Magnetic-field-induced insulator-quantum Hall conductor-insulator transitions in doped GaAs/$Al_xGa_{1-x}As$ quantum wells

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We present magnetotransport measurements on GaAs/$Al_xGa_{1-x}As$ multiple quantum wells doped with impurities at the centers of GaAs layers. Magnetic-field-induced insulator-quantum Hall conductor-insulator transitions with a well defined scaling behavior were observed. The critical exponents as well as the resistivities at the two critical magnetic fields are close to each other. Their values are, however, different from the values obtained from similar studies performed on modulation-doped GaAs/$Al_xGa_{1-x}As$ heterostructures. [S0163-1829(97)07747-3]

Phase transitions in a three-dimensional electron system (3DES) and a two-dimensional electron system (2DES) have been the subject of intensive studies for many years. In a 3DES, according to the theory of Anderson localization,[1] there exists a mobility edge that separates extended states from localized states. At zero magnetic field ($B=0$), a metal-insulator transition occurs when the Fermi level of the 3DES passes through the mobility edge. In a 2DES, though metallic behavior is observed in high-mobility samples down to very low temperature ($T\sim 20$ mK) at $B=0$, it is generally believed to be insulating in the limit of infinite sample size according to the scaling theory of localization.[2] Therefore, phase transition is not expected for a 2DES at $B=0$.[3] On the other hand, the theoretical understanding of the quantum Hall effect requires the presence of extended states in the center of a broadened Landau level in the high-B limit. The vanishing and reappearance of the extended states at different magnetic fields imply that there exists a magnetic-field-induced phase transition, and this subject has been of considerable interest. Recently, Kivelson, Lee, and Zhang[4] proposed a magnetic-field-driven phase transition between the insulating state and the quantum Hall (QH) state in the disorder-B parameter space. Experimentally, a sequence of transitions from an insulator at $B=0$ to a QH conductor at finite B, and then to an insulator again at higher B, have been demonstrated in highly disordered 2DES's.[5–8] Most of the samples used for these studies were modulation-doped GaAs/$Al_xGa_{1-x}As$ heterostructures. In this paper, we report studies of the magnetic-field-driven phase transitions on center-doped GaAs quantum wells (QW's).

The sample used in this study is a GaAs/$Al_{0.3}Ga_{0.7}As$ multiple QW grown by molecular-beam epitaxy. It contains 30 QW's. The width of the GaAs quantum wells is 200 Å, and the width of the $Al_xGa_{1-x}As$ potential barrier is 600 Å. N-type impurities (Si) are placed at the center of each QW. The $Al_xGa_{1-x}As$ layers are undoped. The intended doping concentration in each QW is 3×10^{11} cm^{-2}. Because the carriers and the impurities are both in the QW's, strong impurity scattering can be expected, and the electron mobility of this sample is very low even at high electron concentrations. Such a low electron mobility is difficult to achieve in a modulation-doped GaAs/$Al_xGa_{1-x}As$ heterostructure. The electron mobility of our sample is about 500 cm^2/V s at $T=5$ K. It decreases as the temperature is lower: at $T=0.3$ K, $\mu=250$ cm^2/V s. This sample was made into Hall bars with a length-to-width ratio of 6 by standard lithography and etching processes. Ohmic contacts were made by alloying indium into the contact regions with an annealing temperature of 420 °C. Magneto transport measurements were performed with a 13-T superconducting magnet in conjunction with a top-loading He^3 system, which is capable of reaching a base temperature of 300 mK. A RuO_2 sensor was mounted near the sample to measure its temperature. The measuring current was carefully chosen to avoid self-heating of the sample. Both dc and low-frequency ac lock-in techniques were used to measure the longitudinal resistance (R_{xx}) and Hall resistance (R_{xy}), and the results were identical. Although our sample is a multilayer δ-doped system, complications resulting from interlayer coupling[9] are avoided because of the presence of wide $Al_xGa_{1-x}As$ barriers. Two sharp phase transitions on both sides of the well defined QH conducting phase, corresponding to the Landau-level filling factor $\nu=2$, were observed for this sample. It is found that the resistivities of the sample at the two transition points are almost the same, but their values are far from $h/2e^2$, the value reported in Refs. 7 and 8. In addition, scaling behavior is observed near the transition points, and the two critical exponents are identical within experimental error. However, their values are different from the universal value 0.21 for a spin-degenerate 2DES.[10]

