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Magnetic-field-induced delocalization in center-doped GaAs/Al$_x$Ga$_{1-x}$As multiple quantum wells

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We report magnetotransport measurements and scaling analysis on a series of center-doped GaAs quantum wells. Sharp phase transitions were observed in the magnetic field sweep and it was found that, depending on the doping concentration in the quantum wells, the insulating phase can make transitions to quantum Hall phase with Landau-level filling factors (ν) of 2, 6, and 8. The critical exponents vary from sample to sample and are mobility dependent. The longitudinal resistivities of these samples at the phase transition points decrease with increasing ν, and for a sample with higher mobility, its value is close to $h/\nu e^2$. [S0163-1829(98)01839-6]

The fate of extended states in a two-dimensional electron system (2DES) has attracted much attention recently. According to the scaling theory of localization,[1] at zero magnetic field all states are localized. On the other hand, the theoretical understanding of the quantum Hall effect[2] requires the presence of the extended states at the centers of the broadened Landau levels (LL's) at a finite magnetic field. To explain the evolution from finite extended states at finite magnetic fields to zero extended state at zero magnetic field, Khmel'nitzkii[3] and Laughlin[4] (KL) showed that as the magnetic field decreases, the energy of the extended states will float up and exit through the Fermi level of the 2DES. And, as all the states below the Fermi level become localized at zero magnetic field, a 2DES is in the insulating phase at zero magnetic field. These authors also demonstrated that during floating up the extended states do not merge together; the extended states of lower LL's will float up faster than the extended states of the higher LL's. Based on KL's assumption and other considerations, Kivelson, Lee and Zhang[5] proposed a global phase diagram (GPD) in the disorder-magnetic field plane for the 2DES. According to this phase diagram, with changing magnetic field (or disorder), a series of phase transitions were expected for the 2DES, and some of them were verified experimentally.[6–9] Therefore, the assumption that the extended states float up but do not merge together seems to be true.

However, this assumption was challenged by Shashkin, Kravchenko, and Dolgoplov[10] and by Kravchenko *et al.*[11] experimentally, by Liu, Xie, and Niu (LXN),[12] and by Sheng and Weng (SW)[13] theoretically. The prior two groups[10,11] found that extended states did float up in energy, but not infinitely, and extended states of different Landau bands would coalesce. LXN[12] found that the extended states , instead of floating up in energy, would be destroyed by decreasing the magnetic field or increasing disorder. SW[13] showed that at low magnetic field the extended states merge together and disappear without floating. Furthermore, some recent experiments[7,14] do not seem to support the selection rule suggested by GPD, which implicitly assumes that at low magnetic field the extended states float up in energy but do not merge together. According to GPD, phase transition can occur only between insulting phase and the $S_{xy}=1$ (or equivalently $S_{xy}=2$ for spin degenerate) integer quantum Hall (QH) phase, where S_{xy} is the number of extended levels below the Fermi energy. However, these experiments found that phase transition could occur at higher S_{xy}.[7,14] Therefore the assumption of GPD and KL is still a subject of debate. To address these problems, we have carried out experiments to study magnetic-field-induced phase transitions on three center-doped GaAs multiple quantum wells (MQW's) samples. Sharp phase transitions were observed for all three samples. It is found that the value of the Landau-level filling factor (ν) where the insulating state makes a transition tote QH state is doping dependent, and can happen at filling factors as large as $\nu=8$.

The samples used in this study are GaAs/Al$_{0.3}$Ga$_{0.7}$As multiple QW's grown by molecular-beam epitaxy. Each sample contains 30 QW's. The width of the GaAs quantum wells is 200 Å and the width of the Al$_{0.3}$Ga$_{0.7}$As potential barriers is 600 Å. *N*-type impurities are placed at the center of each QW by the method of δ doping. The Al$_{0.3}$Ga$_{0.7}$As layers are undoped. Intended doping concentrations per quantum well are 3×10^{11} cm^{-2}, 6×10^{11} cm^{-2}, and 9×10^{-11} cm^{-2} for samples M832, M833, and M834, respectively. Because the carriers and the impurities are both in the QW's for these well-doped samples, strong impurity scattering can be expected. The electron mobilities of these samples are thus very low even at high electron concentration. Such low electron mobility is difficult to achieve in modulation-doped GaAs/Al$_{0.3}$Ga$_{0.7}$As heterostructures. The electron mobilities measured at $T=3$ K are about 470, 1160, and 1430 cm^2 V sec for sample M832, M833, and M834, respectively, and they decrease with decreasing the temperature. These samples were made into Hall bars with length-to-

