PHYSICAL REVIEW B VOLUME 53, NUMBER 16 15 APRIL 1996-II

Zero-Hall-resistance state in a semimetallic InAs/GaSb superlattice

M. S. Daly, K. S. H. Dalton, M. Lakrimi, N. J. Mason, R. J. Nicholas, M. van der Burgt, and P. J. Walker
Physics Department, Oxford University, Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, United Kingdom

D. K. Maude and J. C. Portal
Laboratoire de Champs Magnetique Intenses–CNRS, 25 Avenue des Martyrs, Boîte Postale 166, 38042 Grenoble Cedex, France

(Received 11 January 1996)

We observe giant oscillations in the Hall resistivity of a semimetallic superlattice of InAs/GaSb, with almost equal electron and hole densities. A thermally activated zero is observed in the Hall resistivity when the Fermi energy lies within the localized states for electrons and holes with the same Landau index. This is interpreted as the balancing of the electron and hole contributions, and depends critically on the limiting behavior of the conductivity components as they approach quantized values.

Since its discovery in 1980,[1] the quantum Hall effect has provoked extensive interest due to the fundamental accuracy of its quantization and the discussion of the mechanisms by which it occurs. Examples of the quantum Hall effect have been reported for both electron and hole systems, and for systems with co-existing gases of both types of carriers.[2] In this paper, we report an example of the quantum Hall effect in a semimetallic system with almost equal numbers of electrons and holes. The Hall resistivity shows giant oscillations and approaches zero for a specific range of magnetic fields where there are equal numbers of electrons and hole Landau levels occupied. The structures used for this study are semimetallic InAs/GaSb superlattices with very closely matched electron and hole densities (typically $n_e = 1.02 n_h$). The bands in this system have a broken, or crossed gap, alignment in which the conduction-band edge of the InAs falls below the valence-band edge of the GaSb,[3,4] leading to intrinsic charge transfer from the GaSb to the InAs. Ideal structures would therefore be expected to have equal numbers of electrons and holes.

Previous studies of the quantum Hall effect in this system were made on single well structures in which a significant amount of residual extrinsic charge was present, leading to a large imbalance in the numbers of electrons and holes. Such structures showed compensated quantum Hall plateaus,[2] where the number of Hall conductance quanta was given by the (finite) difference in the numbers of occupied electron (ν_e) and hole (ν_h) Landau levels, and so $\rho_{xy} = h/[e^2(\nu_e - \nu_h)]$, where ν_e and ν_h are integers. At the same time the resistivity ρ_{xx} showed pronounced minima. This behavior was interpreted as being due to a Fermi level, which lies simultaneously within the localized states of both the electrons and holes. In our recent studies of superlattices with more closely matched electron and hole concentrations,[5,6] the structure in the Hall resistivity became more dramatic, with the observation of large oscillations. The present paper describes the final limit of this behavior, where we now have structures in which the localized states of both electrons and holes can be made to overlap for equal numbers of Landau levels. This generates qualitatively new behavior, in which a zero Hall resistance state appears, accompanied by a strong divergence of the diagonal resistivity ρ_{xx}.

The classical Hall effect for a two carrier system is dominated by the highest mobility carriers at low fields, while at high fields it measures the total net charge, with the Hall coefficient R_H given by $1/(n_e - n_h)e$, where n_e and n_h are the electron and hole densities, respectively.[7] For an intrinsic semimetal this means that the high-field Hall resistivity would be expected to diverge when $n_e = n_h$. The Hall *conductivity* is given by $\sigma_{xy} = \sigma_{xy}^e - |\sigma_{xy}^h|$, and for a two-dimensional (2D) system when the Fermi level lies within the localized states for both carrier types $\sigma_{xy} = (\nu_e - \nu_h)(e^2/h)$. When the system is intrinsic we expect that the filling factors for the electron and hole Landau levels are equal, leading to a zero Hall conductivity. Since $\rho_{xy} = \sigma_{xy}/(\sigma_{xy}^2 + \sigma_{xx}^2)$, the quantum limit behavior of the experimentally measured Hall *resistivity* will therefore depend on the limiting behavior of both conductivity components as they tend to zero. If there is a finite σ_{xx}^2 that tends to zero less quickly than σ_{xy}, a zero Hall resistance state will occur as a special condition of the quantum Hall effect. By contrast, ρ_{xy} will diverge if $\sigma_{xx} \sim \sigma_{xy}$, corresponding to the case of $\Delta\rho_{xy} \sim \rho_{xx}$ (and thus of $\Delta\sigma_{xy} \sim \sigma_{xx}$), which has been observed for deviations from the exact quantum Hall resistance near integer plateaus in silicon devices.[8]

