Insulator-quantum Hall conductor transitions at low magnetic field

C. F. Huang,¹ Y. H. Chang,^{1,*} C. H. Lee,¹ H. T. Chou,¹ H. D. Yeh,¹ C.-T. Liang,¹ Y. F. Chen,¹ H. H. Lin,² H. H. Cheng,³ and G. J. Hwang⁴

¹*Department of Physics, National Taiwan University, Taipei 106, Taiwan*

²*Department of Electrical Engineering, National Taiwan University, Taipei 106, Taiwan*

³*Center for Condensed Matter Sciences, National Taiwan University, Taipei 106, Taiwan*

⁴*National Measurement Laboratory, Center for Measurement Standard, Industrial Technology Research Institute, Hsinchu 300, Taiwan*

(Received 9 May 2001; published 26 December 2001)

Insulator-quantum Hall conductor transitions at low magnetic field B were studied with a gated GaAs-AlGaAs heterostructure. A low field disorder-magnetic field phase diagram was constructed based on the experimental results. This phase diagram shows no floating up of the extended state and allows transitions from the insulating state directly to any Landau level states. The critical filling factor can change from 16 to 6 as the disorder in the sample increases. By inspecting the raw data from this and the other samples and analyzing the scaling behaviors near the transition points, we found that the observed transition has the properties of a genuine phase transition.

DOI: 10.1103/PhysRevB.65.045303

PACS number(s): 73.43.-f, 71.30.+h, 71.55.Jv, 72.15.Rn

Magnetic-field-induced insulator-quantum Hall conductor (IQH) transitions in two-dimensional electron systems (2DES) and two-dimensional hole systems (2DHS) have attracted much attention recently.¹⁻⁹ According to the theory of localization, all states of a noninteracting 2DES (or 2DHS) are localized regardless of the amount of disorder present in the system.¹⁰ The integer quantum Hall effect (IQHE), however, implies the existence of extended states in a 2DES when there is a perpendicular magnetic field B . The evolution of electronic states from being extended at finite B to being localized at zero B was first explained by Laughlin and Khmelnitzkii.^{11,12} They argued that as B decreases, the energies of the extended states float up and eventually pass through the Fermi level. When all the extended states have energies greater than the Fermi level, there is no extended state below the Fermi level and the 2DES make a transition from a QH conductor to an insulator. This scenario was later used by Kivelson *et al.* in the construction of the global phase diagram (GPD).¹³ According to the float-up scenario, or the GPD, the only allowed IQH transition in the integer quantum Hall region is between the insulating and the $\nu = 1$ quantum Hall states, where ν is the number for the quantum Hall state characterized by $\sigma_{xy} = \nu e^2/h$. With this definition, $\nu = 0$ means no extended state below the Fermi level and represents the insulating state. In addition to the float-up scenario, there is a different way of understanding the destruction of extended states by disorder. Several groups performed simulations with the tight binding method (TBM) to study the behaviors of the two-dimensional (2D) electronic states when there are disorder and applied magnetic field.^{14,15} They found that the extended states could exist in low disorder and high B , but with increasing disorder and/or decreasing B the extended states were destroyed. A low- B phase diagram for the 2DES was constructed based on this interpretation, and it allows a direct transition from the insulating state to quantum Hall states with arbitrary ν .

Experimentally, there are evidences supporting float-up scenario,^{16,17} but it is difficult to trace the energy of the extended states down to zero magnetic field and the float up

was usually associated with the $\nu = 1$ LL only. On the other hand, there are also evidences against the float-up interpretation.^{5,7,9,14,15} It was found that a 2DES (or 2DHS) can make a direct transition from the insulating state to a Landau level with the filling factor ν greater than 2.^{5,7,9} These observations are inconsistent with GPD and are consistent with TBM. Recently, the low field phase diagram of the Ge/SiGe 2D hole system is found to be similar to what was obtained from TBM.⁹ However, since the experiments were performed at finite T and finite sample size, it was argued that the observed insulator-quantum Hall conductor (IQH) transitions that occur at high ν are not real phase transitions. They are only crossovers due to weak localization and a reduction of the conductivity when Landau quantization becomes important.¹⁸ To further study this subject we performed the studies of the IQH transitions with a gated GaAs/AlGaAs system. The $0-\nu$ transitions were observed at ν as high as 16. A low field phase diagram was constructed based on our experimental results. We also analyzed the temperature dependence of the longitudinal resistance at the transition point and the scaling behaviors for this sample and the doped quantum well system that show IQH transition.⁷ We found that the observed transition has the properties of a genuine phase transition.

