Fractional quantum Hall effect in bilayer two-dimensional hole-gas systems

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We have studied the fractional and integer quantum Hall effect in high-mobility double-layer two-dimensional hole-gas systems. The large hole effective mass inhibits tunneling, allowing us to investigate the regime in which the interlayer and intralayer interactions are comparable without significant interlayer tunneling occurring. As the interlayer separation is reduced we observe the formation of bilayer-correlated quantum Hall states at total filling factor $\nu=3/2$ and $\nu=1$. We find that the bilayer $\nu=3/2$ state is rapidly destroyed by small carrier density imbalances between the layers, whereas the bilayer $\nu=1$ state evolves continuously into the single-layer $\nu=1$ state. [S0163-1829(96)51132-X]

In a bilayer system, integer and fractional quantum Hall (QH) states can be observed which have no counterpart in single-layer systems. A good example is the $\nu=1/2$ state: in a clean single-layer system, this filling factor corresponds to a compressible Fermi liquid,[1] whereas in a bilayer system with total filling factor 1/2 a well-defined fractional QH state can be observed.[2] Similarly, at $\nu=1$ (i.e., $\nu=1/2$ in each layer) an interlayer-correlated QH state can be formed,[2,3] although in electron systems it can be difficult to distinguish this state from a single-particle QH state due to interlayer tunneling.[4] In addition to these new quantum Hall effect states, there is also the possibility of bilayer Wigner crystallization, which is expected to occur at larger carrier densities and filling factors than in single-layer systems.[5]

In this paper we present studies of the integer and fractional quantum Hall effect in bilayer two-dimensional (2D) hole systems. We use 2D hole gases (2DHG's) because the large heavy-hole mass ($0.38m_e$) allows the layers to be brought into close proximity without significant interwell tunneling occurring. This helps us to distinguish between QH states arising from the symmetric-antisymmetric gap (Δ_{SAS}) and those arising from interlayer interactions. We find that as the layers are brought closer together, quantum Hall states form at $\nu=3/2$ and $\nu=1$. The former is the electron-hole conjugate of the Ψ_{331} $\nu=1/2$ bilayer state.[6] Temperature-dependence measurements confirm that the latter is also a correlated state, Ψ_{111}, rather than being due to the single particle tunneling gap Δ_{SAS}. However, despite their common origins, we find that these two states have a very different response to carrier density imbalance between the two wells.

The samples were grown by MBE on (311)A-oriented GaAs substrates, and consist of two modulation-doped 150 Å quantum wells, separated by $Al_{0.33}Ga_{0.67}As$ barriers of thickness d_B=20 Å, 25 Å, and 35 Å. All of the samples have very similar carrier densities and exceptionally high mobilities, with $p_s=1\times10^{11}$ cm^{-2} and $\mu=1\times10^6$ cm^2 V^{-1} s^{-1} in each well. Measurements were performed with the samples mounted in the mixing chamber of a dilution refrigerator with a base temperature less than 30 mK. Temperature-dependence measurements were performed using a calibrated resistor mounted in a flux-cancelled region of the mixing chamber. Standard low-frequency ac lock-in techniques were used with measurement currents less than 2 nA to avoid heating effects.

A Schottky front gate was used to tune the carrier density and charge asymmetry in the quantum wells. Figure 1 shows the carrier densities (p_s) in the two layers for the d_B=25 Å sample, obtained from Fourier transforms of the low-field ($B<0.9$ T) magnetoresistance oscillations. The sum of these densities agrees well with the carrier density obtained from the low-field Hall resistance. For gate voltages $V_g>0.3$ V only the lower hole gas is occupied. As V_g is reduced the upper 2DHG starts to occupy, partially screening the lower layer from further reductions in V_g. While the carrier density in the upper 2DHG rises as V_g is reduced, the carrier density in the lower layer decreases from 1.3×10^{11} cm^{-2} at

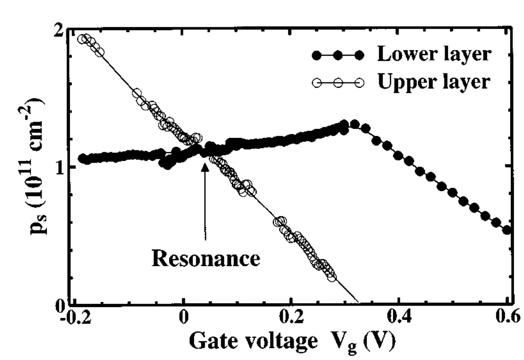

FIG. 1. Carrier density as a function of gate voltage for the d_B=25 Å sample. At V_g=0.05 V the carrier density in the two wells is equal, and at this symmetric point the system is on resonance. The solid lines are a guide to the eye.