The sample used for the majority of the work presented here is a long-period superlattice of 20 layers of 220-Å InAs alternating with 21 layers of 190-Å GaSb, with the whole structure terminated at each end with a short period (36-Å InAs/30-Å GaSb) superlattice. The outer superlattices are designed to have a semiconducting energy gap and hence have no intrinsic charge carriers present at low temperatures. The samples are grown by metal organic vapor-phase epitaxy[9] (MOVPE) onto a GaAs substrate, with a precoating and buffer layer of 2 μm of GaSb. They have very low levels of extrinsic charge, so that the short-period superlattices are insulating at low temperatures, and the overwhelming majority of the carriers in the long-period region of the structure arise due to intrinsic charge transfer. The interfaces are grown with a gas switching sequence ordered to produce well-defined interfaces composed of a monolayer of InSb, as demonstrated by Raman scattering.[10] Samples were patterned into 500-μm-wide Hall bars. The experiments used both high pulsed magnetic fields (45-T pulses of 15 msec) down to 600

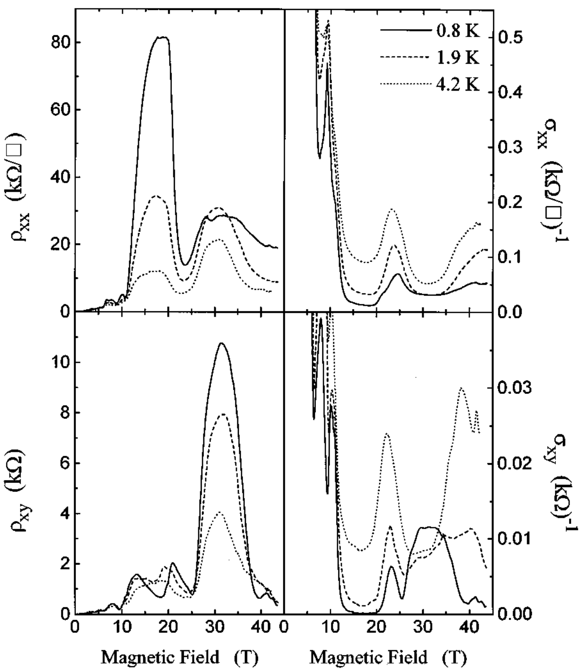

FIG. 1. The resistivity and conductivity components of the 20-period semimetallic superlattice measured using a pulsed field at three different temperatures.

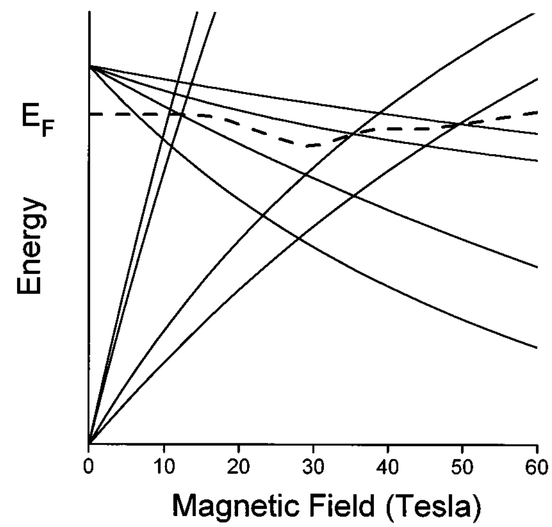

FIG. 2. A schematic picture of the electron and hole Landau levels (solid lines) and the motion of the Fermi energy (dashed line) as a function of magnetic field. This is a simplification of the results of a multiband **k·p** calculation as in Ref. 11, but neglecting the effects of band mixing.

mK, and a dilution refrigerator with steady magnetic fields at high hydrostatic pressures (up to 8.6 kbar). Due to the large difference between the magnitudes of the ρ_{xy} and ρ_{xx} signals small amounts of mixing between the two components due, e.g., to an imbalance in the contacts or an inhomogeneity in the structure may be very significant, so that all traces were measured by reversing the magnetic field and calculating $\rho_{xy}=[\rho_{xy}(B)-\rho_{xy}(-B)]/2$ for both steady and pulsed magnetic fields.

