Quantum Hall Effect in a Two-Dimensional Electron-Hole Gas

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We have shown experimentally that in a two-dimensional gas with coexisting electrons and holes the quantum Hall effect is determined by the degree of uncompensation of the system. A classical analysis of low-field magnetotransport measurements in GaSb-InAs-GaSb heterostructures gives individual carrier concentrations and mobilities for both electrons and holes. In the quantum Hall regime, with the Fermi level between electron and hole magnetic levels, the filling factor is the difference between the electron and hole filling factors. Similarly, the carrier density is the difference between the electron and hole densities, in analogy with the infinite-field limit of the classical Hall effect.

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A two-dimensional (2D) electron gas, in the presence of a strong magnetic field B perpendicular to it, shows a unique behavior manifested by the quantum Hall effect.[1] The density of states consists of a series of sharp peaks (magnetic levels), each with a degeneracy of eB/h, whose tails are increasingly localized with decreasing temperature T. If the number of electrons per unit area N is constant, like in GaAs-GaAlAs heterostructures, the Fermi level E_F jumps from one level to the next with increasing field. When E_F is inside regions of localized states, the diagonal conductivity σ_{xx} is zero and the off-diagonal conductivity σ_{xy} is $\nu e^2/h$, where ν is the number of filled magnetic levels. This gives rise to zero-magnetoresistance regions ρ_{xx} $[\rho_{xx}=\sigma_{xx}/(\sigma_{xx}^2+\sigma_{xy}^2)]$ with corresponding plateaus in the Hall resistance ρ_{xy} $[\rho_{xy}=-\sigma_{xy}/(\sigma_{xx}^2+\sigma_{xy}^2)]$ at values $h/\nu e^2$, $\nu=1,2,3\ldots$. In the low-temperature limit, where most of the states are localized, a plot of ρ_{xy} vs B consists essentially of a series of wide plateaus connected by very steep straight lines[2] (corresponding to very narrow regions of extended states around the center of the magnetic levels). This phenomenon, known as the quantum Hall effect (QHE), is not limited to a 2D electron gas: It has also been observed in 2D hole systems,[3,4] and preliminary studies in an electron-hole gas have been reported.[5,6]

In this Letter we address the question of the QHE in a 2D gas with coexisting electrons and holes, as exemplified at the interface of an InAs-GaSb heterostructure. The two kinds of carriers result from the intrinsic transfer of GaSb valence-band electrons to the InAs conduction band. Because of the charge separation, the Coulomb scattering is largely reduced, resulting in high mobilities for both types of carriers at low temperatures. In contrast to the GaAs-GaAlAs system, where the carrier density is field independent, in the InAs-GaSb system, in the extreme quantum limit, the electrons are transferred back to GaSb.[7]

For an ideal system with equal numbers of electrons N and holes P, the magnetic levels associated with electrons would cross E_F simultaneously with the hole magnetic levels and, consequently, $\sigma_{xx}=\sigma_{xx}^e+\sigma_{xx}^h=0$ and $\sigma_{xy}=\sigma_{xy}^e-|\sigma_{xy}^h|=0$. In general, N and P are not the same, and only for certain magnetic fields and carrier densities would the Fermi level lie at the same time between localized regions of the electron and hole magnetic levels. In the case of $N>P$, for example, the Hall conductivity would be quantized to a value $\sigma_{xy}=(\nu_e-\nu_h)e^2/h$, where ν_e and ν_h are the electron and hole filling factors, respectively. Thus, the quantum Hall effect should be only sensitive to the difference between the electron and hole filling factors, and therefore only measure the degree of uncompensation in the system, $N-P$, similarly to the classical Hall effect in the infinite-field limit.

For the experiment, a 150-Å InAs film was grown by molecular-beam epitaxy on a thick GaSb buffer layer deposited on an insulating GaAs substrate. The structure was completed with 200 Å of GaSb. The sample was shaped photolitographically into a Hall bar and Ohmic contact to the 2D gases was achieved by evaporation of Au-Ge, with subsequent annealing at 400 °C. The width of the InAs well was such that only the ground electron (InAs) and heavy-hole (GaSb) levels were occupied[7] (electric quantum limit).

