronic motion becomes completely quantized with discrete energy levels, $E_N = (N+\frac{1}{2})\hbar\omega_c \pm g\mu_B B/2$, where μ_B is the Bohr magneton and g is the g factor. These energy levels or Landau levels have a degeneracy of $(2\pi l_0^2)^{-1}$ per unit area (not counting the spin degeneracy). The formation of pure Landau levels can be characterized by a δ-function peak in the density of states centered about each E_N. In the presence of scattering, however, the Landau levels are broadened and the δ functions must be replaced by Gaussians of width Γ, centered at each E_N.

The theory of magnetotransport in strong magnetic fields is primarily concerned with calculating the level broadening and the corresponding change in the density of states in the presence of impurity scattering.[3] Ando *et al.*[4,5] have used a self-consistent Born approximation to calculate the conductivity in the presence of short-range scattering in the limit $\mu_0 B \gg 1$ and $\hbar\omega_c \gg kT$,

$$\sigma_{xx} = \frac{e^2}{\pi\hbar}\int_0^\infty dE\left(\frac{-\partial f}{\partial E}\right)\sum_{N=0}(N+\tfrac{1}{2})\exp\left(\frac{4(E-E_N)^2}{\Gamma^2}\right) \tag{2}$$

where $f = f_0 e^{-E/kT}$ is the Boltzmann distribution function, f_0 is the exponent of the chemical potential, and Γ is a field-dependent level width

$$\Gamma \simeq \left(\frac{2}{\pi}\right)^{1/2}\frac{e\hbar}{m_{el}}\frac{B^\gamma}{\mu^{1-\gamma}} \ , \tag{3}$$

where in the case of δ function scatters $\gamma \simeq \frac{1}{2}$ and $\mu \simeq \mu_0$. Since we will be interested in determining the field dependence of Γ from experimental data we will treat γ as a fitting parameter. Similarly, we have allowed the high-field scattering time τ and corresponding mobility μ to be different from their zero-field values, τ_0 and μ_0, by treating μ as an adjustable parameter. The density of states used in Eq. (2) is of Gaussian form[6]

$$D(E) = \frac{1}{\pi l_0^2}\sum_{N=0}^{\infty}\left(\frac{2}{\pi}\right)^{1/2}\frac{1}{\Gamma}\exp\left(\frac{-2(E-E_N)^2}{\Gamma^2}\right) - \frac{1}{2\pi l_0^2}\left(\frac{2}{\pi}\right)^{1/2}\frac{1}{\Gamma}\exp\left(\frac{-2(E-E_0)^2}{\Gamma^2}\right) \ , \tag{4}$$

where the second term accounts for the fact that the g factor is two in our system so that the Zeeman splitting is equal to the Landau-level separation, i.e., $E_{N+1,\uparrow} = E_{N,\downarrow}$. The chemical potential f_0 is determined by

$$n_0 = \int_0^\infty f(E)D(E)dE \ . \tag{5}$$

Equations (2)–(5) can now be combined and numerically integrated to determine $\sigma_{xx}(B)$ for arbitrary μ and B with the requirement, of course, that $\mu B \gg 1$.

We have employed the capacitive detection method of Sommer and Tanner[7] to monitor the response of the 2D EG to an oscillating electric field. Hydrogen crystals were grown on a 25 mm diameter by 0.5-mm-thick sapphire plate placed upon a concentric-ring parallel plate detector. Electrons were deposited onto the H_2 and the conductance of the 2D EG was measured via its capacitance coupling to the detector, using a capacitive bridge in conjunction with a dual-phase lock-in amplifier. The in-phase and

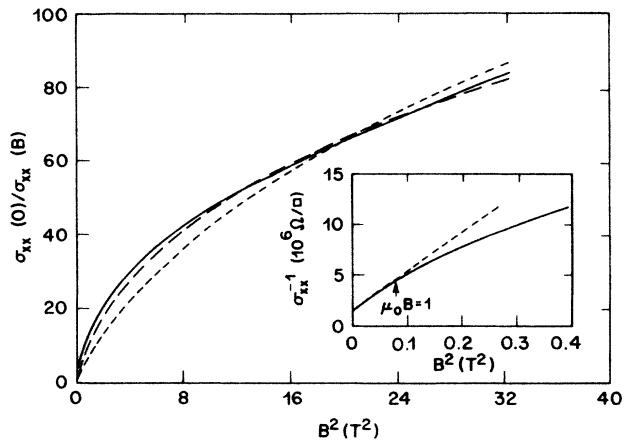

FIG. 1. Solid curve, magnetoresistance of the 2D EG at $T=4.2$ K and $\mu_0=5.1$ m^2/Vs [curve (f) in Table I]. The long-dashed curve is the theoretical prediction using Eqs.(2)–(5). The short-dashed curve is the theoretical prediction neglecting Zeeman splitting. The inset displays the magnetoresistance in the region of $\mu_0 B=1$.

quadrature components of the lock-in output were in turn monitored by a computer and σ_{xx} was measured as a function of applied perpendicular field B for field up to 6 T.