Figure 1 shows the resistivity and Hall voltage in the above structure for several temperatures from 4.2 to 0.8 K up to 45 T. The resistivity ρ_{xx} shows a large magnetoresistance, as expected for a system with comparable numbers of electrons and holes, while the sign of the Hall coefficient is electronlike with its magnitude at low fields dominated by the higher mobility electrons. Fitting the low-field transport to a classical two carrier formula[7] gives total electron and hole densities of 13.5 and 13.3×10^{12} cm^{-2}, and mobilities of 55 000 and 9 500 cm^2 V^{-1} s^{-1} respectively. These values, taken together with low-field Fourier transforms of the resistivity, indicate that all 20 layers within the structure are active, and are consistent with the assumption that almost all of the carriers present arise due to charge transfer from the GaSb to the InAs layers. Calculating the energy levels and confinement energies self-consistently from the measured densities gives a band overlap of 153 meV, consistent with the conventionally accepted value.[3,4]

At higher fields, strong oscillatory features develop in both the diagonal resistivity and Hall voltage, with thermally activated peaks occurring at around 18 T in ρ_{xx} and 32 T in ρ_{xy}. At the highest fields (~44 T) the Hall resistivity shows a rapid decrease, which approaches zero at low temperatures. Converting to conductivity, it can be seen that there are two strong minima in σ_{xy} in the regions around 18 and 44 T at low temperatures, and that both of these features correspond to fields where ρ_{xx} shows a thermally activated increase. Previous experimental and theoretical studies of the Landau levels in this system[4,6] suggest that these features correspond to magnetic fields at which the Fermi levels lies in the gap between hole Landau levels such that either both (18 T) or one (44 T) of the spin states of the lowest Landau levels of the electrons and holes are occupied. Assuming that the system is close to charge neutrality, as indicated by the near equality of the electron and hole concentrations at low fields, we can plot schematically the motion of the Fermi energy as a function of magnetic field, as shown in Fig. 2. The fields at which the minima in σ_{xy} occur correspond to the points where the Fermi energy lies in a gap between both the electron and hole Landau levels. At fields just above these points, the levels cross each other, corresponding to a Fermi energy lying in the extended states where the divergent peaks occur in the Hall resistivity. At still higher fields, there is a rapid fall in the carrier density as the levels uncross, as demonstrated by high-field cyclotron resonance studies.[11] It is expected theoretically[11–13] that mixing of the conduction and valence bands will occur, leading to level repulsion, thus preventing the crossing of the electron and hole levels and causing the formation of a small energy gap. This mixing will be relatively small in longer period structures, and at present there is no clear experimental evidence of the formation of this gap.

In practice, it is relatively difficult to use pulsed magnetic fields to investigate precisely the behavior of the features for which the Hall voltage approaches zero. This is due to the simultaneous divergence of ρ_{xx}, which leads both to a high effective impedance of the system and to the small values of the Hall voltages relative to those measuring the diagonal resistivity. We therefore adopt the alternative procedure of applying hydrostatic pressure to the system, which is known to reduce the value of the band overlap,[14,15] and hence will move the strong features down in magnetic field proportional

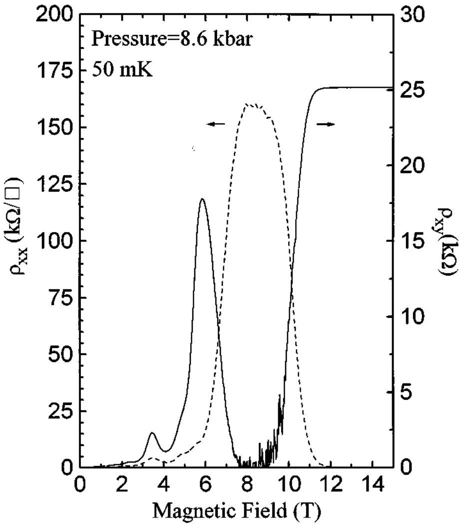

FIG. 3. The magnetic-field dependence of the diagonal (ρ_{xx}) and Hall (ρ_{xy}) resistivity of the 20-period superlattice at 50 mK at a pressure of 8.6 kbar.

