Zero-resistance state of two-dimensional electrons in a quantizing magnetic field

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When the Fermi level is pinned in the energy gap between two Landau levels of two-dimensional electrons, the response of electrons in the completely filled levels to an electric field is a dissipation-free Hall current perpendicular to the field. Our low-temperature measurements on GaAs-$Al_xGa_{1-x}As$ heterojunctions give an upper limit for the resistance along the current path of $\rho_{xx} \lesssim 5 \times 10^{-7}$ $\Omega/\Box$ which corresponds to a three-dimensional resistivity of $\rho \leqslant 5 \times 10^{-13}$ Ω cm. This resistivity is more than one order of magnitude lower than the resistivity of any nonsuperconducting material.

In a quantizing magnetic field B the energy spectrum of a two-dimensional (2D) electron gas is a series of discrete Landau levels, each having a degeneracy $\beta = \gamma eB/h$. (Here, h/e is the flux quantum and γ stands for the spin and valley degeneracies.) Scattering removes the orbital degeneracy and broadens each level into a band of states. The electrical transport properties of the system are determined primarily by the position of the Fermi level E_F in relation to these "Landau subbands."[1] When a "subband" is half filled, it acts like a good conductor and its diagonal conductivity σ_{xx} reaches a maximum. When a "subband" is completely filled, the presence of an energy gap between the filled and the empty Landau levels inhibits scattering and the vanishing of densities of states at E_F causes σ_{xx} to vanish at $T=0$. However, unlike an insulator, the off-diagonal Hall conductivity $\sigma_{xy} = ne/B = ie^2/h$, where n is the electron density and i is the number of filled Landau levels.[2] This condition, $\sigma_{xx}=0$ and $\sigma_{xy} \neq 0$, implies that the Hall angle equals 90° and the Hall current is free from dissipation. In other words, the diagonal resistivity $\rho_{xx} = \sigma_{xx}/(\sigma_{xx}^2 + \sigma_{xy}^2)$ also vanishes at $T=0$ and the 2D electron system is in a zero-resistance state. However, the realization of this state would not be expected in an isolated 2D electron system with no localized states, where E_F would always stay inside a Landau level and, except for singular values of n or B, there would always be a partially filled level.

Recently, quantization of the Hall effect of the 2D electrons was observed in the inversion layers of Si-MOSFET's (metal-oxide-semiconductor field-effect transistors)[3] and GaAs-$Al_xGa_{1-x}As$ heterojunctions.[4] It has been shown that the Hall resistance ρ_{xy} follows

$$\rho_{xy} = \frac{h}{e^2 i} \ , \tag{1}$$

where i is the number of filled Landau levels, to an accuracy of better than a part in 10^5 in finite ranges of n and B. These observations suggest that the Landau levels remain filled for finite ranges of n or B and the zero-resistance state, which we have discussed, may be attainable in these physical systems. In fact, previous measurements have already shown ρ_{xx} to be vanishingly small[5] and given $0.1\,\Omega/\Box$ as an upper limit.[4] We have carried out experiments on GaAs-$Al_xGa_{1-x}As$ heterojunctions to explore this peculiar zero-resistance state of 2D electrons and obtained a much lower value for the upper limit of ρ_{xx} at 1.2 K. Our results give $\rho_{xx} \lesssim 5 \times 10^{-7}$ $\Omega/\Box$, 5×10^8 times lower than ρ at $B=0$. It corresponds to an electron scattering time $\tau \gtrsim 1.5 \times 10^{-3}$ sec, if we assume $\tau = m^*/ne^2\rho_{xx}$.

The GaAs-$Al_xGa_{1-x}As$ heterostructure was prepared by molecular beam epitaxy. Its dimensions and constituents are given in the insert *a* to Fig. 1. The two-dimensional electron gas (2DEG) in GaAs results from ionized donors in the $Al_xGa_{1-x}As$ layer and it is confined to the interface between the $Al_xGa_{1-x}As$ and the GaAs underneath it. The interface between the top GaAs layer (grown to facilitate ohmic contacts) and the $Al_xGa_{1-x}As$ is depleted of free electrons by the surface potential. A standard "Hall bridge" [insert (b) to Fig. 1] and a ring similar to a Corbino disk geometry (insert to Fig. 2) were photolithographically defined. Electrical contacts were made by alloying indium into the epilayers at 400 °C in hydrogen atmosphere. The quality of all contacts was checked by comparing resistances and I-V characteristics measured across various combinations of contacts in temperatures down to 1.2 K. No contact resistance was detected. From standard resistivity and low-field Hall-effect measurements at 4.2 K an areal density of $n = 2.4 \times 10^{11}$ cm^{-2} and a mobility of 79 000 cm^2/Vsec were deduced.