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width ratio of six by standard lithography and etching processes. Ohmic contacts to the samples were made by alloying indium into the contact regions with annealing temperature of 420 °C for 10 min. Magnetotransport measurements were performed with a 13-T superconducting magnet in conjunction with a top-loading He^3 Heliox system. The samples were studied in the temperature range between 0.3 K and 3.2 K and a RuO_2 sensor was mounted near the samples to measure their temperatures. The measuring current was carefully chosen to avoid self-heating of the samples. Both dc and low-frequency (10 Hz) ac lock-in techniques were used to measure the longitudinal resistance (R_{xx}) and Hall resistance (R_{xy}), and the results were the same.

In order to get longitudinal resistivities (ρ_{xx}) and Hall resistivity (ρ_{xy}) per layer, we must know the number of active layers. This can be achieved through two ways. First, it is obtained by taking the ratio between 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, due to the appearance of the plateau in R_{xy} at the Landau filling factor $\nu = n$, we can compare the resistance of the plateau with $e^2/nh\,\Omega$. The number of contacted layers obtained for M832, M833, and M834 by the first method were 22, 23, and 26 layers, and by the second method were 25, 25, and 27 layers, respectively. The numbers obtained from these two methods differ only by roughly 8% and is probably due to the inaccuracy in determining the low-field carrier concentration in the Hall measurement. Since the value of the QH plateau is a universal constant, it is believed that the values calculated from the latter method (25, 25, and 27 layers) are more accurate. The missing layers are possibly not contacted by In or were depleted due to surface effect. Carrier concentration per QW obtained from the SdH measurement is approximately $3.8\times10^{11}\ \mathrm{cm}^2$, $7.2\times10^{11}\ \mathrm{cm}^{-2}$, and $10.4\times10^{11}\ \mathrm{cm}^{-2}$ in each QW, for M832, M833, and M834, respectively. These values are 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 M832 are shown in Fig. 1(a). By examining these curves, it could be found that longitudinal resistivity ρ_{xx} decreases very rapidly from $B = 0$ to $B = 0.7$ T. This giant negative magnetoresistance (MR) is a general property of disordered 2DES. For $B = 0.7$ to 5 T, ρ_{xx} decreases slowly and monotonically. In this range, the indication of a SdH dip for $\nu = 4$ is observed at $B = 4.1$ T. A broad minimum in ρ_{xx}, corresponding to $\nu = 2$, could be found at around $B = 8$ T. Furthermore, a well-developed QH plateau could also be observed in the experimental recording of the ρ_{xy} vs B curve. Therefore, it is obviously a QH phase. After passing through the region of $\nu = 2$, ρ_{xx} increases very quickly as B increases and is strongly temperature dependent. From the temperature dependence of ρ_{xx}, it can be seen that there exist two sharp phase transition points on both sides of the resistivity minimum. At these two critical fields, all the ρ_{xx} curves merge together and the critical points sharply separate ρ_{xx} curves into three regions. When $B < B_{c1} = 5.5$ T and $B > B_{c2} = 9.9$ T, 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 decreases and the QH plateau appears. This is typical of a QH conductor. These results are quite similar to the previous experiments on $GaAs/Al_xGa_{1-x}As$ heterostructures.[6–9] Therefore, in multi-δ-doped $GaAs/Al_xGa_{1-x}As$ QW's, there also exist transitions of insulator–QH ($\nu = 2$)–insulator ($0\rightarrow2\rightarrow0$), which is consistent with a GPD for a spin-degenerate 2DES. Detailed analysis on this sample was published elsewhere.[15]

Considering the fact that the system has 25 active well-doped QW's, it is unusual that the phenomenon of sharp phase transition can be observed in such a system. As the broad barriers prohibit the mutual interactions between QW's, this system conducts effectively like 25 parallel conducting channels, and the measured resistivities are thereby the combined effect of 25 resistors in parallel. In such a case, if any one of the layers does not have well-defined phase transition, the sharp transition point of this system will be lost. Moreover, for each layer the transition point must occur at the same magnetic field, otherwise, the critical magnetic field will not be well defined. In other words, despite the fact that the impurity configuration in the QW's may vary from layer to layer, the overall behavior of each QW in the magnetic field must be nearly identical.