Ideally, the hole level would be doubly degenerate (ignoring spin) since identical hole wells would be formed on each GaSb layer. In practice, however, an asymmetry between the two wells is likely to occur as a result of the epitaxial growth process, similarly to GaAs-GaAlAs quantum wells. Such asymmetry would break the degeneracy and, as recent calculations show,[8] might even preclude the charge transfer from one of the GaSb regions. In the following, we will assume nondegeneracy, which is later confirmed by the analysis of the experimental results.

Possible complexities of the subband hole structure have been ignored. At high fields, when the QHE is observed, those complications are irrelevant[3]; at low fields, the fact that the magnetoresistance is temperature independent in the range considered here (see Fig. 3), in contrast to 2D holes in GaAs,[4] suggests either that the hole subband structure of 2D holes in GaSb is relatively simple or that its effect is masked by the much larger conductivity of InAs.

Figure 1 shows low-field magnetotransport measurements at 4.2 K. Both the strong positive magnetoresistance and the nonlinear Hall resistance, independent of temperature, are indicative of two-carrier conduction. A fit of the data by classical magnetotransport expressions[9] yields the carrier densities $N=9.6\times10^{11}$ cm^{-2} and $P=2.2\times10^{11}$ cm^{-2} and mobilities $\mu_e=1.5\times10^5$ $cm^2/V\cdot s$ and $\mu_h=1.2\times10^4$ $cm^2/V\cdot s$, for electrons and holes, respectively. The departure from the ideal condition $(N=P)$ reflects the presence of uncontrolled charged centers, either residual impurities or interface states. Thick epitaxial layers of undoped InAs show consistently a residual impurity concentration of $<5\times10^{16}$ cm^{-3}, insufficient to explain the extra carriers in the InAs quantum well. Moreover, the electron mobility could not be so high if we were to assume a uniform distribution of charged centers across the well. We believe that the extrinsic carriers originate at interface states, especially in view of the $\simeq 0.7\%$ lattice mismatch between InAs and GaSb. The large difference between the electron and hole mobilities arises mostly from the much heavier mass of the GaSb holes ($0.33m_0$, compared to $0.023m_0$ for the InAs electrons), and, to some extent, from the larger electron Fermi velocity.

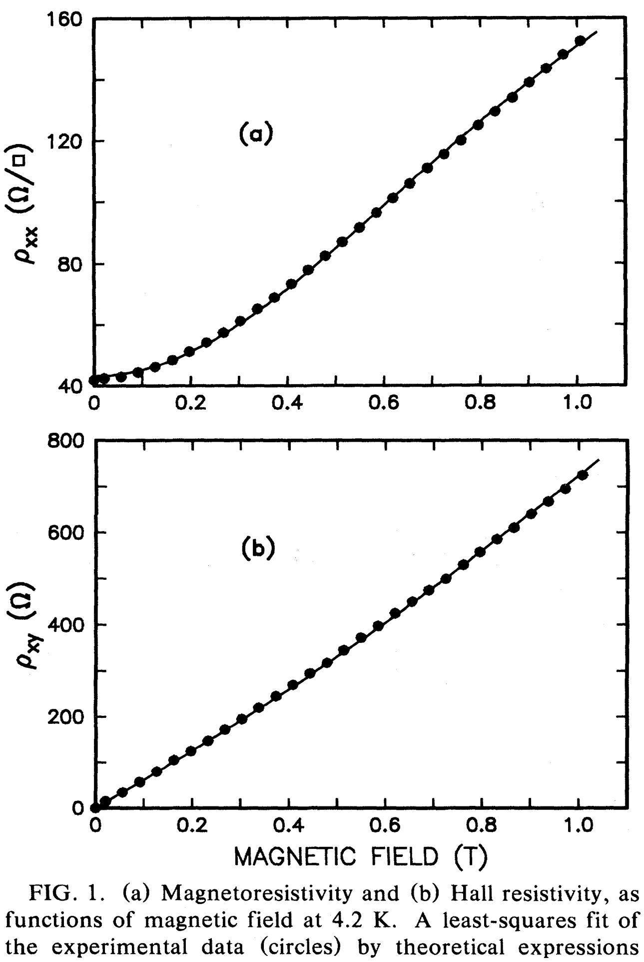

FIG. 1. (a) Magnetoresistivity and (b) Hall resistivity, as functions of magnetic field at 4.2 K. A least-squares fit of the experimental data (circles) by theoretical expressions (continuous lines) yielded the density and mobility of two-dimensional electrons and holes: $N=(9.65\pm0.02)\times10^{11}$ cm^{-2}, $P=(2.19\pm0.01)\times10^{11}$ cm^{-2}, $\mu_e=(1.47\pm0.01)\times10^5$ $cm^2/V\cdot s$, and $\mu_h=(1.25\pm0.02)\times10^4$ $cm^2/V\cdot s$. The magnetoresistance curve is very sensitive to small deviations from the fitted values of the adjusting parameters.