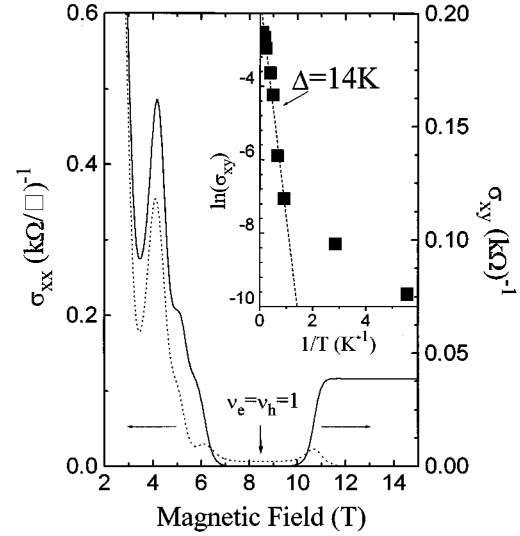

FIG. 4. The conductivity components deduced from Fig. 3. The inset shows the activation plot measured from the Hall conductivity minimum at 8.5 T.

to the decrease in the separation of the hole and electron levels. This allows the use of dc fields and dilution refrigerator temperatures. Figure 3 shows the resistivity components ρ_{xx} and ρ_{xy} of the same structure studied at a pressure of 8.6 kbar at 50 mK. The overlap of the conduction- and valence-band edges at zero field is now reduced to $\sim$70 meV, giving electron and hole densities of $\sim$5.6 and 5.3×10^{12} cm^{-2} at low fields, with all 20 layers still active. The large oscillatory features now occur at much lower magnetic fields, and at $\sim$8.5 T only one spin state of one Landau level is occupied by the electrons and holes for each layer (corresponding previously to $\sim$44 T). At this point, the Fermi level lies within the localized states for both electrons and holes, and the Hall effect from both carriers is quantized with equal magnitude and opposite sign. The Hall effect disappears, and the diagonal resistivity is seen to diverge. The corresponding traces for σ_{xy} and σ_{xx} both show minima at this point (Fig. 4), but some finite σ_{xx} remains. At slightly lower fields the extended states of the electrons and holes overlap, leading to a classical value for the Hall resistance, namely a divergence with $R_H=1/(n_e-n_h)e$, and $(n_e-n_h)\ll n_e$. For higher fields, the levels begin to uncross, and a conventional quantum Hall plateau is observed at a resistivity of h/e^2. This is thought to arise due to the small number ($\sim3\times10^{11}$ cm^{-2}) of residual electrons in the superlattice becoming confined in only a single layer.

The magnitude of the gap between the localized states responsible for the appearance of the zero in the Hall resistance can be estimated from an activation plot of the σ_{xy} minimum. Fitting the data from 5.6 to 1 K to a conventional Arrhenius plot of $\sigma_{xy}\sim\exp-(\Delta/2\ kT)$ gives a value of $\Delta=14$ K, as can be seen in the inset to Fig. 4. This value is approximately half that of the expected spin splitting of the lowest hole Landau level, which is a few tens of Kelvin, as estimated by comparison with the spin splitting observed for a hole gas in a GaSb/InGaSb quantum well.[16] This difference is quite reasonable given the expected reduction of the activation gap by Landau-level broadening, which is estimated to be of order 15 K, using the low-field Hall mobility of the holes.

The observation of a zero Hall resistance states is crucially dependent on the limiting behavior of σ_{xy} and σ_{xx} in a region where both conductivity components are tending to zero. In studies on localized systems in both three and two dimensions, Viehweger and Efetov[17] and Kivelson, Lee, and Zhang[18] have recently shown that a finite, essentially classical, value of ρ_{xy} occurs at the same time as ρ_{xx} diverges in the quantum limit for a single carrier system, known as the Hall insulator. This requires $(\sigma_{xy}/\sigma_{xx}^2)\approx(B/ne)$, while both conductivity components tend to zero, as suggested by the scaling theory of weak localization in two dimensions.[19] Using a Landau-level attachment transformation Kivelson, Lee, and Zhang[18] predict that deviations from exact quantization of integer units of the Hall conductivity will take place with $\Delta\sigma_{xy}\propto\sigma_{xx}^2 B/ne$. For an exactly compensated system, where the conductivity components are tending to zero, one might therefore expect a finite but nonquantized value of ρ_{xy}. However, for an intrinsic semimetallic system, the deviations from exact quantization of the Hall voltage about the center of the plateau will balance with $\Delta\sigma_{xy}^e\approx-|\Delta\sigma_{xy}^h|$, i.e., equal numbers of electrons and holes will contribute to σ_{xy} by equal and opposite amounts, whereas both will contribute positively to σ_{xx}. Thus $(\Delta\sigma_{xy}^e-|\Delta\sigma_{xy}^h|)\ll(\sigma_{xx}^{e2}+\sigma_{xx}^{h2})B/ne$ leading to the experimentally observed result of a zero Hall resistance state.