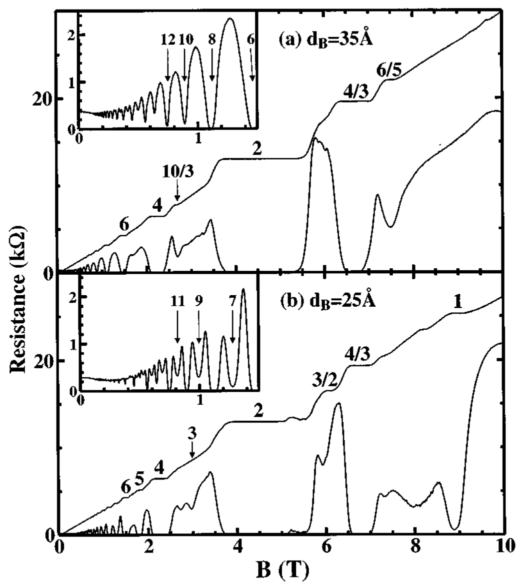

FIG. 2. Hall (R_{xy}) and magnetoresistance (R_{xx}) traces for the d_B=35 Å and d_B=25 Å samples at resonance. The insets show the low-field ($B<1.5$ T) magnetoresistance. R_{xx} traces are at $T<30$ mK; R_{xy} traces are at (a) $T=100$ mK and (b) $T=80$ mK.

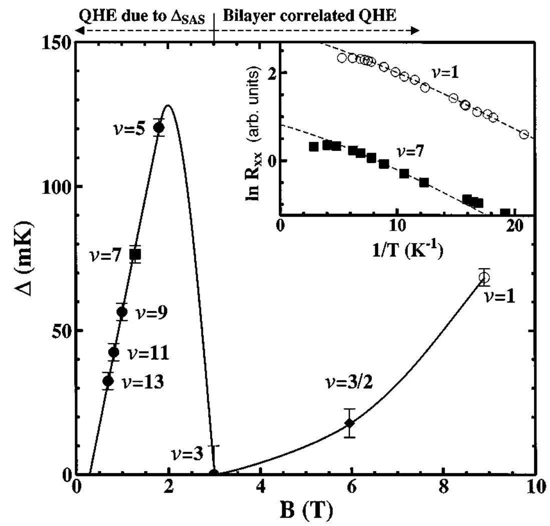

FIG. 3. Activation energies of the ν=odd QH states for the d_B=25 Å sample at resonance, as a function of magnetic field. The solid line is a guide to the eye. The inset shows typical Arrhenius plots, for $\nu=7$ and $\nu=1$, together with Fermi-Dirac fits from which the activation energies were obtained.

V_g=0.3 V to 1.1×10^{11} cm^{-2} at $V_g=-0.2$ V. This decrease is due to intralayer interactions in the upper hole gas, which cause it to have a negative compressibility.[7,8] This negative compressibility effect is significantly larger in hole gases than their electron gas counterparts, due to the large hole effective mass.[9] When V_g=0.05 V the carrier density in the two wells is equal, and the system is on resonance. At this point the two wave functions are no longer localized in the two wells, but become delocalized across both wells. Despite the small barrier thicknesses in these samples we were unable to resolve an anticrossing in the Fourier transform data, which implies that $\Delta_{SAS}<85$ μeV. This is in agreement with self-consistent Hartree calculations which find that Δ_{SAS} is approximately 30 μeV and 10 μeV for the d_B=25 Å and 35 Å samples, respectively. These Δ_{SAS} values are almost two orders of magnitude smaller than those obtained for identical electron gas samples, highlighting the reduction in tunneling brought about by the large effective mass.

