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Observation of the $\nu=1$ quantum Hall effect in a strongly localized two-dimensional system

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We observe a magnetic-field-driven transition in the two-dimensional electron system in GaAs/$Al_xGa_{1-x}As$, from a strongly localized insulating phase at $B=0$ to the integer quantum Hall phase that includes a fully developed $\nu=1$ state. The quantum Hall phase terminates with an additional transition from the $\nu=1$ state to an insulating phase.

The prevailing association of the quantum Hall effect (QHE) with clean, low-disorder two-dimensional electron systems (2DES) is rooted in the historical development of the field.[1] In the course of the last two decades many of the new discoveries related to the QHE were a direct result of improvements in sample quality. In recent years, however, attention has shifted towards lower quality samples. Jiang *et al.*[2] and others[3,4] demonstrated that even highly disordered 2DES that are strongly localized at zero B field can exhibit the integer quantum Hall effect (IQHE). Surprisingly, only the $\nu=2$ IQHE was observed in these samples, with the $\nu=1$ missing even at fields as high as 10 T. This should be contrasted with cleaner samples, that are "metallic" at $B=0$, where the spin-polarized $\nu=1$ IQHE state has been observed at B as low as 0.15 T.[5]

A B-field-induced insulator to QHE transition has been predicted theoretically by Kivelson, Lee, and Zhang[6] (KLZ) as a part of a global phase diagram they suggested for spinless electrons. One consequence of their phase diagram is that a continuous transition from the IQHE phase to the insulator can only take place from the lowest Landau level. According to their framework, the experimentally observed transition from the $\nu=2$ IQHE state to an insulating phase can only occur if the electron system is spin degenerate. The absence of the spin-split $\nu=1$ IQHE state at B fields higher than 10 T,[4] at which the 2DES in GaAs/$Al_xGa_{1-x}As$ heterostructure is unlikely to remain spin degenerate, may be regarded as inconsistent with the phase diagram proposed by KLZ.

In this paper we report on a study of samples that are similar to the samples of Refs. 2–4 in that they are insulating at $B=0$, and undergo a well-defined transition into the $\nu=2$ IQHE state. In contrast to the samples of previous studies, these samples also exhibit a well-defined, fully-developed $\nu=1$ IQHE state. This state is observed for B as low as 0.8 T. For lower density samples that are even more insulating at $B=0$, the $\nu=2$ IQHE state can no longer be resolved, and a transition directly to the $\nu=1$ IQHE is observed. In both cases, as B is increased beyond the $\nu=1$ state, the IQHE phase terminates with a single transition from the $\nu=1$ IQHE to an insulating phase.

The results in this work were obtained from two samples cut from a single GaAs/$Al_xGa_{1-x}As$ wafer grown by molecular-beam epitaxy technique. They were wet etched to the shape of a standard Hall bar 100 μm wide, with a 290-μm distance between the voltage probes. In-Sn contacts were alloyed at 450 °C. Measurements were done in a dilution refrigerator capable of a base temperature (T) of 20 mK, using an ac lock-in technique with an excitation current of 0.1 nA. The carrier density n (and the effective disorder) was controlled in the range $0.8–2.9\times10^{10}$ cm^{-2} by biasing, for sample C70E, an In back gate situated 500 μm and for sample C70G, an aluminum front gate a distance of 2300 Å away from the plane of the 2DES. Similar results were obtained with the two gating methods. For brevity, in this paper we will only show data for sample C70G.

In Fig. 1, we present resistivity (ρ) vs T data obtained at $B=0$ for sample C70G, taken at several values of the front gate bias voltage, V_{fg}. At $V_{fg}=+10$ mV the sample exhibits metallic behavior down to our lowest T, in the sense that ρ is only weakly T dependent and is always less than 25 kΩ. This is no longer the case for V_{fg} values that are lower than -21 mV. A strong T dependence develops below $T=250$ mK with $\rho(T)$ rapidly increasing as $T\rightarrow0$, typical of insu-

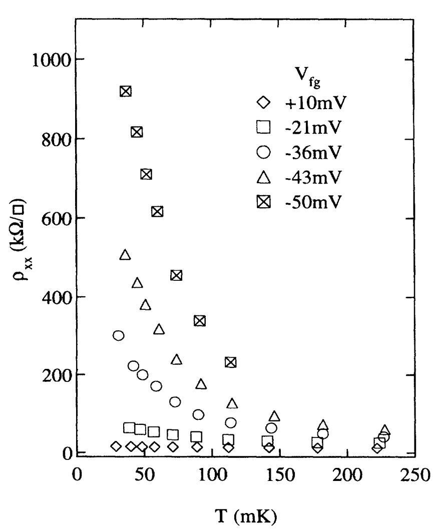

FIG. 1. ρ_{xx} vs T at $B=0$ for several values of V_{fg}.

