Transport Evidence for Phase Separation into Spatial Regions of Different Fractional Quantum Hall Fluids near the Boundary of a Two-Dimensional Electron Gas

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Near the boundary, a 2D electron gas can phase separate into fractional quantum Hall fluid regions of successively lower filling factors (ν), in the case of a slowly increasing boundary potential. We present experimental evidence in the $\nu=\frac{1}{3}$, $\frac{2}{3}$, and 1 quantum Hall regimes on a four-lead Hall junction showing that by *side gating* the junction boundary, the Hall resistance can be made to approach the quantized value of *the lower ν fluids in the top-gated leads*, rather than the higher-ν fluid at the junction center. This implies the presence of the lower-ν fluids near the junction boundary.

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Recently, considerable interest has been focused on the transport properties of quantum Hall systems in realistic sample geometries of finite size enclosed by boundaries [1-11]. When approaching a boundary from the bulk, the potential energy increases and eventually exceeds the Fermi energy. As a result, the probability of finding carriers falls off from some average value and approaches zero. If the confinement is soft, this falloff may be characterized as a carrier density inhomogeneity in the form of a monotonic decrease [12,13]. Moreover, even within the bulk, density inhomogeneities can exist due to the unavoidable presence of impurities and imperfections in real systems. The presence of density inhomogeneities gives rise to the possibility whereby the two-dimensional electron gas (2DEG) can phase separate into spatial regions of different quantum Hall states (QHS). The idea of regions of different QHS is sensible when the confinement potential is sufficiently soft, so that the size of a region exceeds the magnetic length l_0.

In the absence of an explicitly built-in density gradient, the quantum Hall and longitudinal resistances are determined by the average density of Landau filling factor regardless of the presence of local inhomogeneities. Even in the case where large regions within the bulk well away from the boundaries are at a different average density, the transport properties within a well quantized regime are minimally affected. On the other hand, if the regions of different densities occur at the boundary and extend into the metallic contact regions, the situation is entirely different and observable consequences can be expected.

A useful geometry to demonstrate the effect of phase separation near a boundary is shown in Fig. 1(a), where a four-lead Hall junction containing a boundary (upper left in this case) which can be gated via a side gate is depicted. Within the bulk conducting regions, the density is uniform. The magnetic field is adjusted until a quantum hall effect (QHE) at a particular filling factor, ν, is observed. Next the top gates in the adjacent leads 1 and 2, corresponding to a current and a voltage lead, respectively, are negatively gated to reduce the electron density underneath until a lower-filling QHE at ν_{tg} is obtained ($\nu_{tg} < \nu$). If the electron density in all regions other than underneath the top gates is uniform all the way to the boundaries, then the Hall voltage measured $R_H \equiv R_{13,24}$ would be $h/\nu e^2$ regardless of the direction of the magnetic field B where $R_{13,24}$ denotes current passed between leads 1 and 3, and voltage measured between 2 and 4. In contrast, if there is a region near the side-gated boundary which is at filling $\nu_{sg}=\nu_{tg}$ instead of ν, so that phase separation has occurred away from the center of the Hall junction, and if this region is sufficiently wide in the direction perpendicular to the boundary, then with B pointing out of the page, one would measure $R_{H+}=h/\nu_{tg}e^2$ instead, while $R_{H-}=h/\nu e^2$ with B pointing into the page, where R_{H+} and R_{H-} refer to the Hall resistance measured with $+$ or $-$ B. The reason R_{H+} can be different from R_{H-} is due to the presence of a nonequilibrated chemical potential at the ν_{sg} and ν boundary.

