Metal-Insulator Oscillations in a Two-Dimensional Electron-Hole System

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The electrical transport properties of a bipolar InAs/GaSb system have been studied in a magnetic field. The resistivity oscillates between insulating and metallic behavior while the quantum Hall effect shows a digital character oscillating from 0 to 1 conductance quantum e^2/h. The insulating behavior is attributed to the formation of a total energy gap in the system. A novel looped edge state picture is proposed associated with the appearance of a voltage between Hall probes which is symmetric on magnetic field reversal.

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The quantum Hall effect has become well known since its first observation by von Klitzing *et al.* [1] but still raises a number of fundamental questions, including the role of edge states which ensure the possibility of dissipationless conduction [2,3]. Here we examine the quantum Hall effect and magnetotransport properties of a bipolar system of coupled electrons and holes and demonstrate that such a system shows qualitatively different behavior to that observed for single carriers. Such systems have generated considerable interest due to the possibilities of gap formation by both excitonic [4,5] and single particle [6] interactions. The electron-hole system introduces the new possibility that the edge states of the electron and hole systems may interact, breaking the normal quantum Hall conditions. The first observation of quantum Hall plateaus in an electron-hole system by Mendez *et al.* [7] found that conventional plateaus were formed at quantum numbers corresponding to the difference in the occupancies of the electron and hole Landau levels. Subsequently Daly *et al.* [8] found that in superlattices with closely matched electron and hole densities the special case of zero Hall resistance could be seen. Here we study the behavior of insulating states formed in a structure containing one layer each of electrons and holes which interact via interband mixing. If mixing occurs between edge states, a total energy gap may appear for the system leading to the insulating behavior. Several gaps can result from the mixing between different electron and hole Landau levels, and as a result the system displays oscillatory metallic and insulating behavior as a function of magnetic field and the Hall conductivity follows a binary sequence oscillating from 0-1-0 conductance quanta.

The samples studied consisted of a single layer of InAs sandwiched between thick layers of GaSb. This system has a broken gap lineup with the conduction band edge of the InAs 150 meV below the valence band edge of the GaSb. The samples are grown by metal organic vapor phase epitaxy and have a relatively low level of impurities so that the majority of charge carriers are created by intrinsic charge transfer from the GaSb layers to the InAs layer. Typical structures are grown on semi-insulating GaAs with a 2 μm buffer layer of GaSb. The InAs layer is typically 30 nm thick, followed by a 90 nm GaSb cap. Fitting the low field magnetoresistance and Hall effect to classical two carrier formulas gives carrier densities of the electrons and holes of order 6.5×10^{15} m^{-2} and 4.5×10^{15} m^{-2}, respectively. Evidence from magnetotransport suggests that the structures are asymmetric due to pinning of the Fermi level E_F at the surface causing the holes to be on one side of the structure giving Fermi surfaces for the electrons and holes of similar magnitudes [9,10]. Determination of the carrier mobilities is less straightforward due to the minigap caused by the electron-hole interaction. However, by applying a large parallel magnetic field, which is known to decouple the bands [10,11], the mobilities for the decoupled electrons and holes are estimated to be $\sim$20 and 1 m^2 V^{-1} s^{-1}. Five wafers were studied in detail and all gave similar results independent of the contacting methods used.

Magnetotransport measurements were made using ac techniques with a dilution refrigerator and 15 T superconducting magnet, and a ^{3}He cryostat and 50 T pulsed field magnet system on wide Hall bars of width 0.5 mm. Measurements were made with the magnetic field in both forward ($B+$) and reverse ($B-$) directions so that the resistances can be separated into symmetric (S) and antisymmetric (A) parts with respect to field reversal:

$$R^S_{xx} = [R_{xx}(B+) + R_{xx}(B-)]/2 = \rho_{xx} \times L/W\,,$$
$$R^A_{xx} = [R_{xx}(B+) - R_{xx}(B-)]/2\,,$$
$$R^S_{xy} = [R_{xy}(B+) + R_{xy}(B-)]/2\,,$$
$$R^A_{xy} = [R_{xy}(B+) - R_{xy}(B-)]/2 = \rho_{xy}\,.$$

The symmetric part of R_{xx} was used with the length to width ratio (L/W) of the bar to give the diagonal resistivity

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ρ_{xx}, and the antisymmetric part of R_{xy} is taken to be the Hall resistivity ρ_{xy}, according to the Onsager relations. The antisymmetric part of R_{xx} is generally found to be negligibly small, and the symmetric part of R_{xy} is usually attributed to the (small) admixing of the diagonal resistivity [12].