Magnetoresistance traces at the resonance point are shown for the d_B=35 Å and 25 Å samples in Fig. 2. Great care was taken to locate this resonance point, as the magnetoresistance data was extremely sensitive to any carrier density imbalance between the two wells. For the d_B=35 Å sample there is essentially no tunneling between the two wells, and so the system behaves as two independent 2D hole gases with equal carrier densities. The magnetoresistance data therefore look like those for a single 2D system with a double degeneracy and only even-numerator QH states, such as ν=4/3, 2, 10/3, 4... are observed, corresponding to ν=2/3, 1, 5/3, 2... in each well. The only exception to this is a weak feature at ν=3/2 (B=6 T), which will be discussed later. Reducing d_B to 25 Å [Fig. 2(b)] increases tunneling between the two wells, allowing the energy gap Δ_{SAS} between the symmetric and antisymmetric eigenstates to be resolved. At very low magnetic fields ($B<0.2$ T) a weak beating is seen in the magnetoresistance traces due to the slightly different carrier densities in the symmetric and antisymmetric subbands. At slightly higher magnetic fields odd index QH states, such as ν=5, 7, 9..., become resolved, due to the Δ_{SAS} gap [inset to Fig. 2(b)]. The behavior of the odd-index QH states at larger magnetic fields is more complex; the $\nu=3$ state is extremely weak, but the $\nu=1$ state is stronger again. The feature at ν=3/2 has also become much stronger.

To determine whether the ν=odd QH states in the d_B=25 Å sample are due to the Δ_{SAS} gap or to many-body correlations, we have performed temperature-dependence measurements at the resonance point, shown in Fig. 3. The energy gap associated with a given QH state was obtained from fitting the central linear regions of the Arrhenius plot (inset to Fig. 3) to the Fermi-Dirac formula $R_{xx} \propto [1+\exp(\Delta/2kT)]^{-1}$. For low magnetic fields Δ increases linearly with B, due to Landau-level mixing,[10] and then collapses abruptly at $B=3$ T due to the increasing importance of interlayer correlations.[10,11] As the magnetic field is increased the number of holes in the highest occupied Landau level rises, and the average distance between adjacent holes *within* this Landau level, $\langle r_{ij}\rangle$, decreases. As $\langle r_{ij}\rangle$ becomes smaller, interparticle Coulomb interactions become increasingly important. This interparticle Coulomb energy can be reduced if the holes change from being delocalized across both wells to being localized in one well, thereby slightly increasing $\langle r_{ij}\rangle$. If this reduction in Coulomb energy is larger than Δ_{SAS}, tunneling is suppressed, the ground state of the system becomes a gapless bilayer state, and all ν=odd states disappear. The magnetic field at which this occurs in our samples is in excellent agreement with the theory of Ref. 10. This magnetic-field-induced collapse of the Δ_{SAS} gap explains why we do not observe odd numerator fractions such as ν=5/3 in Fig. 2(b), as the system is doubly degenerate at large B (e.g., ν=4/3 corresponds to ν=2/3 in each layer[12]). Hence the odd-denominator QH states that we observe above