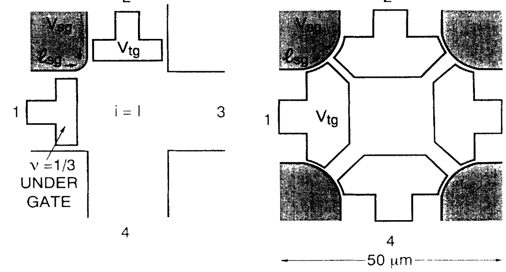

FIG. 1. (a) A four-terminal Hall junction with the appropriate gates—side gate (V_{sg}) and top gates (V_{tg})—to demonstrate phase separation. (b) The junction used in the present experiment. The side-gate length, l_{sg}, for the four boundaries is 2, 3, 4, and 5 μm, respectively, clockwise from the top left.

R_{H+} will also be denoted by $R_{H_{\rm neq}}$. The width of this $\nu_{\rm sg}$ spatial region, $w_{\rm sg}$, is given by approximately $\Delta/|\nabla V|$ [3,11,14,15], where Δ is the energy gap and $|\nabla V|$ is the gradient of the boundary potential, and can therefore be controlled by the application of different side-gate voltages to vary $|\nabla V|$. For a long boundary R_{H+} approaches R_{H-} as $\exp(-l_{\rm sg}/l_{\rm eq})$, where $l_{\rm sg}$ denotes the boundary length and $l_{\rm eq}$ a chemical potential equilibration length.

Much recent theoretical interest has been devoted to the edge excitations at the $\nu=1$ to $\frac{2}{3}$ boundary and the $\nu=\frac{2}{3}$ to $\frac{1}{3}$ boundary. Because of the fact that in the bulk, the $\nu=\frac{1}{3}$ and $\frac{2}{3}$ fractional QHE's (FQHE) represent electron-hole conjugates, complicated boundary excitations are conjectured to be present [16,17], and unusual consequences in transport are thought possible on the appropriate length scale. Experimentally, little is known about the $\nu=\frac{2}{3}$ to $\frac{1}{3}$ boundary and its significance to transport. Thus far, only one experiment has been performed to address the question of phase separation in the fractional quantum Hall regime. Using a different but equivalent geometry to the above, Kouwenhoven *et al.* [18] obtained evidence for the separation of a $\nu=1$ electron gas into a $\nu_{\rm sg}=\frac{2}{3}$ region near the boundary. Although their two-terminal resistance did not show a well-defined $\frac{2}{3}$ plateau, a three-terminal resistance corresponding to R_{H+} ($R_{H_{\rm neq}}$ exhibited a plateau near $h/\frac{2}{3}e^2$. To explain their observations, it was necessary to hypothesize the existence of a $\nu_{\rm sg}=\frac{1}{3}$ region adjacent to the $\frac{2}{3}$ region.