Magnetic-field-dependent ρ_{xx} taken between $T = 0.3$ and 3.2 K, and ρ_{xy} taken at 0.3 K for M833 and M834 are shown in Figs. 1(b) and 1(c). Similar to what was observed for M832, the samples exhibit large negative magneticoresistance at low magnetic field. As the magnetic field increases, SdH oscillations can be clearly observed. From these oscillations, Landau-level filling factor ν can be determined, and they are marked in the figures. Quantum Hall plateaus corresponding to $\nu = 4$ and $\nu = 2$ for M833, and $\nu = 4$ for M834 could be observed in the experimental recording of the ρ_{xy}. For these two samples, there also exist well-defined critical magnetic fields (B_c) where all the ρ_{xx} curves merge. The critical magnetic fields are 4.8 T for M833 and 5.2 T for M834, respectively. By examining the ρ_{xx} curves more carefully, we find that like M832, B_c, separates two different phases by their temperature dependence. For $B < B_c$, the samples are in the insulting phase and for $B > B_c$ the samples are in the QH phase. The transition from the QH phase back to the insulating phase is expected to occur at $B > 13$ T and could not be observed. Despite the similarities, there are important differences between the results obtained for these two samples and that of M832. For M832, the transition follows the sequences $0\rightarrow2\rightarrow0$ and is not in apparent contradiction to the prediction of the GPD, here 0 indicates insulating state. However, we could see from these figures that the transition between insulating and quantum Hall states occurs at $\nu = 6$ ($0\rightarrow6$) for sample M833 and the transition occurs at $\nu = 8$ ($0\rightarrow8$) for sample M834. Moreover, the QH plateaus do not appear until $\nu = 4$ for these two samples. Before the appearance of the quantized plateau, ρ_{xy} curves are conventional straight lines. These two features are inconsistent with KLs' picture of floating up of extended states and are inconsistent with the selection rule required by GPD. On the contrary, we found, as can be seen in Fig. 2, that if ν_c is defined as Landau-level filling factor where the phase transition happens, ν_c varies approximately linearly with the doping concentration. This implies that, for the center-doped MQW structures, the phase transition can happen at even higher Landau-level filling factor if the doping concentration is el-