Figure 1 gives a survey over the field dependence of ρ_{xy} and ρ_{xx} at 4.2 K. A detailed account of it was given in Ref. 4. Here, we note that the minima indicated by L_1 and L_2 in ρ_{xx} correspond to the complete

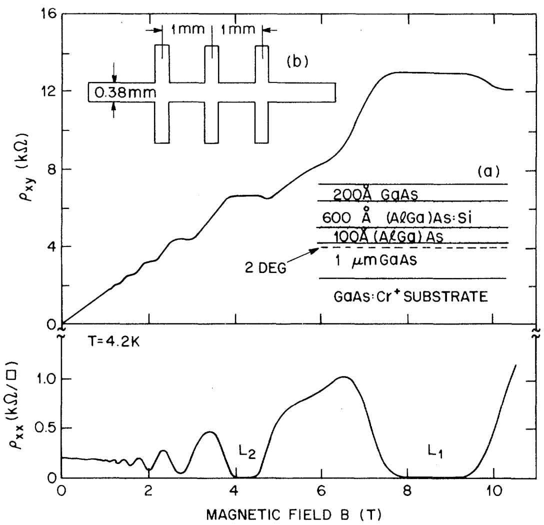

FIG. 1. A survey over the field dependence of ρ_{xy} and ρ_{xx} of a GaAs-$Al_xGa_{1-x}As$ heterojunction at 4.2 K (taken from Ref. 4). Insert (a) shows the dimensions and constituents of the sample and insert (b) shows the geometry of the "Hall bridge."

filling of one and two Landau levels, respectively, each with a twofold spin degeneracy. In the B field region of ~ 0.4 T around L_1 and ~ 0.1 T around L_2, while ρ_{xy} shows plateaus constant to 1 part in 10^4, ρ_{xx} appears to approach zero, suggesting the vanishing of resistance along the current path.

Due to the smallness of ρ_{xx}, which is difficult to determine accurately in the above geometry, we measure σ_{xx} instead and calculate ρ_{xx} by inverting the conductivity tensor $(\hat{\sigma})^{-1} = \hat{\rho}$. Limiting our analysis to the regions where relation (1) holds, we find $\rho_{xx} = \sigma_{xx}\rho_{xy}^2$ as long as $\rho_{xx} << \rho_{xy}$. We have $\rho_{xy} = 12.9 \times 10^3$ Ω at the L_1 minimum and 6.5×10^3 Ω at the L_2 minimum.

The conductivity σ_{xx} was measured in a ring geometry (insert to Fig. 2) by applying a constant voltage V across two opposing contacts and measuring the current I across them with a high resolution (10^{-14} A) digital ammeter. As we restrict our measurements to the regions of B where $\rho_{xx} \lesssim 10^{-3}$ Ω, this geometry is equivalent to a Corbino disk, the standard geometry to determine σ_{xx}.

Figure 2 shows ρ_{xx} at $T = 1.23$ K, obtained from measuring σ_{xx} around the L_1 minimum as a function of B. The finite resolution of our ammeter requires the application of voltages which exceed the range of a linear I-V characteristic. Measurements further away from the minimum indicate that a linear relation between I and V requires $V < 10$ mV. Our data, which are taken at considerably higher V, clearly show the decrease of ρ_{xx} with decreasing V. When $V = 50$ mV is used, ρ_{xx} is not measurable at all from

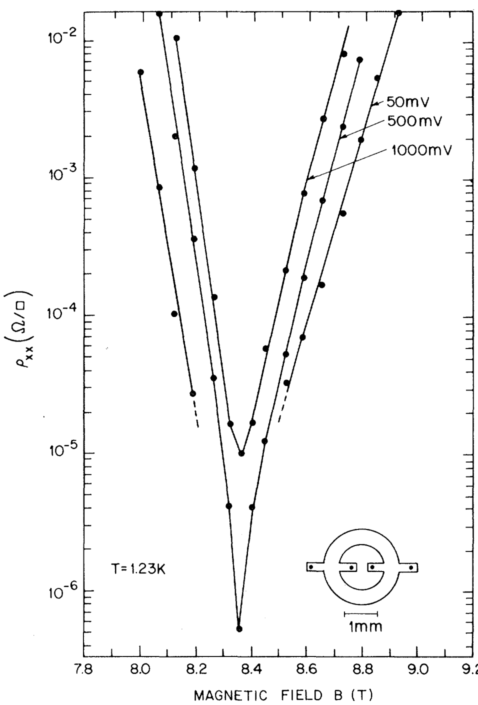

FIG. 2. Shows ρ_{xx} around the L_1 minimum of Fig. 1. ρ_{xx} is obtained from measuring σ_{xx} using the Corbino disk sample illustrated in the insert.