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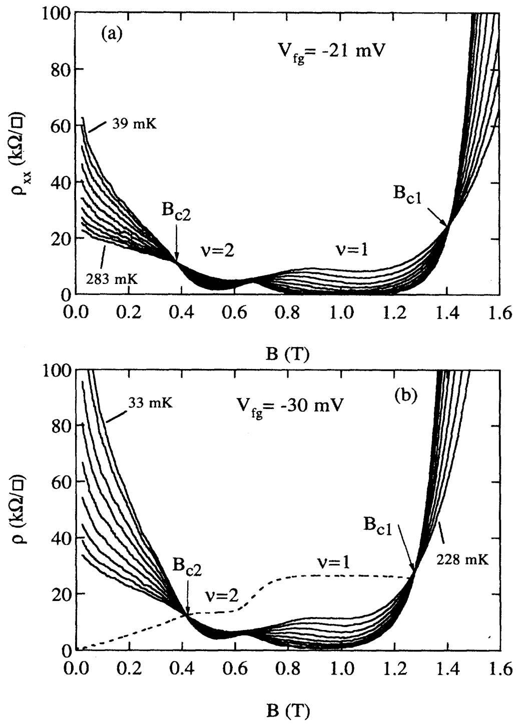

FIG. 2. Solid lines are ρ_{xx} vs B traces at various T's for two V_{fg} values. The T's in (a) are 39, 47, 57, 71, 89, 112, 141, 178, 224, and 283 mK, and in (b) 33, 43, 60, 73, 91, 114, 144, 182, and 228 mK. Dashed line in (b) is a trace of ρ_{xy} at $T=44$ mK. B_{c1} and B_{c2} are the phase transition points (see text).

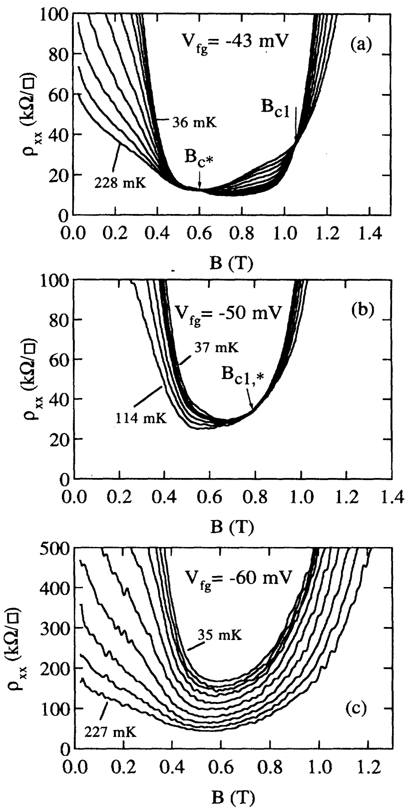

FIG. 3. ρ_{xx} vs B traces at various T's for three V_{fg} values. T in (a) are 36, 45, 51, 61, 74, 92, 115, 146, 182, and 228 mK, in (b) 37, 45, 52, 60, 74, 91, and 114 mK, and in (c) 35, 45, 51, 60, 74, 91, 115, 144, 181, and 227 mK.

lating behavior. This behavior becomes more dramatic for lower V_{fg} and for $V_{fg}=-50$ mV, ρ reaches 920 kΩ at our lowest T. These results indicate that sample C70G is in a strongly localized, insulating state at $B=0$ for $V_{fg}\leqslant-21$ mV.

We now focus on the high-B behavior at $V_{fg}\leqslant-21$ mV, for which sample C70G exhibits insulating behavior at $B=0$ (cf. Fig. 1). In Fig. 2 we show two sets of B-field traces of the diagonal resistivity, ρ_{xx}, for $V_{fg}=-21$ mV [Fig. 2(a)] and -30 mV [Fig. 2(b)], taken at various T's between 33 and 283 mK. We have also included a Hall resistivity ρ_{xy} trace taken at $V_{fg}=-30$ mV and $T=43$ mK [dashed line in Fig. 2(b)]. For both values of V_{fg}, we clearly observe a T-independent transition point, designated by B_{c2} in the figure (at $B=0.389$ and 0.415 T for $V_{fg}=-21$ and -30 mV, respectively), that separates the low-B insulator and the $\nu=2$ IQHE state. A similar transition point has been reported in Refs. 2–4. The new feature in our data is the existence of a clearly defined $\nu=1$ IQHE state, characterized by a wide minima with $\rho_{xx}\rightarrow0$ as $T\rightarrow0$, and a plateau in ρ_{xy} quantized to h/e^2 [cf. Fig. 2(b)]. To the best of our knowledge, the spin-resolved $\nu=1$ IQHE state in a sample that exhibits insulating behavior at $B=0$ has not yet been reported. This state terminates at higher B with an additional transition to an insulator (B_{c1} in Fig. 2), which is similar to the transitions studied by Shahar *et al.*[7] Thus, at these V_{fg} values, the observed reentrant transition pattern in our samples is insulator-2-1-insulator (the numbers denote the IQHE states), rather than insulator-2-insulator reported previously.[2–4]