The sample used for this study is a gated GaAs/Al_{0.22}Ga_{0.78}As heterostructure grown by molecular beam epitaxy. The heterostructure consists of a 0.5 μm thick GaAs layer grown on a semi-insulating GaAs substrate. A 100 $\text{\AA}$ thick undoped Al_{0.22}Ga_{0.78}As spacer, a 300 $\text{\AA}$ thick Si-doped Al_{0.22}Ga_{0.78}As layer with doping concentration $8 \times 10^{17}/\text{cm}^3$, a 100 $\text{\AA}$ thick undoped Al_{0.22}Ga_{0.78}As layer, and a 100 $\text{\AA}$ thick Si-doped GaAs cap layer with doping concentration $8 \times 10^{17}/\text{cm}^3$. The Hall pattern was made by standard lithography and etching processes. Indium was alloyed into contact regions at 450 $^\circ\text{C}$ in N_2 atmosphere to form Ohmic contacts. Au was deposited on the surface of the Hall bar to serve as the Schottky gate. Magneto transport measurements were performed with a top-loading He³ system and a superconductor magnet. ac lock-in technique was used and a cur-

FIG. 1. The longitudinal resistivities ρ_{xx} at $V_g = 0$ V. The transition occurs at $B = 0.58$ T, at which the filling factor $\nu \sim 13.6$. The inset shows well-developed quantum Hall effect at high B when $T = 0.33$ K.

rent of $0.1 \mu\text{A}$ was applied to the sample. Applying a gate voltage on the sample can affect both the electron concentration and mobility in the sample. With $V_g = 0.15, 0, -0.2, -0.25$, and -0.3 V, the carrier concentrations are $1.98 \times 10^{11}/\text{cm}^2$, $1.88 \times 10^{11}/\text{cm}^2$, $1.72 \times 10^{11}/\text{cm}^2$, $1.68 \times 10^{11}/\text{cm}^2$, and $1.65 \times 10^{11}/\text{cm}^2$, and the mobilities are 1.48×10^4 , 1.17×10^4 , 6.24×10^3 , 4.72×10^3 , and $3.13 \times 10^3 \text{ cm}^2/\text{Vs}$. The small density change in the applied gate voltage range is believed to be caused by the screening effect of the low mobility carriers in the doping layer.

Typical traces of the longitudinal resistivities (ρ_{xx}) of the sample with $V_g = 0$ V, B between 0 and 1.5 T, and T between 0.33 to 1.07 K are shown in Fig. 1. The data were taken by sweeping B at different T . The inset in this figure shows a well-developed QH plateau in ρ_{xy} and oscillation of ρ_{xx} at $T = 0.33$ K. The SdH oscillations could be clearly identified at $B = 0.8$ T, and $\nu = 6$ quantum Hall plateau appears at about $B = 1.3$ T. From this figure we could find that at $B = 0.58$ T, ρ_{xx} is temperature independent. This magnetic field is taken as the critical magnetic field (B_c) where the IQH transition takes place. B_c separates the temperature dependence of ρ_{xx} into two different regions. For $B < B_c$, ρ_{xx} increases while T decreases, and the sample is in the insulating region. For $B > B_c$, ρ_{xx} decreases with decreasing T and the sample is in the quantum Hall region. By dividing the electron concentration by the Landau level degeneracy, we found that $\nu \sim 13.6$ at B_c .