For magnetic fields above 1 T, for which $\omega_c\tau \gg 1$ for electrons (quantum regime), ρ_{xx} shows Shubnikov–de Haas oscillations periodic in B^{-1}. The circles in Fig. 2 represent the inverse-field positions of the minima versus the filling factor, related to the Landau level index n by $\nu=2n+1$. A least-squares fit by $\nu=h/eNB^{-1}$ yields an electron concentration of 9.9×10^{11} cm^{-2}, in good agreement with the value obtained from the low-field analysis.

At high magnetic fields the 2D holes enter the quantum regime and, except for certain fields, the situation becomes rather complicated, as seen in Fig. 3. The Fermi level will be between completely filled electron and hole levels, whenever $N=(e/h)B\nu_e$ and $P=(e/h)B\nu_h$, which occurs in the present case at $\nu_e=4\nu_h$, as $N\simeq 4P$. The two prominent minima in ρ_{xx} at $B=5$

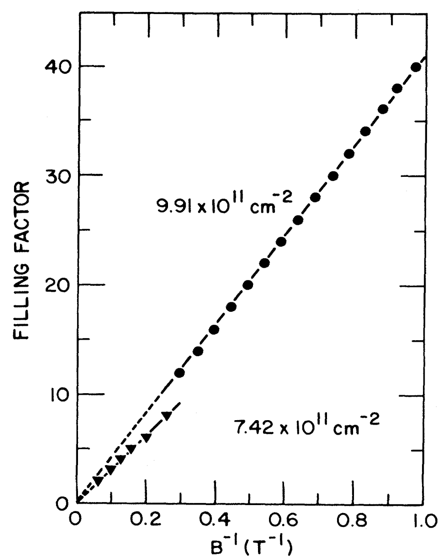

FIG. 2. Plots of the magnetic field positions of the Shubnikov–de Haas minima (circles) and of the Hall plateaus (inverted triangles), as a function of the filling factor. The carrier density determined from the Shubnikov–de Haas data represents the electron density N, whereas the one obtained from the quantum Hall plateaus corresponds to the amount of uncompensation, $N-P$.

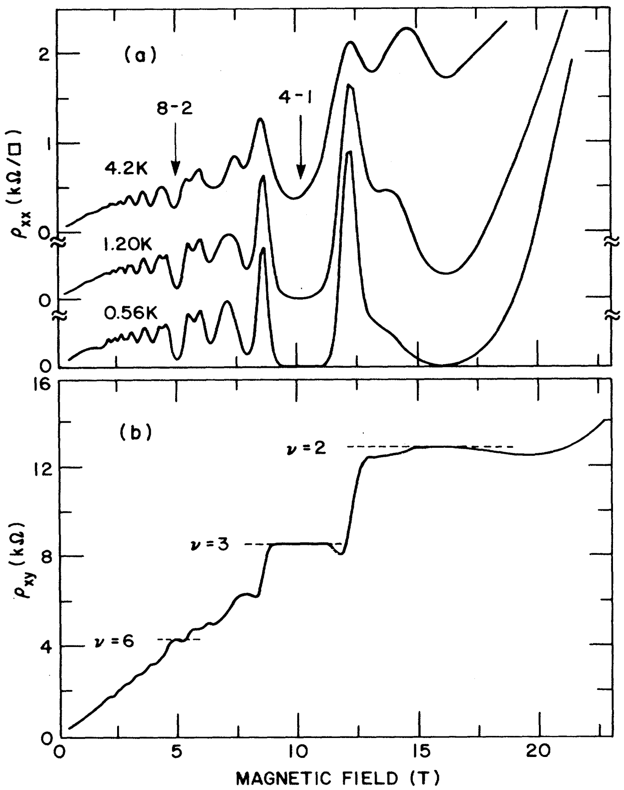

FIG. 3. (a) Magnetoresistivity at three representative temperatures, and (b) Hall resistivity at 0.56 K, vs magnetic field. Although Shubnikov–de Haas oscillations due to electrons are shown at low fields in (a), the emphasis is on high fields, when both electrons and holes are in the quantum regime. The arrows indicate the fields at which the Fermi level is simultaneously between electron and hole magnetic levels and the labels above them give the corresponding filling factors. The broken lines in (b) indicate the theoretical values $h/\nu e^2$, for $\nu = 2,3,6$, so that the filling factor determined by the quantum Hall effect represents the difference between the electron and hole filling factors. The small dips at the high-field end of the Hall plateaus have also been observed in one-carrier systems (Ref. 10) and are believed to be due to geometrical effects.