In Fig. 3 we plot similar B field traces of ρ_{xx} for yet lower V_{fg}. Remarkably, for $V_{fg}=-43$ mV [Fig. 3(a)], the first transition to the $\nu=2$ IQHE state is no longer observed. Instead, a new transition point [B_{c*} in Fig. 3(a)] from the insulator to the $\nu=1$ IQHE state emerges. Thus, for $V_{fg}=-43$ mV, the transition pattern is insulator-1-insulator. At $V_{fg}=-50$ mV [Fig. 3(b)] the two transitions, B_{c1} and B_{c*}, appear to have merged into one transition point and the QHE can no longer be resolved. At $V_{fg}=-60$ mV [Fig. 3(c)], insulating behavior prevails at all B values (note the expanded ordinate), although a broad minimum is observed at $B\sim0.6$ T for all T's.

The five sets of B-field traces of ρ_{xx} presented in Figs. 2 and 3 reflect the evolution of our sample, as a function of disorder, from a QHE state exhibiting the $\nu=1$ and 2 states to an insulator at all B values. This evolution sees the gradual destruction of the $\nu=2$ state with increasing disorder, followed by the destruction of the more robust $\nu=1$ state at higher disorder. The only assumption implicit in identifying the region between B_{c*} and B_{c1} in Fig. 3(a) as the $\nu=1$ IQHE state is that the transition from the QHE to the insulating phase is a direct transition. We cannot rule out the possibility of the existence of an intermediate phase between the QHE and the insulator. We note that an apparent intermediate phase can result from the fact that our experi-

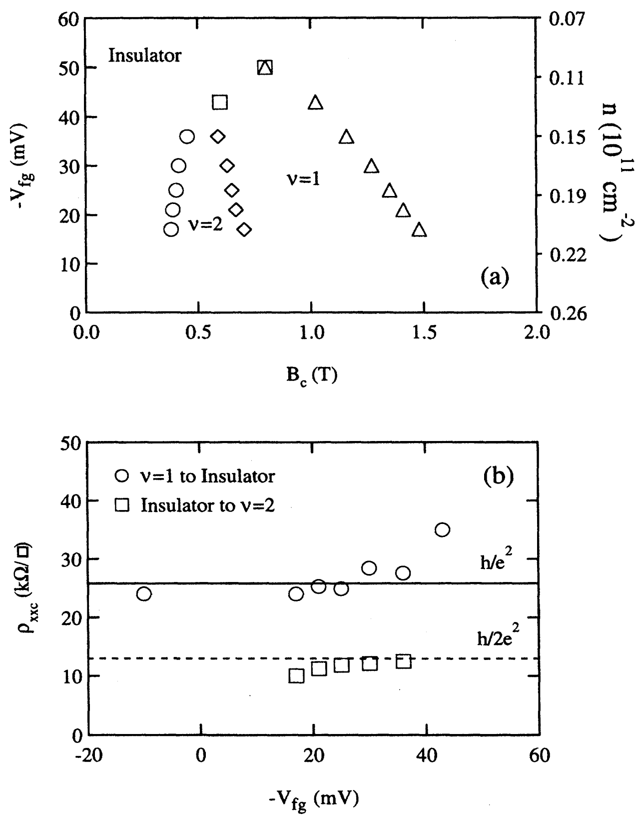

FIG. 4. (a) The phase diagram for sample C70G, in the V_{fg}-B_c plane. The B_c values for each V_{fg} are deduced from the T-independent transition points in Figs. 2 and 3. Symbols designate transition from the $\nu=1$ to the insulator (△), from the insulator to $\nu=1$ (□), from the insulator to $\nu=2$ (○), and between $\nu=2$ to $\nu=1$ (◇). The density is calculated from V_{fg} using a capacitive model. (b) ρ_{xx} at the transition points vs $-V_{fg}$. The solid line is at $\rho_{xx}=h/e^2$ and the dashed line is at $\rho_{xx}=h/2e^2$.

ment is carried out at finite T and finite sample size.