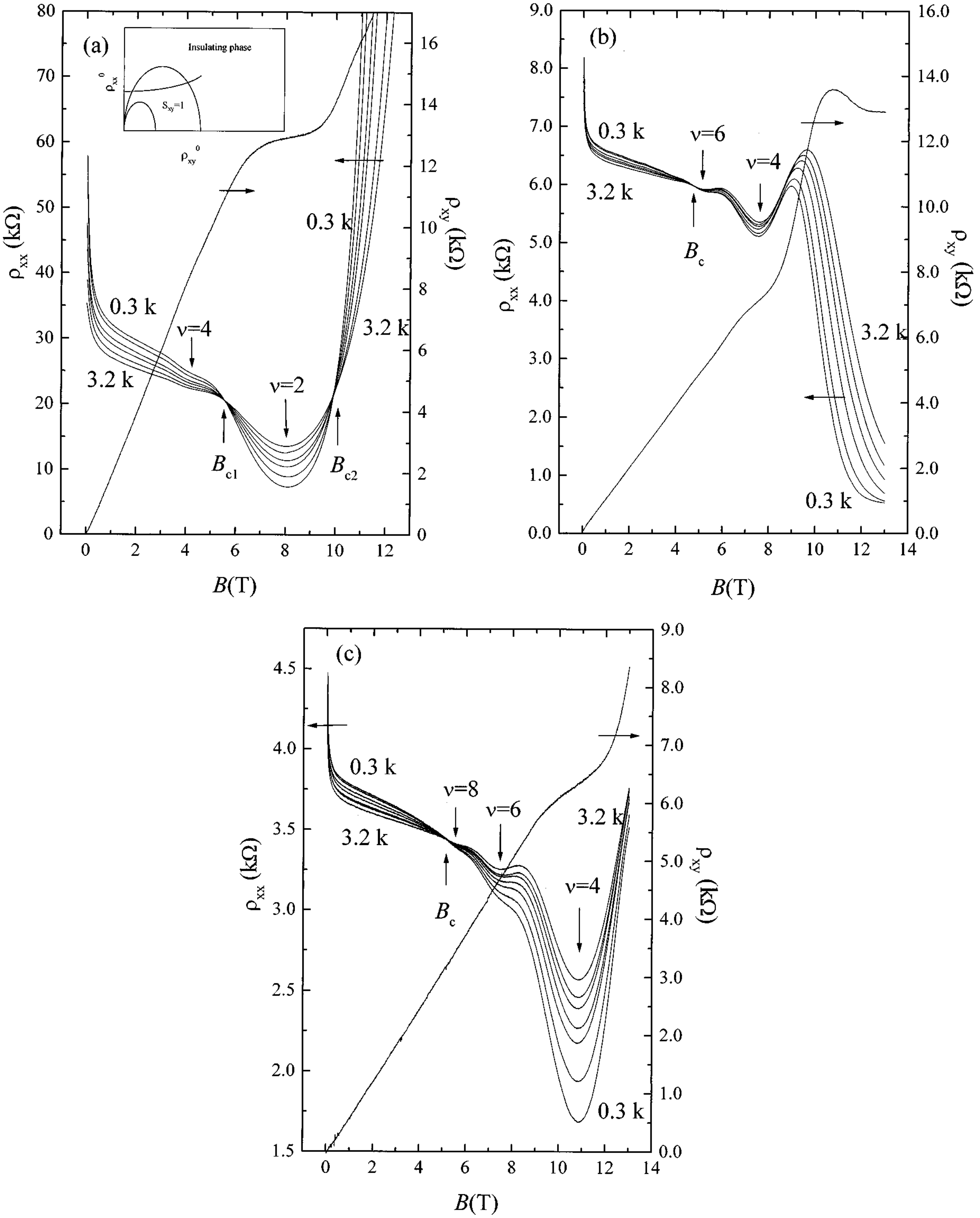

FIG. 1. ρ_{xx} (left axis) and ρ_{xy} (right axis) per layer vs magnetic field B for M832 (a), M833 (b), and M834 (c). The temperature of ρ_{xy} is 0.3 K for all samples. The temperatures of ρ_{xx} are 0.3, 0.5, 0.8, 1.2, 2, and 3.2 K for M832, 0.3, 0.6, 1.1, 1.6, 2.1, and 3.2 K for M833, and 0.3, 0.5, 0.8, 1.2, 1.7, 2, and 3.2 K for M834. Inset in (a) is the global phase diagram, which permits only the transition between insulating and the $\nu=1$ quantum Hall state.

evated, or the phase transition will disappear if the doping concentration is low enough. In other words, the phase transition can happen at arbitrary Landau-level filling factor.

In the previous studies, it was found by Shahar *et al.*[16] that at the phase transition point, the resistivity of the sample is independent of whether the transitions are $1\rightarrow 0$ or $1/3\rightarrow 0$ and is close to h/e^2. Later, the same group reported that for the $0\rightarrow\nu$ transitions, the critical resistivity was near $h/\nu e^2$.[9] Here, we examine whether there is such a critical resistivity in our sample. For M832, there are two temperature-independent points for this sample and their resistivities are approximately 20 kΩ (20 500 Ω and B_{c1} and 21 060 Ω at B_{c2}) if we take the number of the active layers to be 25. 20 kΩ is quite different from the expected $h/2e^2$ (12 813 Ω). For M833 and M834, the resistivities at the critical points are around 6 and 3.4 kΩ, respec-