and 10 T in Fig. 3(a), the latter of which reaches a value of zero at the lowest temperature, correspond to the situations with $\nu_e = 8$, $\nu_h = 2$ and $\nu_e = 4$, $\nu_h = 1$, as indicated. At these fields the Hall resistance in Fig. 3(b) exhibits plateaus at the values of $h/e^2\nu$ with $\nu = \nu_e - \nu_h = 6$ and 3. With decreasing T, ρ_{xx} tends also to vanish at 6.3, 7.8, and 16 T, while the corresponding plateaus approach their theoretical values of $h/e^2\nu$ with $\nu = 5$, 4, and 2.[11] A plot of ν vs the inverse field is shown in Fig. 2 as inverted triangles, from which the carrier concentration of 7.4×10^{11} cm^{-2} is deduced. That this value agrees with the difference $N - P$ demonstrates that the quantum Hall effect measures only the number of uncompensated carriers in an electron-hole system. Moreover, the facts that the high-field slope gives $N - P$ (rather than $N - P/2$) and that $\nu_e - \nu_h = 3\nu_h$ (and not $7\nu_h$) are consistent with the assumption on the asymmetry of the two hole wells.

These results are quite general and lend themselves to situations when individual magnetic levels cross the Fermi level. Since σ_{xy}^e and σ_{xy}^h have opposite signs, σ_{xy} will increase by e^2/h whenever E_F jumps from one electron level to the next, and decrease by the same amount when the jump is between hole levels. Consequently, ρ_{xy} in principle would not show an ever-ascending ladder behavior.

In this regard, the relative simplicity of the main features in our experimental results is surprising. The fact that between 5.5 and 10 T only three Hall plateaus are observed at very low temperatures[12] ($\nu = 5,4,3$), while four electron levels and one hole level pass by the Fermi level, requires that two electron levels cross E_F simultaneously with the hole level. The peak in ρ_{xx} at 6 T, as well as the one at 14.5 T for $T = 4.2$ K, may be a manifestation of the effect. Their behavior is rather peculiar: Both decrease in amplitude with decreasing temperature, the former vanishing exponentially with decreasing T (Ref. 12), and their peak positions shift to lower fields at lower T, as is evident in Fig. 3 for the 14.5-T structure. Associated to these peaks there are plateaus in ρ_{xy} (for $5 < \nu < 6$ and $2 < \nu < 3$), whose center positions coincide with minima in ρ_{xx}, and which merge with the regular plateaus ($\nu = 5, 2$) in the low-T limit. The detailed behavior of these structures is complicated; the close vicinity in magnetic field at which E_F is crossed by the electron and the hole levels, together with their difference in temperature activation, is believed to contribute to the complexity.

In summary, we have considered the general question of the quantum Hall effect in a two-carrier system, using InAs-GaSb heterostructures as a prototype example. The system can be treated as a consisting of a 2D electron gas and a 2D hole gas in parallel, whose difference in density governs the Hall plateaus and the filling factors. We have also shown that considerable information can be obtained by analysis of the magnetotransport results in different regimes throughout the entire field range. This has led for the first time to the observation of holes in InAs-GaSb and to the quantitative determination of the degree of compensation in the system.

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[11]The slow trend towards the zero-resistance states for $\nu = 5,4,2$ is a direct consequence of conduction through the 2D hole channel, whose magnetic levels are partially occupied. This phenomenon is different from three-dimensional parallel conduction, frequently observed in GaAs-GaAlAs heterostructures, whose signature is a resistance background that increases with field, preventing zero-resistance regions, and a saturation of the Hall resistance. For a detailed study of that effect see, e.g., B. J. F. Lin, Ph.D. thesis, Princeton University, 1984 (unpublished).

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