In order to obtain longitudinal resistivities (ρ_{xx}) and Hall resistivity (ρ_{xy}) per layer, we must know the number of ac-

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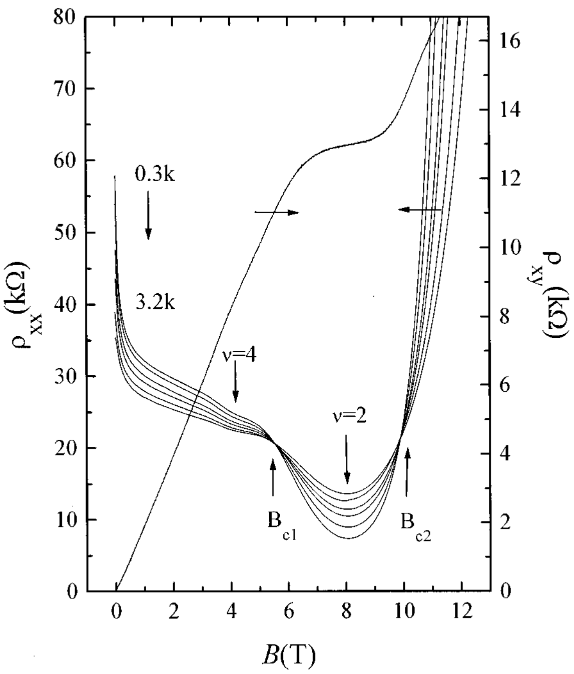

FIG. 1. ρ_{xx} (left axis) and ρ_{xy} (right axis) per layer vs magnetic field B. The temperatures of ρ_{xx} are 0.3, 0.5, 0.8, 1.2, 2, and 3.2 K, the temperature of ρ_{xy} is 0.3 K.

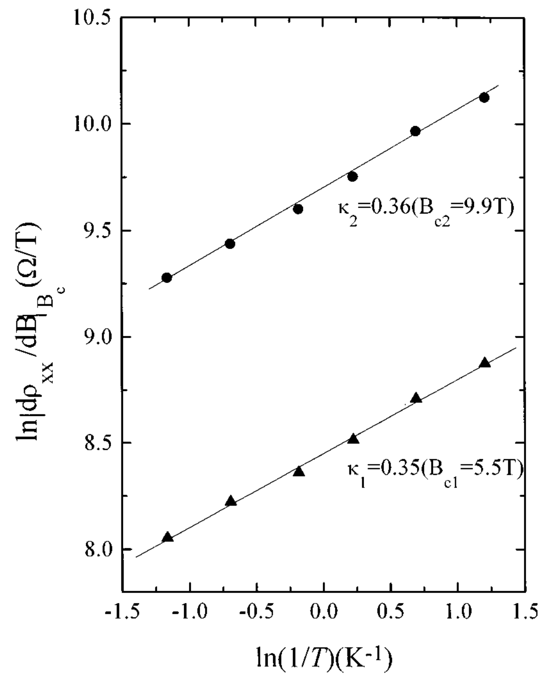

FIG. 2. Scaling fitting of $\ln|d\rho_{xx}/dB|_{B_c}$ vs ln $1/T$ for B_{c1} and B_{c2}. The slopes of the solid line are the critical exponents.

ive layers. This can be achieved in two ways. First, it can be obtained by taking the ratio between the low-field Hall measurement (which measures total electron concentration in the sample) and the Shubnikov–de Hass (SdH) measurement (which measures carrier concentration per layer). Second, from the plateau in the R_{xy} vs B curve at Landau filling factor $\nu=2$, we can compare the resistance of the plateau with $h/2e^2$ (12 906Ω). The number of active layers we obtained from these two ways were 22 and 25, respectively, with roughly 12% error. Since the value of the QH plateau is a universal constant, it is believed that the latter one (25 layers) is more accurate. The carrier concentration per QW obtained from the SdH measurement is approximately 3.8×10^{11} cm^{-2}, which is reasonably close to the intended doping concentration.