The observation of T-independent transition points that clearly separate the QHE states and the insulator allowed us to construct an experimentally derived phase diagram for sample C70G. Following Ref. 8, we plot in Fig. 4(a) the B position of the various transition points vs $(-V_{fg})$. We only plot the high-disorder part of the diagram, for which our sample exhibits insulating behavior at $B=0$. This phase diagram illustrates clearly the new features of this work. First, we note that if the $\nu=2$ IQHE state is observed for a given V_{fg}, it must be followed at higher B with the $\nu=1$ IQHE state. Second, the phase diagram reflects the new transitions pattern, from the low-B insulator to the $\nu=1$ IQHE state, followed by an additional transition to the insulator at higher B [cf. Fig. 3(a)]. We have not observed, for any of our samples, the theoretically expected[6,12,13] insulator-1-2-1-insulator pattern of transitions.

The phase diagram deduced for our samples is qualitatively different from those of Refs. 2, 4, and 8. The main difference stems from the observation of the spin-polarized $\nu=1$ IQHE state in our samples, which is absent in previous studies of samples that are insulating at $B=0$. Although the source of this disagreement is still unclear, we wish to point out several features that distinguish our samples from those of Refs. 2–4 and 8. First, the Si donors that contribute the conduction electrons to the 2DES are separated by a 1000-Å undoped spacer layer from the conducting channel, whereas in Refs. 2–4 the donors are deliberately placed at (or close to[3]) the conducting channel, resulting in a potential which is highly disordered and, consequently, these systems are in the $B=0$ insulating regime at very high densities (1.4–5×10^{11} cm^{-2}). The much smoother potential fluctuations in our samples allowed us to operate at much lower n, typically ten times lower than the n of the samples in Refs. 2–4.

We emphasize that, since our samples are of much lower n than those of Refs. 2–4, the B-field range of this study is correspondingly lower and, consequently, the energy gap at $\nu=1$ is expected to be smaller. However, the low n and relatively smooth disorder potential in our samples suggest that an electron-electron interaction may cause large enhancement of the energy gap at $\nu=1$, Δ_1, thus increasing the possibility for the observation of the $\nu=1$ state. This effect is usually described by an enhanced effective g factor through $\Delta_1=g_{\mathrm{eff}}\mu_B B$, where μ_B is the Bohr magneton. Our largest value of g_{eff}, obtained from the activation behavior at the $\nu=1$ minimum for $V_{fg}=+10$ mV, is 4.5, which is within the range of the values obtained in previous studies of standard, "metallic" samples.[10]

In a recent theoretical paper, Fogler and Shklovskii[9] studied the effect of the interplay between disorder and electron-electron interactions on the spin splitting of the Landau levels and constructed a phase diagram that modifies the phase diagram proposed by KLZ to include the spin degree of freedom. The topology of their phase diagram does not allow the insulator-1-insulator pattern of transition observed in our samples. Rather, they predict that at high disorder an insulator-2-insulator transition pattern should be observed, in agreement with the results of Refs. 2, 4, and 8. They did note, however, that due to complications arising from the formation of Skyrmions at the lowest Landau level,[11] the regime of applicability of their theory does not include the $\nu=1$ state. Our observation of the $\nu=1$ IQHE state in our low n, insulating, samples warrants further theoretical investigations relevant to the physics of the spin splitting of the lowest Landau level.

In a previous work,[7] we studied the transitions from the $\nu=1$ IQHE (and $\nu=1/3$ fractional quantum Hall effect) to the insulating phase in several samples, and obtained evidence for the existence of a universal value of ρ_{xx} at the transition point. In this work we are able to follow ρ_{xxc}, the value of ρ_{xx} at the critical point, for different values of disorder in a single sample. As can be seen in Fig. 4(b), where we plot ρ_{xxc} vs V_{fg} from sample C70G, ρ_{xxc} remains relatively close to h/e^2 (solid line) through most of our V_{fg} range and starts to deviate upwards only for the strongest bias, where the $\nu=1$ IQHE state itself begins to weaken significantly. We also included in Fig. 4(b) the value of ρ_{xxc} at the transition from the low-B insulator to the $\nu=2$ IQHE state. Clearly, ρ_{xxc} for this transition is different from that of the $\nu=1$ IQHE to insulator transition and is, in fact, scattered around $h/2e^2$ (dashed line), the value reported in Refs. 4 and 8.

To summarize, we observed a transition from a $B=0$ insulating state to an IQHE phase that includes the $\nu=2$ and the $\nu=1$ IQHE state. At higher disorder we observed an insulator to $\nu=1$ IQHE to insulator pattern of transitions. Based on our results, we constructed a phase diagram for our samples that is qualitatively different from those reported previously. We stress that a larger number of samples of various densities and disorder needs to be studied before a general phase diagram for 2DES at high B can be deduced.

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