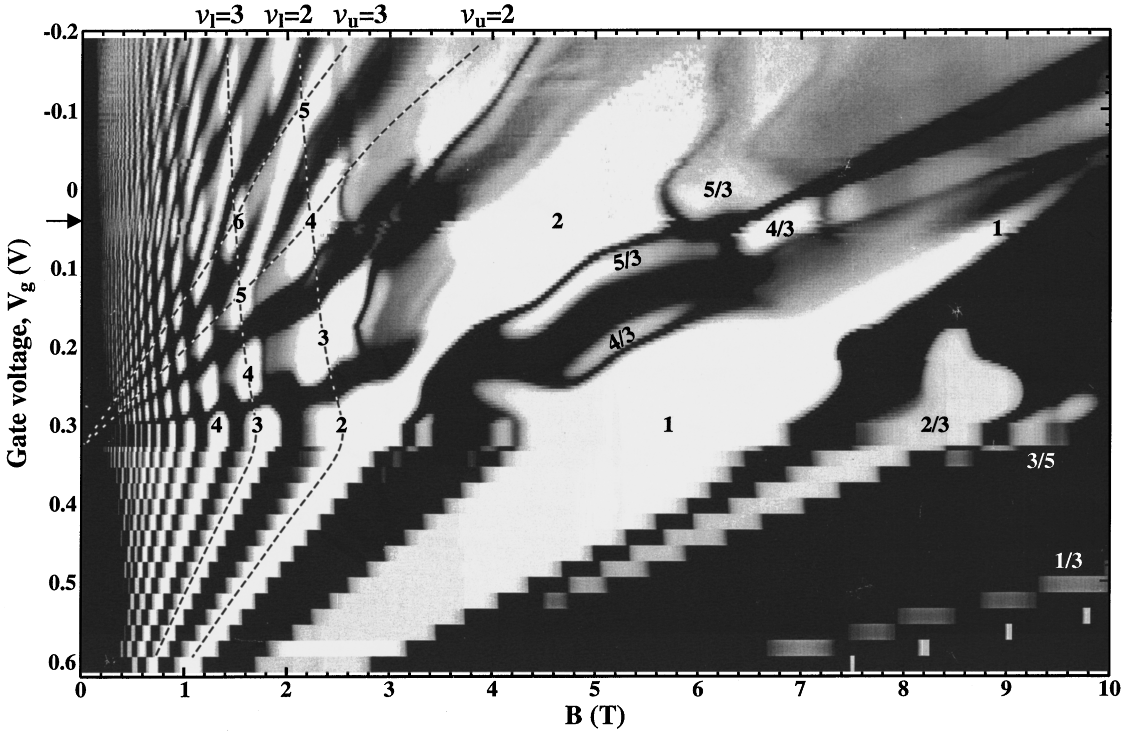

FIG. 4. Gray-scale plot of the longitudinal resistance R_{xx} as a function of magnetic field B and gate voltage V_g for the $d_B=25$ Å sample at $T<30$ mK. The depth of shading is proportional to R_{xx}, with white regions denoting QH states where $R_{xx}\rightarrow 0$. The resonance point is indicated by an arrow. The dashed lines show the filling factor in the upper and lower layers, ν_u and ν_l, calculated from the data of Fig. 1.

$B=3$ T are not due to tunneling, but must be bilayer-correlated states. The state at $\nu=3/2$ is therefore the electron-hole conjugate of the Ψ_{331} bilayer $\nu=1/2$ state (in bilayer systems electron-hole symmetry transforms $\nu\rightarrow 2-\nu$), and the state at $\nu=1$ is the Ψ_{111} bilayer state.[4]

We now examine the effects of carrier density imbalance on the various QH states. Magnetoresistance traces for the $d_B=25$ Å sample, taken at many different gate voltages, are shown as a gray-scale plot in Fig. 4. Each magnetoresistance measurement for a given V_g is represented by a horizontal slice of the figure. In the gray scale the darkness of the shading is proportional to the longitudinal resistance R_{xx}. Thus the white regions indicate QH states ($R_{xx}\rightarrow 0$), where the Fermi energy lies in the localized states between Landau levels, and the dark regions correspond the the Fermi energy lying in the extended states of a Landau level. The numeric labels on the gray scale identify the total filling factor in the system. Although the detailed shape of the gray scale is rather complex (and is explained in more detail elsewhere[13]), a simple explanation is given below.

The dashed lines in Fig. 4 show the filling factor in the upper and lower layers, ν_u and ν_l, calculated from the data of Fig. 1 using the relation $\nu eB/h=p_s$. For $V_g>0.33$ V only the lower layer is occupied, and a normal Landau fan diagram is seen originating from $V_g=1.1$ V. In this regime the dashed lines therefore mark the positions of the $\nu=2$ and $\nu=3$ QH states, which move to larger magnetic fields as the carrier density is increased by reducing V_g. We can also see the evolution of the fractional QH effect in the lower layer, with states at $\nu=1/3$, 2/3, and 3/5 becoming more clearly resolved as p_s increases.

At $V_g=0.33$ V the upper layer starts to occupy, and a second Landau fan emerges. As shown in Fig. 1, once the upper layer is occupied it partially screens the lower layer from changes in V_g, so the Landau levels associated with the lower layer remain at almost constant magnetic fields. For example, if we follow $\nu_l=3$ we see QH states of the bilayer system (indicated by the white regions where $R_{xx}\rightarrow 0$) at total filling factor $\nu=\nu_u+\nu_l=4, 5, 6\ldots$, which correspond to $\nu_l=3$ and $\nu_u=1, 2, 3\ldots$, respectively. Away from resonance, therefore, QH states form whenever the Fermi energy lies in the localized states in both layers, as indicated by the intersections of the dashed lines.

When the two wells are on resonance (at $V_g=0.05$ V, indicated by the arrow) the wave functions are delocalized across the two wells, and we can no longer identify the individual filling factors in the wells. At this point we not only see $\nu=$even QH states at the intersections of the dashed lines, as we would for two uncoupled 2D systems [c.f. Fig. 2(a)], but also states at $\nu=$odd, due to the SAS gap [c.f. Fig. 2(b)].