Magnetic-field-dependent ρ_{xx} per layer taken between $T=0.3$ and 3.2 K, and ρ_{xy} per layer taken at 0.3 K for the sample, are shown in Fig. 1. From $B=0$ T to $B=0.7$ T, ρ_{xx} decreases very rapidly [$\rho_{xx}(0\text{ T})/\rho_{xx}(0.7\text{ T})=1.7$ at 0.3 K]. This part corresponds to the giant negative magnetoresistance (MR). It is then followed by a slowly monotonical decrease of ρ_{xx} from $B=0.7$ to 5 T. The indication of a SdH dip at $\nu=4$ is observed at $B=4.1$ T. A broad minimum in ρ_{xx} could be found at around $B=8$ T, which corresponds to $\nu=2$. Around this magnetic field, a well-developed QH plateau could also be observed in the ρ_{xy} vs B curve. After passing through the region of $\nu=2$, ρ_{xx} increases very quickly as the magnetic field increases, and is strongly temperature dependent. The most important feature in the ρ_{xx} vs B curves is that there exist two phase-transition points on both sides of the minimum, $\nu=2$. These two critical magnetic fields are $B_{c1}=5.5$ T and $B_{c2}=9.9$ T, and their corresponding resistivities are 20 500Ω and 21 060Ω, respectively. At these two critical points, all the curves of ρ_{xx} for different temperatures merge. Considering the fact that the measured resistivities are the combined effect of 25 QW's, with each QW having a different impurity configuration, it is quite surprising that the critical magnetic fields are so well defined. Based on the temperature dependence of ρ_{xx}, the critical points sharply separate ρ_{xx} curves into three regions. At $B<B_{c1}$, this sample behaves like an insulator in the sense that ρ_{xx} increases as T decreases. For $B_{c1}<B<B_{c2}$, ρ_{xx} decreases as T is lower, and the QH plateau appears. That is typical of a QH conductor. For $B>B_{c2}$, ρ_{xx} increases as T decreases, indicating that it is in the insulating phase again. At the two points of the phase transition, the resistivity can remain unchanged even when the temperature is varied by a factor of 10. These results are quite similar to the previous experiments on modulation-doped $GaAs/Al_xGa_{1-x}As$ heterostructures.[5–8] Therefore, in multilayer δ-doped $GaAs/Al_xGa_{1-x}As$ QW's, there also exist insulator–QH conductor $(\nu=2)$–insulator transitions, which are consistent with global phase diagram for a spin-degenerate 2DES.

The universality of the conductivity at the phase transition has been suggested.[11] Shahar, Tsui, and Cunningham[8] found that the resistivities at the critical point were approximately h/e^2 times a constant. This constant is equal to the value of the Landau-level filling factor, where the QH-insulator transition takes place. From Fig. 1, there are two temperature-independent points, and their resistivities are approximately 20 kΩ (20 500Ω at B_{c1} and 21 060Ω at B_{c2}) if we take the number of the active layers to be 25. 20 kΩ is far from the universal constant $h/2e^2$ (12 906Ω), which is expected for the transition between insulator to $\nu=2$ QH state.[7,8] The resistivities per well would be smaller (18 040Ω at B_{c1} and 18 530Ω at B_{c2}) if 22 is taken as the number of active layers, but these values are still much larger than $h/2e^2$. Our results indicate that the value of ρ_{xx} at the phase transition may be system dependent.