By applying the gate voltage, the carrier concentration and the sample mobility were both changed. The effects of the gate voltages on ρ_{xx} and the phase transitions are shown in Fig. 2. We can see that when the sample mobility is low, there is a large negative magnetoresistance in ρ_{xx} and the phase transition point could be more easily identified. As the mobility of the sample increases, the negative magnetoresistance becomes smaller, and its temperature dependence becomes weaker. Although the transition for $V_g = 0$ and 0.15 V are barely discernible in this figure, it can be seen clearly in

FIG. 2. The effects of the gate voltages V_g on IQH ρ_{xx} transitions were observed for all V_g . The measurements were performed at $T = 0.32, 0.49, 0.62$, and 0.86 K for $V_g = 0.15$ V, $T = 0.33, 0.51, 0.67$, and 0.84 K for $V_g = 0$ V, $T = 0.32, 0.53, 0.69$, and 0.9 K for $V_g = -0.2$ V, $T = 0.34, 0.52, 0.64$, and 0.86 K for $V_g = -0.25$ V, and $T = 0.32, 0.49, 0.66$, and 0.83 K for $V_g = -0.3$ V. The inset shows the T dependences of ρ_{xx} near the transition point.

Fig. 1 that these two transitions are well defined. We could see in this figure that as the gate voltage becomes more negative, the critical magnetic field increases. At $V_g = 0.15$ V, $B_c = 0.52$ T and it increases to 1.2 T at $V_g = -0.3$ V. Since the term “disorder” is not quantitatively defined, we take the inverse of the electron mobility (μ^{-1}) at $B = 0$ as a measure of the disorder. We found there is a correlation between the sample mobility and B_c , the lower the electron mobility, the higher the critical magnetic field B_c . By taking the maximum in ρ_{xx} to approximate the position of the extended states and using inverse of mobility as a measure of disorder, we were able to plot the phase diagram of the 2DES in the magnetic field-disorder plane, as is shown in Fig. 3. The dashed line in this figure, which could be taken as the boundary that separates the insulating and quantum Hall states, is drawn by connecting B_c at different gate voltages. We could see that this phase diagram is quite different from what was

FIG. 3. The phase diagram of the 2DES in the magnetic field-disorder plane. The dashed line is the boundary that separates the insulating and quantum Hall states. The solid lines are obtained by tracing the maximum in ρ_{xx} .

predicted by the global phase diagram that allows only the $0 \rightarrow 1$ transition, but is similar to the phase diagram constructed from p -type Ge/SiGe 2DHG system and theoretical calculation based on TBM.^{9,14,15} In this phase diagram a system can make a direct transition from the insulating state to a quantum Hall state with arbitrary filling factors. If the sample has high disorder, it can remain in the insulating phase even at high magnetic field, but for sample with low disorder it enters into quantum Hall states at low magnetic field. If we draw a horizontal line (fixed disorder) across the figure we could also find that the extended states of lower LL's can survive larger disorder and remain extended but the LL's with higher index are more easily destroyed by the disorder and become localized. This means that the extended state in the lower LL's is more robust against disorder than the extended state in the higher LL's and is consistent with the prediction of TBM. At low magnetic field, because the spacing between the LL's are small and the B dependence of the resistivity is also small, it is much more difficult to observe conclusively the IQH transitions. Nevertheless, we were able to observe the IQH transition at filling factor $\nu = 16$ for this sample.