Shown in the inset of Fig. 1 is a typical low-field magnetoresistance trace from which μ_0 and n_0 were determined by a best fit to Eq. (1). Note the deviation from linear B^2 dependence in the region in which $\mu_0 B \simeq 1$. This was observed in all of the data, independent of the value of μ_0. The solid line in Fig. 1 is the corresponding normalized magnetoresistance at high fields. The large deviation from linearity represents a transition from Drude B^2 behavior to an essentially positive linear field dependence. This observation has also recently been reported for electrons on helium by Van De Sanden *et al.*,[8] who provide a simple argument for $\sigma_{xx} \simeq n_0 e^2/m_{el}\omega_c$ in the extreme quantum limit. Note that our data are not in this limit since $\hbar\omega_c$ is never larger than $2kT$. The long-dashed line in Fig. 1 is the prediction of Eqs. (2)–(5) in which μ and γ were varied to obtain the best fit. The short-dashed line in Fig. 1 is the best fit neglecting the degeneracy between the Zeeman splitting and the Landau separation. This has the effect of weighing the lowest-energy level too heavily in the density of states and predicts a stronger field dependence than observed.

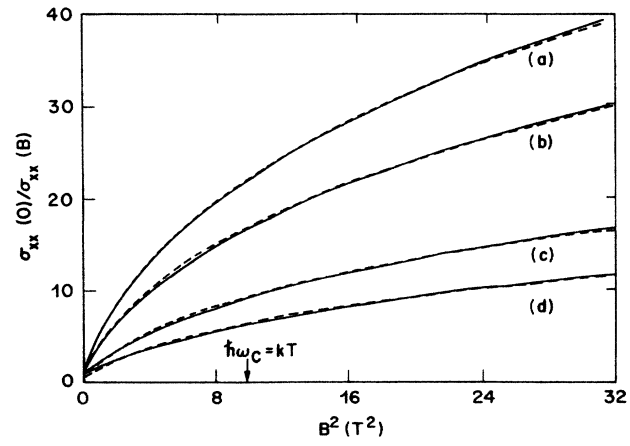

FIG. 2. Magnetoresistance at various zero-field mobilities in the presence of ^{4}He gas atom scattering at $T=4.2$ K. The gas densities are as follows: curve (a), 0.1×10^{18} cm^{-3}, curve (b), 1.7×10^{18} cm^{-3}, curve (c), 5.2×10^{18} cm^{-3}, curve (d), 8.3×10^{18} cm^{-3}. The dashed curves are the theoretical predictions; see Table I.

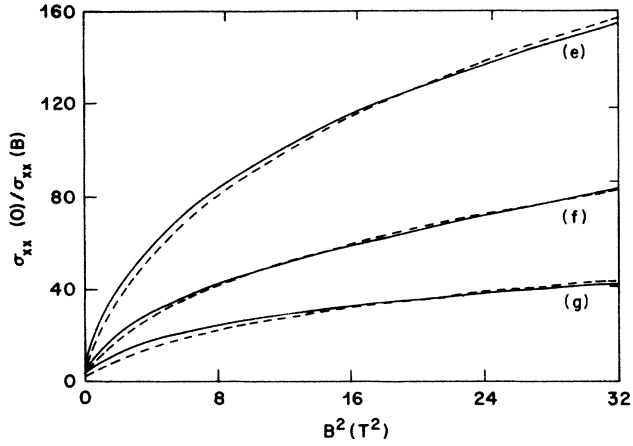

FIG. 3. Magnetoresistance at various zero-field mobilities in the presence of surface defect scattering. The dashed curves are the theoretical predictions; see Table I.

We have also studied the high-field behavior as a function of the zero-field mobility. The scattering rate of high mobility surfaces ($\mu_0 \gtrsim 3$ m^2/Vs) was systematically increased by either adding ^{4}He gas to the cell or by inducing surface defects via direct photodesorbtion of H_2 surface molecules. Shown in Fig. 2 is the normalized magnetoresistance of a crystal, with an initial mobility of $\mu_0=2.5$ m^2/Vs, at various ^{4}He densities. The dashed lines in Fig. 2 are the predictions of Eqs. (2)–(5) in which μ and γ were varied for the best fit. Not only are the fits of high quality, but the values of μ were found to be within 10% of the corresponding values of μ_0 (see Table

TABLE I. The zero-field mobility μ_0, high-field mobility μ, and exponent γ as determined from fits to the data. (Mobility in units of m^2/Vs).

Curve	μ_0	μ	γ
(a)	2.5	2.5	0.49
(b)	2.0	2.1	0.50
(c)	1.3	1.4	0.49
(d)	0.95	1.1	0.48
(e)	6.6	6.5	0.51
(f)	5.1	4.1	0.50
(g)	3.3	2.8	0.50

I). This agreement is impressive when compared to mobility measurements in GaAs heterostructures[9] where μ can be an order of magnitude smaller than μ_0. It is believed that in GaAs long-range potential fluctuations cause anomalous level broadening, thereby making the high-field mobility seem low.[10] This conjecture appears to be born out in our data as ^{4}He gas atoms behave as short-range scatterers and we find that $\mu \simeq \mu_0$.

Shown in Fig. 3 is the high-field magnetoresistance at various surface scattering rates. The dashed lines are fits in which, again, μ and γ were varied. Note the substantial systematic error in the form of the fitting function as compared with Fig. 2 and the relatively large deviations between μ and μ_0 for curves (f) and (g); see Table I. We believe that this may be a consequence of a small long-range contribution to the scattering as a result of charges trapped in deep surface defects. Notwithstanding the quality of the fits in Fig. 3 we again find reasonable agreement between the zero-field and high-field mobilities.

In conclusion, we have measured the magnetoconductance of a dilute 2D EG in the high-field limit and find very good agreement with theory. In contrast to measurements in GaAs heterojunctions, we find that the high-field and zero-field scattering times are approximately within 10% of each other.

We gratefully acknowledge Dr. J. P. Eisenstein and Dr. F. M. Peeters for enlightening discussions and helpful suggestions.

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