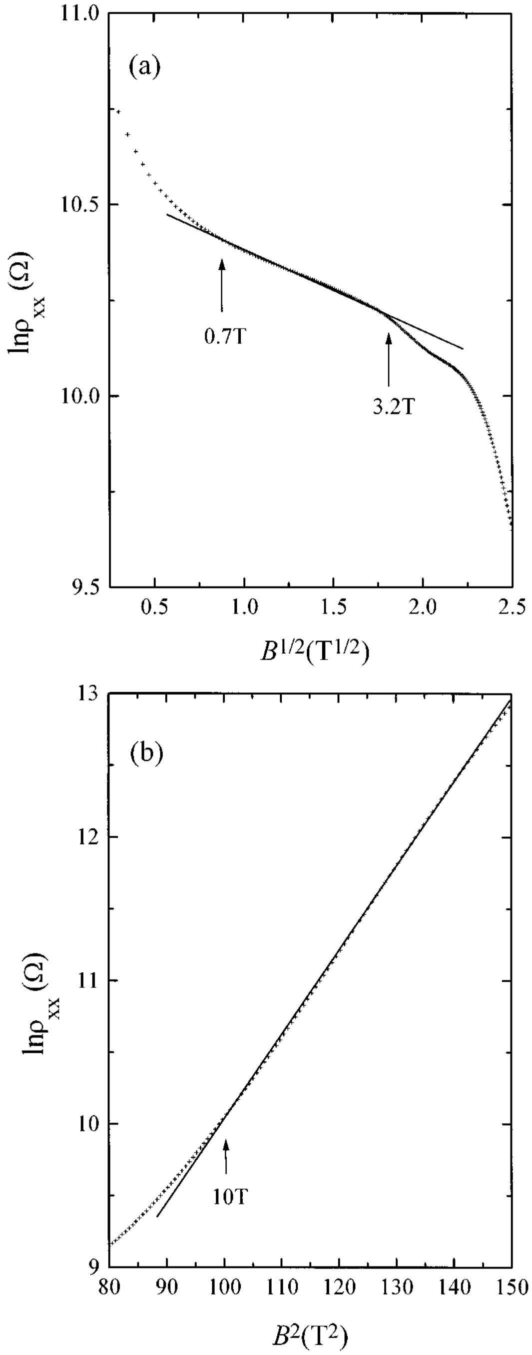

FIG. 3. Magnetic-field dependences of ρ_{xx} at 0.3 K. (a) $\ln \rho_{xx} \propto B^{1/2}$ for 0.7 T$<B<$3.2 T, and (b) $\ln \rho_{xx} \propto B^2$ for $B>10$ T.