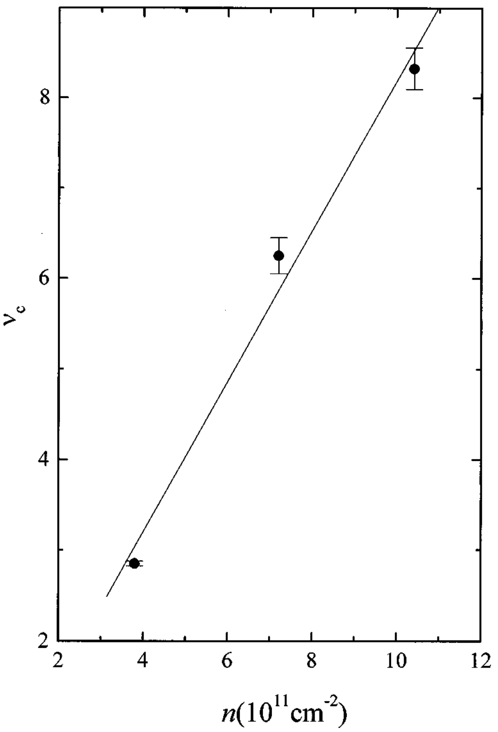

FIG. 2. The critical Landau-level filling factor vs doping concentration for the three samples. The dash line is a guide to the eyes.

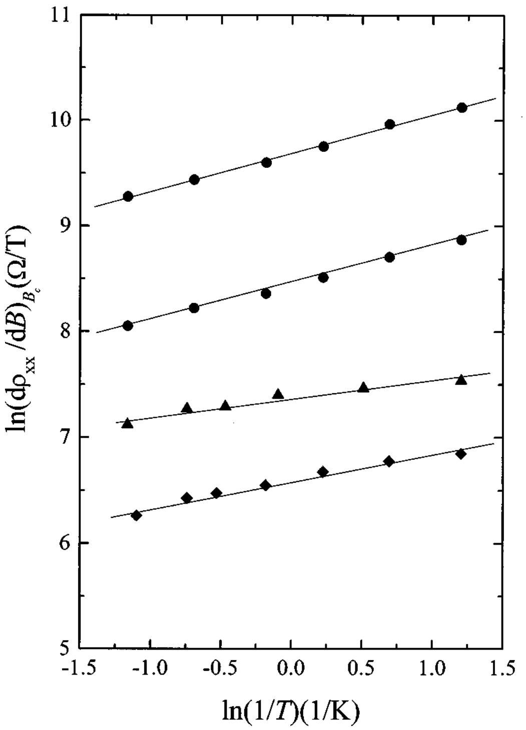

FIG. 3. Scaling fitting of the critical exponent at the critical magnetic fields for M832 ($B_{c2}=9.9$ T), M832 ($B_{c1}=5.5$ T), M833, and M834, from top to bottom, respectively. Well-defined scaling behavior was observed for all three samples.

tively. Since the transitions are $0\rightarrow6$ and $0\rightarrow8$ for these two samples, it is found that the two expected values, $h/6e^2$ (4302 Ω) and $h/8e^2$ (3226 Ω) are closer (comparing to M832) to the experimental values, 6 and 3.4 kΩ, respectively, but there is still significant deviation for M833. However, we could find there exists a general tendency that as the sample mobility increases, the agreement between the experimental results and the expected critical resistivity given by $\rho_{xx}=h/\nu e^2$ is better. The deviation from the expected value, $h/\nu e^2$, is 58%, 39%, and 6.6% for M832, M833, and M834, respectively, if the number of active layers are taken to be 25, 25, and 27, respectively. Our experimental results indicate that the resistivity will approach the universal resistivity $h/\nu e^2$ if the mobility is good enough. If we examine the data in the experiment of Shahar *et al.*[9] more closely, we found that the critical resistivity at higher disorder (low mobility) also deviates farther from the expected value. Recently, Hilke *et al.*[17] also observed a similar tendency.