This simple assignment of filling factors to the two layers can also be used to explain some features of the higher B data: the $\nu=4/3$ and $\nu=5/3$ states at $B=5$ T correspond to ($\nu_l=1$, $\nu_u=1/3$) and ($\nu_l=1$, $\nu_u=2/3$), respectively. The Coulomb-interaction-driven collapse of Δ_{SAS} is responsible for the absence of $\nu=3$ and $\nu=5/3$ at resonance, although we see that if the system is taken off resonance $\nu=4/3$ ($\nu_l=\nu_u=2/3$) is destroyed and $\nu=5/3$ reemerges.

The most striking feature of the high-field data, however, is the continuous evolution of the $\nu=2$ and $\nu=1$ from single-layer states in the lower layer ($V_g>0.33$ V) to bilayer states at resonance. We believe these effects, which have also been seen in bilayer electron systems,[14] are caused by charge re-

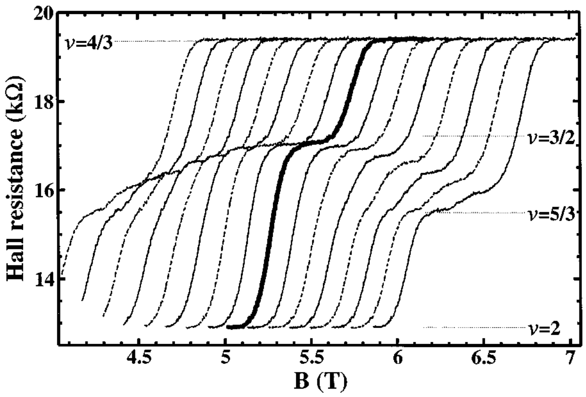

FIG. 5. Hall resistance R_{xy} as a function of magnetic field at different gate voltages near resonance for the d_B=20 Å sample at $T<30$ mK. At resonance (bold trace) a strong QH plateau is observed at $\nu=3/2$, quantized to within 4% of 2/3 e^2/h. The other traces have been horizontally offset for clarity, with each offset trace corresponding to an interlayer charge transfer of $\Delta p_s = 6.4\times10^8$ cm^{-2}.

distribution between the two wells with applied perpendicular magnetic field. Although B has little effect on the wave functions, the discrete density of states in the system means that in order to minimize the Fermi energy it may be energetically favorable to preferentially populate one energy level.[15] This continual redistribution of charge will be enhanced at high B, where the Landau level spacing is large. Thus we see the single layer $\nu_l=2$ evolves into the bilayer $\nu=2$, with $\nu_l=\nu_u=1$, and the single layer $\nu_l=1$ evolves into the bilayer correlated Ψ_{111} $\nu=1$.[16] However, we are unable to explain why the $\nu=1$ state rapidly disappears as we move beyond resonance (i.e., $V_g<-0.01$ V).

In comparison with the behavior of $\nu=1$, Fig. 5 shows the behavior of the $\nu=3/2$ state to carrier density imbalance (these measurements were performed on the d_B=20 Å sample as it showed this state more clearly). Here we see that at resonance (bold trace) a clear QH plateau is seen at $\nu=3/2$, with no feature at $\nu=5/3$. Even moving slightly off resonance causes the $\nu=3/2$ state to weaken, with the associated ρ_{xx} minima disappearing (not shown), and the small carrier density imbalance ($\approx$4%) allows the formation of a state at $\nu=5/3$. This is to be expected, as $\nu=3/2$ is a bilayer-correlated state, whereas the $\nu=5/3$ state seen here corresponds to $\nu=1$ in one layer and $\nu=2/3$ in the other.

In summary, we have presented the first studies of the fractional QH effect in bilayer hole systems. We find that as the layer separation is reduced QH states form at $\nu=1$ and $\nu=3/2$. Temperature-dependence measurements have demonstrated that these states are correlated-bilayer states. We find that the $\nu=3/2$ state is rapidly destroyed by a carrier density imbalance between the layers, consistent with its bilayer origin. The behavior of the $\nu=1$ state with carrier density imbalance is complicated by the existence of a single-layer $\nu=1$ state: the bilayer-correlated $\nu=1$ state evolves continuously into the single layer $\nu=1$ state with increasing carrier density imbalance. Although a simple model of two noninteracting layers is sufficient to describe the evolution of the QH effect with carrier density imbalance at low magnetic fields, it cannot describe the more complex behavior we observe at higher fields (particularly for $\nu=1$ and $\nu=2$), which warrants further investigation.

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