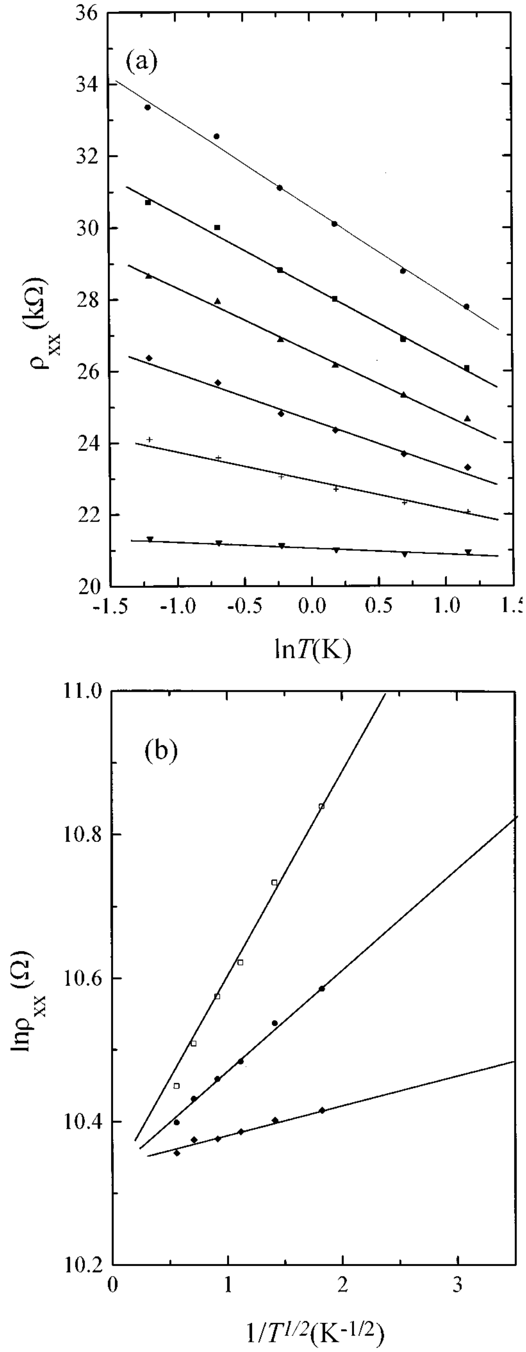

FIG. 4. Temperature dependence of ρ_{xx} at various magnetic fields. (a) In the WL regime, $\rho_{xx} \propto \ln T$. (b) As $B>10$ T, $\ln \rho_{xx} \propto T^{-1/2}$ for hopping conduction. From top to bottom, magnetic fields in (a) are 0.7, 1.5, 2.5, 3.5, 4.5, and 5.4 T, and in (b) are 10.5, 10.2, and 10 T.

For the B-induced quantum phase transition, scaling behavior is expected. Wei *et al.* examined the scaling behavior of the phase transition in a $In_xGa_{1-x}As/InP$ heterostructure. They found that both the maximum in $d\rho_{xy}/dB$ $[(d\rho_{xy}/dB)^{\max}]$ and the inverse of the half-width in ρ_{xx} $[(\Delta B)^{-1}]$ between two adjacent QH plateaus below some critical temperature diverged like $T^{-\kappa}$ with $\kappa=0.42\pm0.04$.[10] For Landau levels where the spin splitting was degenerate, $(d\rho_{xy}/dB)^{\max}$ and $(\Delta B)^{-1}$ followed the power law $T^{-\kappa/2}$.[10] In experiments on an $Al_xGa_{1-x}As/GaAs$ sample, they also obtained the same result.[12] Conversely, Koch *et al.* questioned the universality of the exponent κ. (κ is related to the critical exponent υ of the divergent electron localization length via $\kappa=p/2\upsilon$, with p the temperature exponent of the inelastic scattering length.) Instead of κ, they obtained a universal behavior of υ with a value of $\upsilon=2.3\pm0.1$. The value of p was between 1.3 and 3.8. Therefore, $\kappa=p/2\upsilon$ was not universal.[13] Furthermore, they found that κ increased from 0.28 to 0.81 with decreasing mobility for the spin-splitting samples. They also found that if the spin splitting was unresolved, κ was notably smaller, but not by a factor of 2,[14] as Wei *et al.* claimed.[10] It is shown that near B_c, scaling follows $|d\rho_{xx}/dB|_{B_c} \propto T^{-\kappa}$ (Ref. 6) for data near the phase transition. The critical exponent κ can thus be obtained from the slope of $\ln(d\rho_{xx}/dB)_{B_c}$ vs $\ln(1/T)$. The values determined from this method are shown in Fig. 2. It is found that $\kappa_1 = 0.35 \pm 0.02$ and $\kappa_2 = 0.36 \pm 0.02$ at B_{c1} and B_{c2}, respectively. The two lines are well defined by six points, implying that this sample has a good scaling behavior. Because, within experimental error, $\kappa_1 = \kappa_2$, the two transitions, insulator to QH and QH to insulator, appear to belong to the same universality class. However, κ determined from the transitions does not equal the universal value 0.21.[10] Our results, like the works by Koch *et al.*, do not seem to support universal scaling.

