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]. In this letter 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 behaviour 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 plateaux in an electron-hole system by Mendez et al [7] found that conventional plateaux were formed at quantum numbers corresponding to the differences 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 observed. In this letter we examine the behaviour 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 behaviour. 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 behaviour 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 exhibits a broken gap lineup with the conduction band edge of the InAs 150meV below the valence band edge of the GaSb. The samples are grown by Metal Organic Vapour Phase Epitaxy (MOVPE) 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 onto semi-insulating GaAs followed by 2μm of GaSb to achieve lattice relaxation. The active layer of InAs is typically 30nm thick, followed by a 90nm GaSb cap. Fitting the low field magnetoresistance and Hall effect to classical two carrier formulae 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 structure is asymmetric due to pinning of the Fermi level E_F at the surface so that all of the holes are 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, the mobilities for the decoupled electrons and holes are estimated to be ~ 20 and 1 m^2V^{-1}s^{-1}.

Magnetotransport measurements were made using A.C. techniques with a dilution refrigerator and 15T superconducting magnet, and a ^3He cryostat and 50T 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:

\[
R_{xx}^S = \frac{(R_{xx}(B+) + R_{xx}(B-))/2}{\rho_{xx} \times L/W},
\]

\[
R_{xy}^S = \frac{(R_{xy}(B+) - R_{xy}(B-))/2}{\rho_{xy}},
\]

\[
R_{xx}^A = \frac{(R_{xx}(B+) - R_{xx}(B-))/2}{\rho_{xx} \times L/W},
\]

\[
R_{xy}^A = \frac{(R_{xy}(B+) - R_{xy}(B-))/2}{\rho_{xy}}.
\]
The symmetric part of $R_{xx}$ was used with the length to width ratio ($L/W$) of the bar to give the diagonal resistivity $\rho_{xx}$ and the antisymmetric part of $R_{xy}$ is taken to be the Hall resistivity, $\rho_{xy}$ 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 Fermi surface. The origins of this behaviour are clearer when the resistivity components are converted to conductivity $\sigma_{xx}$ and $\sigma_{xy}$ calculated from the data in Fig. 1. The figures indicate the expected electron ($\nu_e$) and hole ($\nu_h$) Landau level occupancies.

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. Due to the finite interband mixing between the valence and conduction bands the levels anticross leading to the formation of a miniband gap $[10] [11] [12] [13] [14] [15] [16] [17] [18] [19] [20]$, shown schematically in fig. 3i. 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 centre of either electron or hole Landau levels or within the localised tail states of either or both carrier types. In the simplified schematic fig. 3i the Fermi level is shown as constant. The net occupancy of the levels will oscillate between zero 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 $\nu_e - \nu_h = 0 - 1$)
The particularly unusual features of the conduction process occur when the Fermi level 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 behaviour 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 non-dissipative conducting edge states which generate zeroes in the resistivity and quantum Hall plateaux. 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. 3i 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 behaviour. 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 3ii. 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 3ii. 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. 3iii), 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. 3iv.

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 behaviour with compensated quantum Hall plateaux in the Hall resistance and zeros in \( \rho_{xx} \). There is a rotation through \( \sim 90^\circ \) of the equipotentials which lie along the conducting edge states of the bar in the metallic quantum Hall state but were mainly across the bar for the insulating state where no Hall field was generated.

The oscillations between insulating and metallic behaviour occur as the Fermi level moves through regions b,d (metallic) and a,c (insulating) in fig. 3i. 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 re-entrant insulating phase in p-SiGe was tentatively linked to unusual Landau level degeneracy where states may be crossing.
Evidence of a strong distortion of the current in the insulating state comes from the large component (about 50% of $\rho_{xx}$) in $R_{xy}$ occurring at the fields where the system becomes symmetric with respect to field reversal. Fig. 4 shows $R_{xy}$ as measured with respect to the magnetic field. The symmetric and antisymmetric parts are also shown. The inset shows $R_{xy}(B+)/R_{xy}(B−)$. Up to $\sim 9T$ $R_{xy}$ is cosymmetric and the ratio is -1. The Hall conductivity is shown to have unusual behaviour when the Hall resistance becomes symmetric with respect to field reversal. The insulating states have been shown to have unusual behaviour when the Hall resistance becomes symmetric with respect to field reversal.

Another striking feature of the symmetric is the reproducible resistance fluctuations with nearly repeated for $B+$ and $B−$. These are shown in fig. 5, defined by $\Delta R^{S}_{xy} = R^{S}_{xy} - R^{S}_{xy}(B_{0})$. The resistance fluctuations are almost completely symmetric with respect to reversal of the direction of the carrier orbit. The violation of the Onsager relations implies the non-local nature of the symmetric Hall voltage.

The temperature dependence of the resistance components $\rho_{xx}$, $R^{S}_{xy}$ and $\Delta R^{S}_{xy}$ are shown in fig. 5 for the insulating region. The essentially non-Ohm form of the symmetric $R_{xy}$ component leads us to analyse the directly measured resistance rather than resistivity. The diagonal resistivity varies relatively slowly and saturates below $\sim 100\text{mK}$. $R^{S}_{xy}$ and $\Delta R^{S}_{xy}$ are more strongly temperature dependent. Fits to these with exponentially activated conduction only work over a factor of about 2 in temperature range, however simple power laws work from the region of $800$ to $200\text{ mK}$ where $R^{S}_{xy}$ is proportional to $T^{-3}$ and $\Delta R_{xy}$ 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 behaviour when the Hall resistance becomes symmetric with respect to field reversal.

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