Figure 1 shows typical plots of the magneto- and Hall resistivity at temperatures down to 40 mK using steady fields and 500 mK in pulsed fields. The traces show a number of striking features characteristic of two carrier structures [13,14]. There is a very large positive magnetoresistance with relatively weak oscillatory features at low field. At higher fields there are strong minima at 8.5 and 22 T and large maxima at 7, 15, and 45 T which increase rapidly with falling temperature. The peak at 15 T has a resistivity which increases to several thousand times its zero field value at 150 mK. By contrast, the Hall resistivity shows stronger oscillations at low fields, but has only one feature attributable to the formation of a quantum Hall plateau at 8.5 T at the lowest temperatures where $\nu_e - \nu_h = 1$. Minima occur where ρ_{xy} approaches zero at 15 T and 150 mK and at 45 T and 0.5 K.

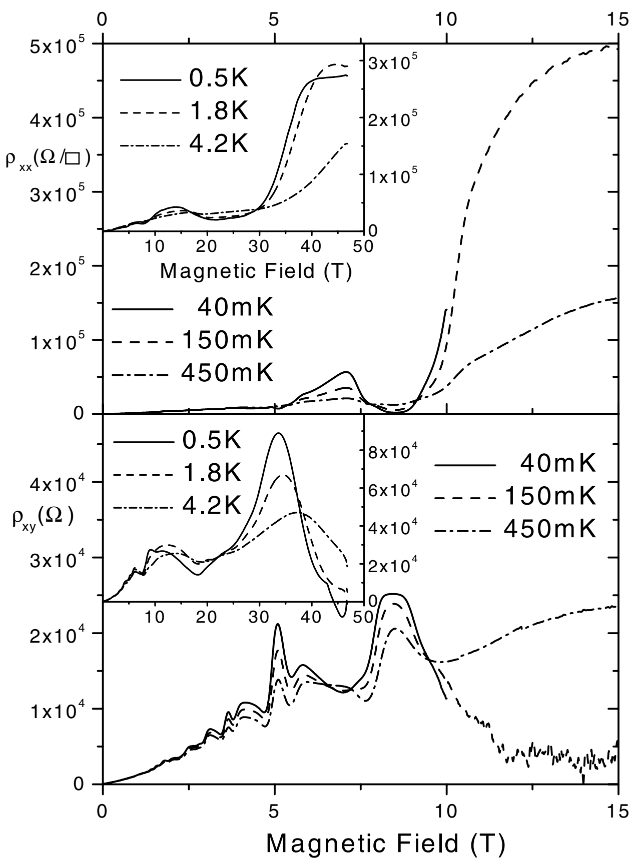

FIG. 1. The magnetoresistivity components ρ_{xx} and ρ_{xy} measured in steady fields (main figure) and pulsed fields (insets) for temperatures from 40 mK to 4.2 K. The maximum measurable resistivity values are restricted in the low field section of the pulsed field data due to capacitative effects.

The origins of this behavior are clearer when the resistivity components are converted to conductivity [15]. Figure 2 shows that σ_{xy} has a low temperature zero above 40 T and in the region 10–15 T, and approaches zero around 7 T. Between these fields one conductance quantum of e^2/h is observed at the lowest temperatures in the steady field data, and a peak moving towards this value with falling temperature is observed at around 20 T in the pulsed field data. Minima occur in σ_{xx} when ρ_{xx} has both minima and strong maxima where $\rho_{xx} \gg \rho_{xy}$.