In this Letter, we describe experiments involving the $i=1$ integral QHE (IQHE) and $\nu=\frac{2}{3}$ and $\frac{1}{3}$ FQHE's using the geometry discussed above. In particular, we study the cases where (i) the junction region is near filling factor $\nu=1$, and the adjacent current and voltage leads equivalent to 1 and 2 in Fig. 1(a) are top-gated through $\nu_{\rm tg}=\frac{2}{3}$ and $\frac{1}{3}$, and (ii) where the junction is near filling factor $\nu=\frac{2}{3}$ and the relevant leads are top-gated through $\nu_{\rm tg}=\frac{1}{3}$. In the first case, we find that side-gating the boundary increasingly negatively at fixed top-gate voltages ($V_{\rm tg}$) corresponding to $\nu_{\rm tg}=\frac{2}{3}$ or $\frac{1}{3}$, the Hall resistance, $R_{H_{\rm neq}}\equiv R_{H+}$, approaches $h/\frac{2}{3}e^2$ and $h/\frac{1}{3}e^2$, respectively. Similarly, in the second case, $R_{H_{\rm neq}}$ approaches $h/\frac{1}{3}e^2$. In contrast, at $V_{\rm sg}=-0.4$ V which is slightly more negative than the depletion voltage, $R_{H_{\rm neq}}\sim h/e^2$ regardless of $V_{\rm tg}$ for the first case, and $\sim h/\frac{2}{3}e^2$ for the second. To measure R_{H-}, we interchange the current and voltage leads. This is equivalent to reversing B in accordance with the symmetry properties predicted by the Buttiker-Landauer multilead formulas [3,19]. We find $R_H\equiv R_{H-}=h/e^2$ and $h/\frac{2}{3}e^2$, for the first and second cases, respectively, to within 3%. These results strongly suggest the presence of the $\nu_{\rm sg}=\frac{2}{3}$ and $\frac{1}{3}$ phase-separated regions near the boundary with the bulk near $\nu=1$, and $\nu_{\rm sg}=\frac{1}{3}$ boundary region with the bulk near $\nu=\frac{2}{3}$. In addition, we study how $R_{H_{\rm neq}}$ approaches the maximum quantized values as a function of the length, $l_{\rm sg}$, along the side-gated boundary. We find that as $l_{\rm sg}$ varies from 2 to 5 μm, $R_{H_{\rm neq}}$ tends to decrease as is expected and extract an equilibration length, $l_{\rm eq}$, of ~ 3 μm for the approach to the $\frac{1}{3}$ quantized resistance. Furthermore, $R_{H_{\rm neq}}$ and R_H approach each other as the temperature is increased. Our results indicate that the behavior involving the $\nu=1$, $\frac{2}{3}$, and $\frac{1}{3}$ fractional QHE's is very similar to that between $\nu=3$, 2, and 1 in the IQH regime, and suggests that at least on the length scales of this experiment, the transport ideas based on the presence of phase separation proposed by Beenakker [12] and Chang [13] are applicable.

Our sample is fabricated from a δ-doped GaAs/Al$_x$-Ga$_{1-x}$As heterostructure starting material. The density is 2.6×10^{11} cm^{-2} and the mobility is 2.1×10^6 cm^2/V sec. The sample pattern, shown in Fig. 1(b), consists of two sets of gates—side gates which extend outward to the boundaries of the chip and are gated to depletion to define the four-lead Hall junction, and the top gates over the leads themselves labeled 1 through 4. The pattern is produced by standard electron beam lithography followed by metallization and lift-off [20]. The overall scale of the pattern is 55 μm, and the junction size is approximately 30 μm$\times$30 μm. The narrow gap between the side and top gates is 0.5 μm. We have made sure that this gap can be properly depleted with the application of a sufficiently negative side-gate voltage by confirming that at $V_{\rm sg}$, -0.4 V, the leads are cut off at the top gate depletion voltage of ~ -0.35 V. The length, $l_{\rm sg}$, along the four different side-gate boundaries is 2, 3, 4, and 5 μm, respectively. By choosing the appropriate pairs of adjacent top-gated leads as the current and voltage leads equivalent to leads 1 and 2 in Fig. 1(a), we are able to study $R_{H_{\rm neq}}$ vs $l_{\rm sg}$.

We perform our transport measurement with a lock-in technique at a frequency of 23 Hz. Our current level was varied between 0.1 and 10 nA. At 0.1 nA, the corresponding excitation voltage gives rise to a chemical potential drop in the range of 2.6 to 7.8 μV which is substantially smaller than the typical gap energy, Δ, of the FQHE of >80 μV. In contrast, at 10 nA, the excitation chemical potential drop is in the range 260–780 μV far exceeding Δ. Nevertheless, in both cases we find qualitatively similar behavior in $R_{H_{\rm neq}}$ and R_H.