Scaling behavior is expected for the B-induced quantum phase transition. Wei *et al.* examined the scaling behavior of the $\text{In}_x\text{Ga}_{1-x}\text{As/InP}$ (Ref. 18) and $\text{Al}_x\text{Ga}_{1-x}\text{As/GaAs}$ (Ref. 19) heterostructures and found that when the temperatures were lower than a critical temperature (T_{sc}), the maximum in $d\rho_{xy}/dB[(d\rho_{xy}/dB)^{\max}]$ and the inverse of the half-width in $\rho_{xx}[(\Delta B)^{-1}]$ between two adjacent QH plateaus would diverge like $T^{-\kappa}$ with $\kappa=0.42\pm0.04$ (Refs. 18 and 19) for the spin-resolved Landau level. For spin-degenerate Landau levels, κ is around 0.21.[18] On the contrary, Koch *et al.*[20] found that κ increased from 0.28 to 0.81 with decreasing mobility for the spin-splitting samples. It is shown that near the transition, scaling follows $|d\rho_{xx}/dB|_{B_c}\propto T^{-\kappa}$ (Ref. 7). The critical exponent κ can be obtained from the slope of $\ln(d\rho_{xx}/dB)$ vs $\ln(1/T)$. The values determined from this method for these three samples are shown in Fig. 3. Each of the four lines is well defined by six or seven points, which implies that these samples have good scaling behavior. Wei *et al.* found that the critical temperature below which scaling behavior can be observed is related to the type of potential fluctuation in the sample. For samples with long-range potential fluctuation such as high mobility modulation-doped $\text{GaAs/Al}_x\text{Ga}_{1-x}\text{As}$ heterostructure T_{sc} is around 200 mK. For samples with short-range potential fluctuation such as in $\text{In}_x\text{Ga}_{1-x}\text{As/InP}$ system, T_{sc} is around 4.2 K. But there is no common criterion to determine T_{sc} for particular sample. Since the average impurity separation in our samples are between 100 and 150 A, which is much shorter than the typical potential fluctuation in high mobility modulation-doped $\text{GaAs/Al}_x\text{Ga}_{1-x}\text{As}$ systems, but larger than the length scale of alloy potential fluctuation in the $\text{In}_x\text{Ga}_{1-x}\text{As/InP}$ system, T_{sc} for our sample should be somewhere between 200 mK and 4.2 K. Judging from the well-behaved scaling fitting displayed in Fig. 3, we believe that the experimental temperature (<3.2 K) is low enough and the observed scaling behaviors are genuine. The critical exponents obtained for sample M832 for the two transitions are $\kappa_1=0.35\pm0.01$ and $\kappa_2=0.36\pm0.01$. Because $\kappa_1\sim\kappa_2$, the two transitions, insulator to QH and QH to insulator, belong to the same universality class. However, they do not equal to the universal value 0.21 expected for spin-degenerate system. The critical exponents obtained for M833 and M834 are 0.17 ± 0.02 and 0.25 ± 0.02, respectively, and are closer to the expected value. Although the exponents we got from these three samples do not equal 0.21, we notice that the deviation is smaller for samples with higher electron mobility.

The experimental observation that both the critical resistivity and scaling exponent depend on the sample mobility indicate the importance of Landau-level separation on the phase transition in a disordered 2D system. Universal scaling and resistivity are usually observed only in high mobility samples, where the mixing between Landau levels is insignificant. For samples with low mobility and at low magnetic field, Landau-level spacing is smaller than Landau-level broadening, and there are no well-defined LL's. In our experiment the condition for the formation of well-defined LL's, $\omega_c\tau > 1$, or alternatively $\mu B > 1$, is not satisfied at the phase transition points. Here ω_c is the cyclotron frequency, τ is the scattering time, μ is sample mobility, and μ and B are in MKS unit. It is thus not surprising that the theory developed based on well-defined LL's is not applicable to explain our experimental results. More theoretical work is required to understand the insulator–conductor transition in highly disordered 2D systems.

In summary, magnetic-field-induced phase transitions (insulator–conductor) were observed in three multilayer δ-doped GaAs/Al$_x$Ga$_{1-x}$As MQW samples. It was found that depending on the doping concentration in the QW's, the phase transition can happen between the insulating state and the QH state with filling factors of $\nu = 2$, 6, and 8. Scaling behavior were observed around the phase transition points, but the critical exponents are mobility dependent. For samples with the lowest mobility, the $0 \rightarrow 2$ and $2 \rightarrow 0$ transitions have the same critical exponent. But the exponent is quite different from the value expected for a spin degenerate ground-state Landau level. For samples with higher mobility, both the $0 \rightarrow 6$ and $0 \rightarrow 8$ transitions have critical exponents that are closer to the expected value. It is also found that the resistivity of the samples at the phase transition point decrease with increasing Landau-level filling factor. For samples with the highest mobility, the critical resistivity is closer to $\rho_{xx} = h/\nu e^2$. Our experimental results show that the transition between insulating and QH phases can happen at large ν. It also shows that the critical exponents as well as the critical resistivity are mobility dependent.

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