An important feature of broken gap systems is that the electron Landau levels start at a lower energy than the hole levels, and as a function of magnetic field the two sets of levels must cross. Because of the finite interband mixing between the valence and conduction bands, the levels anticross leading to the formation of a miniband gap [10,11,16–20], shown schematically in Fig. 3(a). The movement of the levels through each other leads to oscillatory carrier densities due to the varying density of states, but the position of the Fermi level varies much less than in single carrier systems due to charge transfer between the bands. For structures with a small net doping (i.e., $n_e - n_h$ is small and constant) the Fermi level can lie close to the center of either electron or hole Landau levels or within the localized tail states of either or both carrier types. In the simplified schematic Fig. 3(a) the Fermi level is shown as constant. The net occupancy of the levels will oscillate between 0 around positions a (where $\nu_e - \nu_h = 0 - 0$) and c (where $\nu_e - \nu_h = 1 - 1$) and 1 for b (where $\nu_e - \nu_h = 1 - 0$) and d (where $\nu_e - \nu_h = 2 - 1$). The particularly unusual features of the conduction process occur when the Fermi level

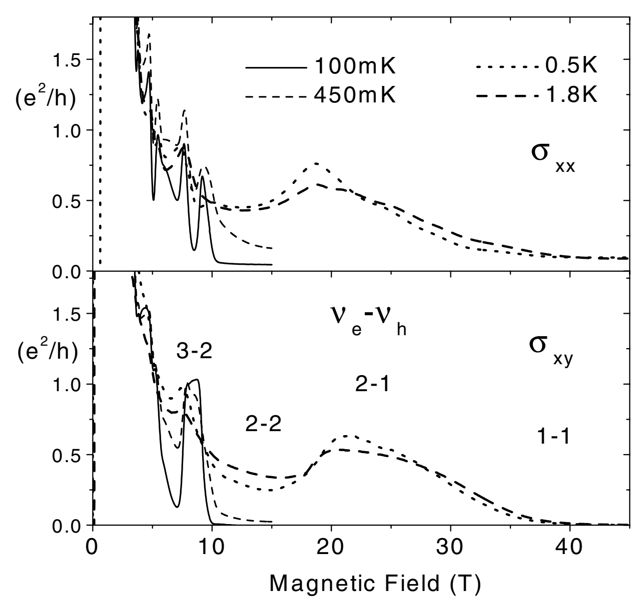

FIG. 2. The conductivity components σ_{xx} and σ_{xy} calculated from the data in Fig. 1. The figures indicate the expected electron (ν_e) and hole (ν_h) Landau level occupancies.

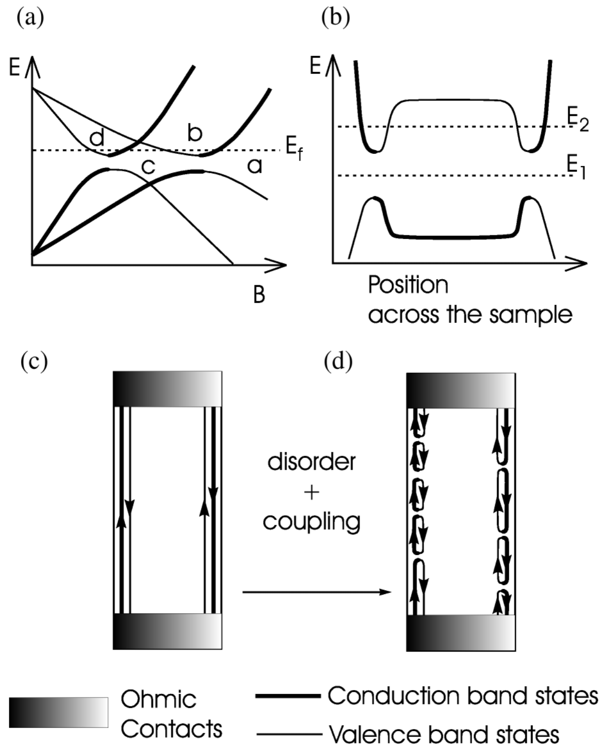

FIG. 3. (a), (b) The electron and hole Landau levels as a function of magnetic field and spatial position, respectively. Electronlike levels are shown in heavier lines. (c), (d) Possible edge current paths in the insulating state with and without the presence of disorder.

lies between equal numbers of electron and hole Landau levels. In this case the system is able to show a complete energy gap which leads to the appearance of oscillatory insulating behavior as a function of magnetic field.