In Fig. 2, we show results for the resistances $R_{\rm 2pt}$ ($R_{42,42}$), $R_{H_{\rm neq}}$ ($R_{31,42}$), R_H ($R_{42,13}$), $R_{xx_{\rm neq}}$ ($R_{41,32}$), and R_{xx} ($R_{32,41}$) vs $V_{\rm tg}$ with the bulk in the $i=1$ QHE and $V_{\rm sg}=-2.75$ V. The temperature is 50 mK, $B=121$ kG out of the page, and the excitation current in 0.1 nA. Here $R_{ij,kl}$ denotes current passed between leads i and j, and voltage measured between leads k and l. The adjacent top-gated leads are 1 and 2 with a corresponding boundary length, $l_{\rm sg}$, of 2 μm. $R_{H_{\rm neq}}$ ($R_{13,24}$) approaches the quantized value $h/\frac{2}{3}e^2$ with decreasing $V_{\rm tg}$ attaining a peak value of $0.985h/\frac{2}{3}e^2$ at -66 mV at the front edge of the plateau. For reference, the two-terminal resistance between leads 4 and 2, $R_{\rm 2pt}$ ($R_{42,42}$), shows a

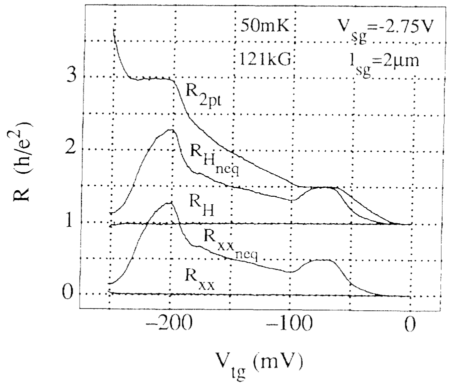

FIG. 2. The resistances R_{2pt} ($R_{42,42}$), $R_{H_{neq}}$ ($R_{31,42}$), R_H ($R_{42,31}$), $R_{xx_{neq}}$ ($R_{41,32}$), and R_{xx} ($R_{32,41}$) vs the top-gate (V_{tg}) voltages on leads 1 and 2, with the gate over leads 3 and 4 at ground. The side gate (V_{sg}) is at -2.75 V, and l_{sg}, the side-gated boundary length, is 2 μm. At $V_{tg}=0$, the electron gas in the bulk is at the $i=1$ integral quantum Hall regime in the junction and leads.

$\frac{2}{3}$ plateau in the same V_{tg} range. Further reduction of V_{tg} yields a peak structure approaching $h/\frac{1}{3}e^2$ with a peak value of $0.73h/\frac{1}{3}e^2$ at -202 mV. This position again correlates well with the position of the $\frac{1}{3}$ effect in the two-terminal resistance. $R_{xx_{neq}}$ ($R_{41,32}$), a nonequilibrium longitudinal resistance, shows analogous behavior with $R_{xx_{neq}}=R_{H_{neq}}-h/e^2$. Upon interchanging the current and voltage leads, which is equivalent to reversing B, we obtain $R_H=h/e^2$ constant to 3% over the entire V_{tg} sweep, and $R_{xx}(R_{32,41})<0.03h/e^2$.

In Fig. 3(a), we show the behavior of $R_{H_{neq}}$ for different boundary length, l_{sg}. $R_{H_{neq}}$ is reduced with an increase in l_{sg} approaching R_H for large l_{sg}. Although the $l_{sg}=4$ μm result appears lower than that for the 5 μm due to slight imperfections in the lithography, the general trend toward a reduction is present. If we assume that the relaxation toward R_H roughly behaves as $\exp(-l_{sg}/l_{eq})$, and plot $\Delta R_{H_{neq}}=R_{H_{neq}}-R_H$ vs l_{sg} in a semilogarithmic plot as indicated in the inset, we find $l_{eq}\sim 3.3$ μm. Figure 3(b) shows the behavior of $R_{H_{neq}}$ vs V_{sg}. A more negative side-gate voltage is expected to yield a larger depletion width and therefore a softer boundary potential [21]. As a result, the width of the phase-separated region, w_{sg}, increases and a slower equilibration of the nonequilibrium chemical potential is indicated by the data.