$B \simeq 8.3$ to 8.5 T. The lowest and still measurable ρ_{xx} is obtained at $B = 8.35$ T with $V = 500$ mV. This upper limit of ρ_{xx} at the L_1 minimum is $\approx 5 \times 10^{-7}$ $\Omega/\square$, 5×10^8 times lower than ρ at $B = 0$. It corresponds to an electron scattering time $\tau \gtrsim 1.5 \times 10^{-3}$ sec if we assume $\tau = m^*/ne^2\rho_{xx}$. The Hall angle θ, given by $\tan\theta \geq 2.6 \times 10^{10}$, is 90°. Considering that the conducting two-dimensional electron system has a thickness of $d \approx 10^{-6}$ cm we determine a three-dimensional resistivity of $\rho = \rho_{xx}d \leq 5 \times 10^{-13}$ Ω cm. This value is more than one order of magnitude lower than the resistivity of any nonsuperconducting material.[6]

A striking feature of Fig. 2 is the absence of a plateau region as observed in ρ_{xy}. Over the field range (~ 0.4 T) where ρ_{xy} is constant within 1 part in 10^4, ρ_{xx} varies by approximately three orders of magnitude. The field dependence can be roughly described by $\rho_{xx} \propto \exp[-27B(T)]$ and $\rho_{xx} \propto \exp[+18B(T)]$ on the two sides of the minimum.

The value of ρ_{xx} decreases with decreasing T, as well as with decreasing the V used in our measurements. Figure 3 shows the T dependence of ρ_{xx} at the L_2 minimum, which, unlike that at L_1 has sufficiently high resistance to allow measurements in the linear I-V regime from 4.2 to 1.2 K. Parallel conduction via the bulk was ruled out as a possible origin of this observed T dependence. The conclusion is based

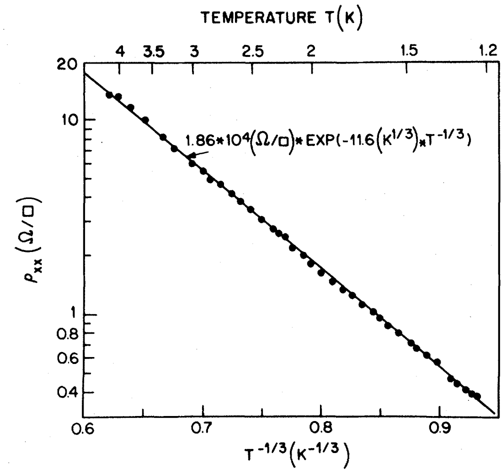

FIG. 3. Temperature dependence of ρ_{xx} at L_2.

on measurements made with the sample surface tilted from B and the fact that the bulk, being three dimensional, depends on the total B while the 2D electrons experience only the component of B perpendicular to the surface. By using total $B = 8.4$ T and keeping perpendicular B at L_2, conduction through the bulk, which must be less than the total conduction observed at $B = 8.4$ T perpendicular to the surface, is shown to be less than 10^{-5}.

It is clear from these data that ρ_{xx} approaches zero as T and V, used in our measurements, approach zero. We have not investigated the dependence of ρ_{xx} on V quantitatively. Our investigation of its T dependence (as shown in Fig. 3) shows that it does not follow $\exp(-T_0/T)$, and thus it excludes simple activation across a constant energy gap as its origin. Our data are adequately described by $\exp(-T_0/T)^{1/3}$ Such a power-law dependence has been attributed to variable range hopping by localized states in two-dimensional systems.[7]

Several theories[8-12] on the quantized Hall resistance invoke immobile electronic states to pin the Fermi level inside the gap between two Landau levels so that an integral number of Landau levels can remain filled for finite ranges of n or B. Such states can be either localized states in the inversion layer or impurity states sufficiently close to allow communication with the inversion layer. Our data are consistent with both types and the following physical picture emerges as a result. When an integral number of Landau levels are filled, E_F can be placed in the gap Δ between two levels. The response of the conduction electrons in these levels to the application of a small electric field E_y gives rise to a Hall current J_x free from dissipation for $kT < \Delta$. J_x results from moving the entire collection of the conduction electrons with $v_d = E_y/B$. In other words, in a reference frame moving with v_d, there is no electric field present and the conduction electrons are simply described by the Landau quantization. The immobile electrons can be activated by temperature as well as applied electric field to hop from site to site even at $kT < \Delta$. These electrons will drift in the moving frame and give rise to dissipation. Our data cannot discern whether the immobile states involved are in the inversion layer, pictured as localized states out of the Landau levels, or impurity states close by. In any case, since the appearance of the ρ_{xy} plateaus results from pinning of E_F in the gap by immobile states, ρ_{xx} can truly be zero only as T and E_y equal to zero. However, increasing B will increase Δ and also the energy barrier and the distance over which the immobile electrons must hop to cause ρ_{xx}. Thus it can be made practically zero at low T by increasing B.

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