In single carrier systems the quantum Hall condition also corresponds to a situation where the Fermi level lies within a mobility gap between Landau levels. As the levels approach the sample edges, however, they move upwards in energy and form nondissipative conducting edge states which generate zeros in the resistivity and quantum Hall plateaus. The picture can be quite different in interacting electron-hole systems. Considering a spatial plot of the energy levels of the electrons and holes shown in Fig. 3(b) we expect that as they approach the edges of the structure the electron levels will move upwards due to the edge confinement, while in contrast the hole levels will move downwards. As a result the electron and hole levels will always approach each other but, due to the interband coupling, the levels will anticross, producing an energy gap. When the Fermi level in the bulk lies between an equal number of electron and hole levels, the structure will always show completely insulating behavior. This conclusion is obvious when the Fermi level in the bulk also corresponds to the anticrossing gap at the edges, e.g., for $E_F = E_1$ in Fig. 3(b). It also holds when it crosses the interacting electron and hole edge states since the number of these states is equal leading to zero net current flow as for $E_F = E_2$ in Fig. 3(b). At contacts to the structure we expect edge states to be at the potential of the originating contact. Although the electron and hole states represent one dimensional current paths with opposite directions [Fig. 3(c)], we might expect that the edges would be equipotentials giving zero resistivity. This is not the case, however, since fluctuations in the potential could cause the gap to rise above the Fermi level, thus disconnecting the channels into two U turns. More than one such disconnection will lead to a series of isolated conducting loops along the sample edge. One possible arrangement is shown schematically in Fig. 3(d).

By contrast, when there is population within the bulk of an unequal number of Landau levels, there is population of a finite net number of edge states. This gives metallic behavior with compensated quantum Hall plateaus in the Hall resistance and zeroes in ρ_{xx}. There is a rotation through ~90° of the equipotentials which now lie along the conducting edge states of the bar in the metallic quantum Hall state.

The oscillations between insulating and metallic behavior occur as the Fermi level moves through regions b, d (metallic) and a, c (insulating) in Fig. 3(a). The appearance of an insulating state is crucially linked to the anticrossing levels, and it is interesting to note that a previous report of a reentrant insulating phase in p-SiGe was tentatively linked to unusual Landau level degeneracy [12] where states may be crossing.

Evidence of a strong distortion of the current paths in the insulating state comes from the large symmetric component (about 50% of ρ_{xx}) in R_{xy} occurring specifically at the fields where the system becomes insulating. Figure 4 shows R_{xy} as measured with both directions of the magnetic field. The symmetric and antisymmetric parts are

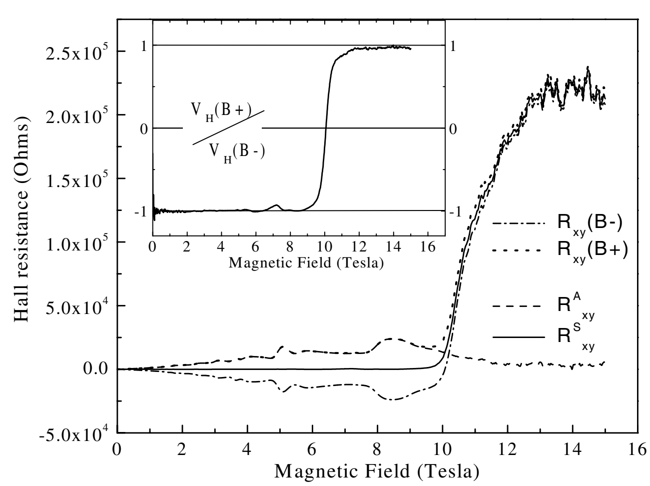

FIG. 4. The experimentally measured Hall resistance components $R_{xy}(B+)$ and $R_{xy}(B-)$, and the values deduced for the symmetric and asymmetric Hall resistance R^S_{xy} and R^A_{xy} measured at 100 mK. The inset shows the ratio of the experimentally measured Hall resistivities on reversing magnetic field direction.