In Fig. 4, we show R_{2pt}, $R_{H_{neq}}$, R_H, $R_{xx_{neq}}$, and R_{xx} vs V_{tg} for $\nu=\frac{2}{3}$ within the bulk, at a magnetic field of $B=148$ kG pointing out of the page. The temperature is 50 mK. Again, in the V_{tg} range corresponding to the $\frac{1}{3}$ plateau region in the two-terminal resistance, $R_{H_{neq}}$ approaches $h/\frac{1}{3}e^2$ with a peak value of $0.83h/\frac{1}{3}e^2$ at -168 mV. Figures 5(a) and 5(b) show $R_{H_{neq}}$ vs l_{sg} and vs V_{sg}, respectively. Similar results are obtained at excitation currents up to 10 nA.

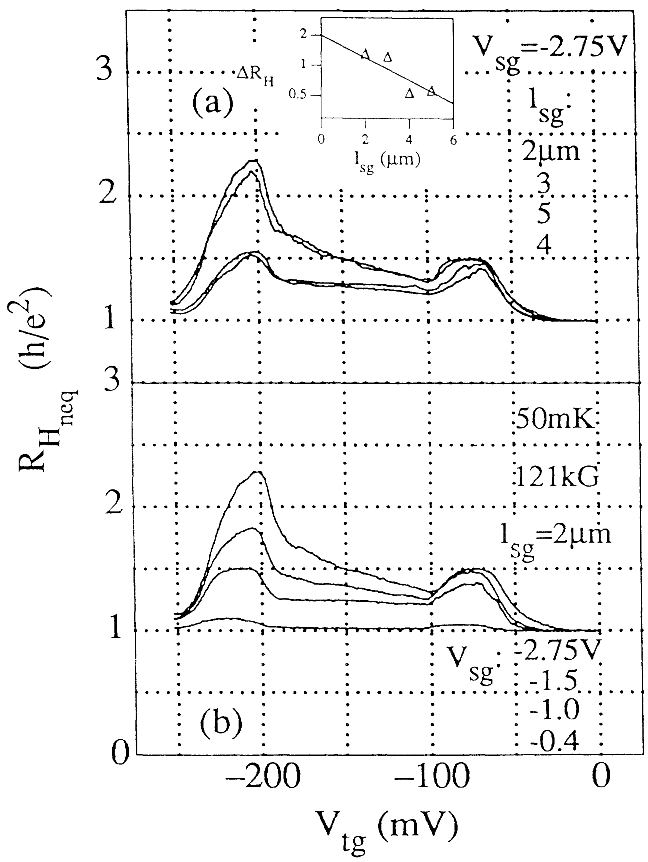

FIG. 3. (a) $R_{H_{neq}}$ vs V_{tg} for various l_{sg} values. $V_{sg}=-2.75$ V. Inset: Semilogarithmic plot of $\Delta R_{H_{neq}}=R_{H_{neq}}-R_H$ vs l_{sg}. (b) $R_{H_{neq}}$ vs V_{tg} for various V_{sg} values for $l_{sg}=2$ μm.

As discussed above, these results provide evidence for the presence of phase separation near the boundary, where the boundary potential is controllable by the side gate. The presence of phase separation constitutes the central finding of this work. Two different interpretations

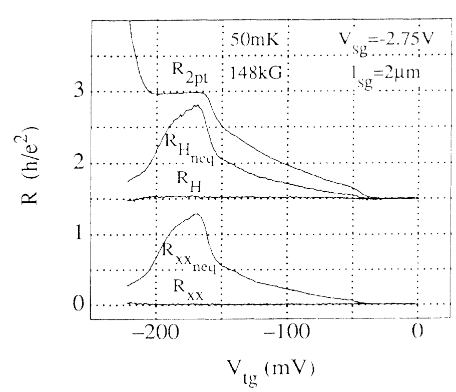

FIG. 4. The resistances R_{2pt}, $R_{H_{neq}}$, R_H, $R_{xx_{neq}}$, and R_{xx} vs V_{tg}. $V_{sg}=-2.75$ V, $l_{sg}=2$ μm, and the electron gas outside of the top-gated region within the bulk is at $\nu=\frac{2}{3}$.