The exact behavior of the system will also be crucially dependent on the presence of any parallel contribution to the conductivity by, for example, any single layer with a different carrier density, and hence we have gone to considerable lengths to terminate the superlattice with nonconducting layers. Well-defined minima in σ_{xy} and σ_{xx} are also observed at similar field values to those described above, for both zero and high pressure, in both 20- and 80-period superlattices grown without the short-period terminating superlattices. However, the minima in σ_{xy} occur at finite values of e^2/h due to the presence of shorting paths attributed to higher-density 2D layers, which occur at the ends of the long-period superlattice,[20] thus preventing the observation of a clear zero Hall resistance state.

In conclusion, therefore, we have observed a new special condition of the quantum Hall effect, in which the contribution to the Hall voltage from electrons and holes exactly balances, leading to a zero Hall resistance. This phenomenon is strongly dependent on the limiting behavior of the conductivity components as they approach the exact quantization condition, and may be a critical test of the scaling of the conductivity components.

We acknowledge the support of the E.P.S.R.C. (U.K.). M.v.d.B. acknowledges support from the E.U. through the HCM program.

[1] K. von Klitzing, G. Dorda, and M. Pepper, Phys. Rev. Lett. **45**, 494 (1980).
[2] E. E. Mendez, L. Esaki, and L. L. Chang, Phys. Rev. Lett. **55**, 2216 (1985).
[3] H. Sasaki, L. L. Chang, G. A. Sai-Halasz, C. A. Chang, and L. Esaki, Solid State Commun. **26**, 589 (1978).
[4] R. J. Nicholas *et al.*, Physica B **184**, 268 (1993).
[5] K. S. H. Dalton *et al.*, Surf. Sci. **305**, 156 (1994).
[6] R. J. Nicholas *et al.*, Physica B **201**, 271 (1994).
[7] R. A. Smith, *Semiconductors* (C.U.P., Cambridge, 1961), p. 107.
[8] A. Hartland, K. Jones, J. M. Williams, B. L. Gallagher, and T. Galloway, Phys. Rev. Lett. **66**, 969 (1991).
[9] G. R. Booker *et al.*, J. Cryst. Growth **145**, 778 (1994); **146**, 495 (1995).
[10] S. Lyapin, P. C. Klipstein, N. J. Mason, and P. J. Walker, Phys. Rev. Lett. **74**, 3285 (1995).
[11] D. J. Barnes, R. J. Nicholas, R. J. Warburton, N. J. Mason, P. J. Walker, and N. Miura, Phys. Rev. B **49**, 10 474 (1994).
[12] A. Fasolino and M. Altarelli, Surf. Sci. **142**, 322 (1984).
[13] M. Altarelli, J. C. Maan, L. L. Chang, and L. Esaki, Phys. Rev. B **35**, 9867 (1987).
[14] J. Beerens, G. Gregoris, S. Ben Amor, J. C. Portal, E. E. Mendez, L. L. Chang, and L. Esaki, Phys. Rev. B **35**, 3039 (1987); **36**, 4742 (1987).
[15] D. M. Symons *et al.*, Phys. Rev. B **49**, 16 614 (1994).
[16] R. W. Martin, S. K. Haywood, G. J. Rees, R. J. Nicholas, N. J. Mason, and P. J. Walker, Phys. Rev. B **42**, 9237 (1990).
[17] O. Viehweger and K. B. Efetov, J. Phys. Condens. Matter **2**, 7049 (1990).
[18] S. Kivelson, D. H. Lee, and S. C. Zhang, Phys. Rev. B **46**, 2223 (1992).
[19] H. Fukuyama, J. Phys. Soc. Jpn. **49**, 644 (1980).
[20] M. S. Daly *et al.*, J. Phys. Chem. Solids **56**, 453 (1995).