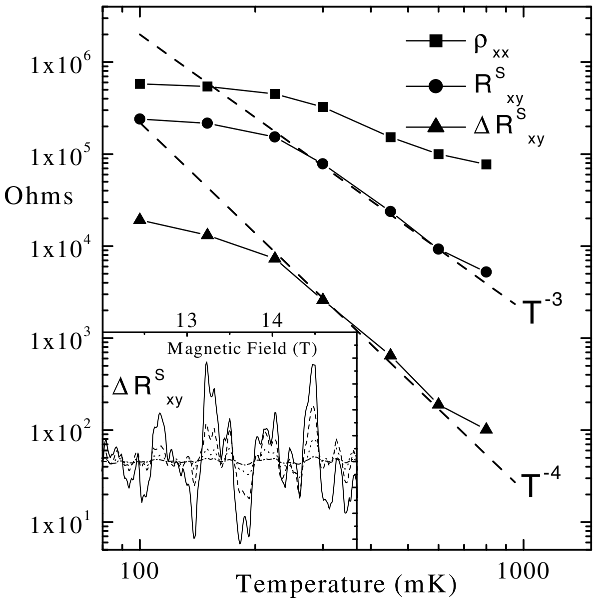

FIG. 5. The temperature dependence of ρ_{xx}, R^S_{xy}, and ΔR^S_{xy}, showing power law behavior for the symmetric components of the Hall resistance. The inset shows ΔR^S_{xy} at 100, 225, 300, and 450 mK, demonstrating that the form of the fluctuations is temperature independent.

also shown. The inset shows the ratio $R_{xy}(B+)/R_{xy}(B-)$. Up to ~9 T, R_{xy} is completely antisymmetric and the ratio is -1. The Hall contacts show almost no admixing ($\leq 0.5\%$) of the diagonal resistivity ρ_{xx}. At the onset of the insulating state, however, R_{xy} switches behavior to become almost totally symmetric: The antisymmetric Hall resistance tends to zero and a large finite voltage is developed across the sample which does not depend on the polarity of the applied magnetic field, thus giving a large value of R^S_{xy}. This resistance has no obvious functional relation to the diagonal resistivity R^S_{xx} which rules out a simple admixing origin. The Hall potential probes, although physically opposite each other to an accuracy of within 10 μm, are not equipotentials despite the fact that $R^A_{xy} = 0$.

Another striking feature of the symmetric part of R_{xy} is the reproducible resistance fluctuations which are accurately repeated for $B+$ and $B-$. These are shown in the inset of Fig. 5, defined by $\Delta R^S_{xy} = R^S_{xy} - \bar{R}^S_{xy}$, where $\bar{R}^S_{xy}$ is the smoothed background. The functional form of the resistance fluctuations remains essentially independent of temperature, increasing only in magnitude. By contrast, the Hall resistivity ($= R^A_{xy}$) shows much smaller fluctuations suggesting that any such disordered current paths are almost completely symmetric with respect to reversal of the direction of the carrier orbit. The violation of the Onsager relations implies the nonlocal nature of the symmetric Hall voltage.

The temperature dependence of the resistance components ρ_{xx}, R^S_{xy}, and ΔR^S_{xy} are shown in Fig. 5 for the insulating region. The essentially non-Onsager form of the symmetric R_{xy} component leads us to analyze the directly measured resistance rather than resistivity. The diagonal resistivity varies relatively slowly and saturates below ~100 mK. The R^S_{xy} and its fluctuations are more strongly temperature dependent. Fits to these with exponentially activated conduction work only over a factor of about 2 in temperature range; however, simple power laws work from the region of 800 to 200 mK where R^S_{xy} is proportional to T^{-3} and ΔR_{xy} to T^{-4}.

In conclusion, we have demonstrated that the electron-hole system oscillates between insulating and conducting states as the magnetic field is increased. A qualitative explanation has been proposed based on the formation of an energy gap due to the anticrossing between the electron and hole edge states. The insulating states have been shown to have unusual behavior when the Hall resistance becomes symmetric with respect to field reversal.

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