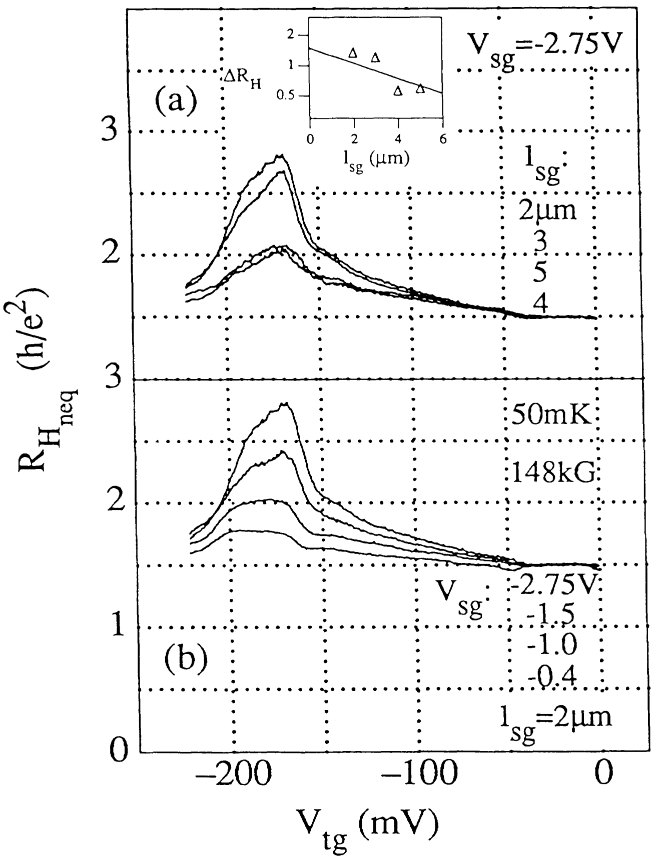

FIG. 5. (a) $R_{H_{neq}}$ vs V_{tg} for various l_{sg} values. $V_{sg}=-2.75$ V. Inset: Semilogarithmic plot of $\Delta R_{H_{neq}} = R_{H_{neq}} - R_H$ vs l_{sg}. (b) $R_{H_{neq}}$ vs V_{tg} for various V_{sg} values for $l_{sg}=2$ μm.

are possible for the mechanism of conduction: (a) edge channel conduction, and (b) different *local* conductivities $(\sigma_{xx}, \sigma_{xy})$ in the distinct phases, both predicting an exponential decay of $R_{H_{neq}}$ with l_{sg} [7,11,14,15,22]. As in the IQHE, it is necessary to determine the temperature dependence of the equilibration length, l_{eq}, to distinguish between the two possibilities. Alternatively, nonlinear effects may be useful [15]. These will be the subject of future work.

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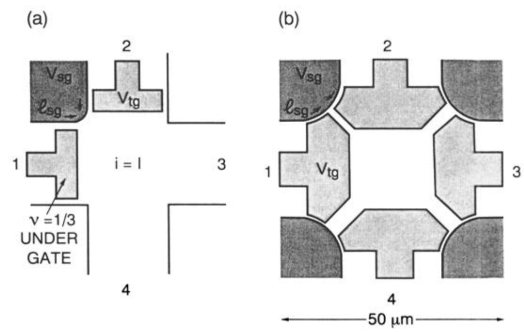

FIG. 1. (a) A four-terminal Hall junction with the appropriate gates—side gate (V_{sg}) and top gates (V_{tg})—to demonstrate phase separation. (b) The junction used in the present experiment. The side-gate length, l_{sg}, for the four boundaries is 2, 3, 4, and 5 μm, respectively, clockwise from the top left.