Here we want to point out that the insulating phases on the two sides of the QH conductor are in different regimes: one is in the weakly localized (WL) regime and the other is in the strongly localized (SL) regime. In the WL regime, the B and T dependences of ρ_{xx} are $\ln \rho_{xx} \propto B^{1/2}$ (Ref. 15) and $\rho_{xx} \propto \ln T$[16,17] respectively. In the SL regime, the B dependence follows the law of $\ln \rho_{xx} \propto B^2$ (Ref. 18) because of the shrinkage of electron wave functions, and, for the T dependence, hopping conduction, $\ln \rho_{xx} \propto T^{-1/2}$,[18] is expected at fixed B. The B dependence, $\ln \rho_{xx}$ vs $B^{1/2}$ and $\ln \rho_{xx}$ vs B^2, were plotted in Figs. 3(a) and 3(b). We found that the system was in the WL regime in the range $B = 0.7 - 3.2$ T, and was in the SL regime for $B \geqslant 10$ T. The deviation from the $B^{1/2}$ law between 3.2 T and B_{c1} is due to the appearance of a SdH dip at $B = 4.1$ T. Because the resistivity behaves well with $\rho_{xx} \propto \ln T$ for $0.7\ \text{T} < B < 5.4$ T, as is shown in Fig. 4(a), we believe that this sample is in the WL regime for $0.7\ \text{T} < B < B_{c1}$. Hopping conduction is observed for $B > 10$ T, and the slope increases with increasing B, as is shown in Fig. 4(b). From these results, we conclude that the origin of the two insulating phases are different.

The giant negative MR we observed in our sample for $0\ \text{T} < B < 0.7$ T is often exhibited in a disordered 2DES. There are many theoretical models on this subject, and a definite conclusion on the mechanism of the giant negative MR is not reached yet. Mareš *et al.*[9] proposed that a δ-doped 2DES would change from SL to WL and to SL again as B increases. In the SL regime, ρ_{xx} is strongly temperature dependent, and will go to infinity as $T \rightarrow 0$. Theoretically,[9] ρ_{xx} is of the order of 40 k$\Omega/\square$ as the SL regime changes into the WL regime. In addition, the range of the SL regime is very narrow at low B.[9] Due to the narrowness and the strong temperature dependence of the SL regime, ρ_{xx} will drop very rapidly from infinite to the value of 40 k$\Omega/\square$ at low B (SL$\rightarrow$WL). This phenomenon is quite similar to high-B behavior, where WL changes into SL, and ρ_{xx} thus increases very dramatically. Therefore, a giant negative MR can be expected at low B just as a large positive increase of ρ_{xx} can be expected at high B. We found in our data that ρ_{xx} is strongly temperature dependent both for $B < 0.7$ T as well as for $B > 10$ T. In addition, at $B = 0.7$ T, where the giant negative MR terminates, ρ_{xx} is around 35 k$\Omega/\square$, which is close to the theoretical value. $B = 0.7$ T is thus the boundary that separates the SL regime from the WL regime, which is also consistent with our previous analysis [Fig. 3(a)]. Our results appear to support the contention that a giant negative MR occurs in the SL regime.

In summary, magnetic-field-induced phase transitions (insulator-QH-insulator) were observed in a multilayer δ-doped GaAs/Al_xGa_{1-x}As QW sample. It is found that the properties of the insulating phases on two sides of a QH conductor are different. At the low-field side, it is in the WL regime; at the high-field side, it is in the SL regime. Despite this difference, the transitions between insulator (WL)–QH and QH–insulator (SL) appear to belong to the same universality class because the critical exponents κ's for both transitions are identical to each other within experimental error. It is also found that the resistivities at the two critical fields are almost the same. Nevertheless, their values are not close to the previously observed values. More theoretical and experimental investigations are required to resolve this discrepancy.

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