Recently, Huckestein argued that the reported low field IQH transitions are not quantum phase transitions but crossovers due to weak localization and a reduction of the conductivity when Landau quantization becomes important.¹⁸ If this assertion is true, the magnetic field dependence of the sample resistivity will switch from one regime to the other regime at some B field. However, because the sample mobility is temperature dependent, the switch over point for sample at different temperatures is expected to spread over a magnetic field range. Experimentally we found, as could be seen in Fig. 2, there is a well-defined T -independent magnetic field that separates the T dependence of the sample resistivity into insulating and conducting regimes. To see this more clearly, we plotted the T dependence of ρ_{xx} for $V_g = 0$ at different B in the inset of Fig. 2. The value of ρ_{xx} at $B = 0.58$ T varies less than 0.02% of the average value when T changes from 0.33 to 1 K. The variation is within the experimental error and thus the resistance is essentially T independent at B_c . Similar results could be found in Ref. 7. In that paper we reported the observations of low field IQH transitions in doped quantum well systems. The variation of ρ_{xx} at B_c between $T = 0.3$ and 3 K in Ref. 7 is also T independent to within experimental error for all three samples. The curves of ρ_{xx} near B_c for the sample M834 were replotted in Fig. 4, in which a well-defined transition point was observed. In addition to the well-defined transition point that could be used to prove the observed transition is a real phase transition, the scaling behaviors near the phase transition provide another strong support that the transition has the properties of a genuine phase transition.^{3,6,7,18-23} It was shown that for the IQH transitions, $\rho_{xx} = f[(B - B_c)T^{-\kappa}]$ near the transition points and $|d\rho_{xx}/dB|_{B=B_c} \propto T^{-\kappa}$, where κ denotes the critical exponent. By plotting $\ln|d\rho_{xx}/dB|_{B_c}$ vs $\ln T$ we could obtain κ . In the spin-degenerate systems, κ is expected to be 0.21.^{3,19-23} The scaling behaviors were observed in the IQH transitions for all the gate voltages. We

FIG. 4. ρ_{xx} vs B from $T = 0.3$ to 3.2 K near the transition point for the sample M834, a centered doped quantum well system. The data were taken from Ref. 5. The inset shows the scaling fit of ρ_{xx} vs $|B - B_c|T^{-\kappa}$ with $\kappa = 0.3$.

obtain $\kappa = 0.21 \pm 0.01$, 0.18 ± 0.01 , 0.14 ± 0.01 , 0.14 ± 0.02 , and 0.24 ± 0.03 for $V_g = 0.15, 0, -0.2, -0.25$, and -0.3 V, respectively, as shown in Fig. 5. We found, as was reported previously that the value of the scaling exponent is close to 0.21 when the sample mobility is good.^{3,7,19-22} It deviates from the expected value when the sample mobility is poor.²³ After obtaining κ , we could plot ρ_{xx} vs $|B - B_c|T^{-\kappa}$ to see if the data collapse into one curve and the results are shown in Fig. 6 for $V_g = -0.2$ V. We could see that indeed all the curves collapse into one single curve and the curves before the transition and after transition are symmetrical with respect to the transition point. Such scaling behaviors were observed under all other gate voltages. Deviation from the scaling behavior begins to show up when SdH oscillation appears in ρ_{xx} . The oscillatory structure is reflected in the scaling curve as could be easily seen in the lower branch in

FIG. 5. The diagram of $\ln|d\rho_{xx}/dB|_{B_c}$ vs $\ln T$ at different V_g . From the slope, we obtained the scaling exponent $\kappa = 0.21 \pm 0.01$, 0.18 ± 0.01 , 0.14 ± 0.01 , 0.14 ± 0.02 , and 0.24 ± 0.03 for $V_g = 0.15, 0, -0.2, -0.25$, and -0.3 V, respectively.

FIG. 6. The curves of ρ_{xx} vs $|B - B_c|T^{-\kappa}$ with gate voltage $V_g = -0.2$ V. All the curves collapse near the transition point.

Fig. 6. We also checked the doped quantum well system mentioned above and found that the same scaling behaviors could be obtained near the transition points as is shown in the inset in Fig. 4. Based on the T independent ρ_{xx} at B_c and

the good scaling behaviors, we found that the observed transition has the properties of a real quantum phase transition.

In conclusion, magnetic-field-induced insulator-quantum Hall conductor phase transitions were observed in a gated GaAs-AlGaAs heterostructure. It was found that the transition could occur at Landau level filling factor as high as 16. By tracing the position of the extended states and the dependence of the critical magnetic field on the gate voltage, we were able to construct a low-field disorder-magnetic field phase diagram for the two-dimensional electron system. At the transition point ρ_{xx} is found to be temperature independent within experimental error. By studying the scaling behaviors near the phase transition point we found the transition has well-behaved scaling property. We also reexamined the data we published on a completely different system, the doped quantum well system. Consistent with the observation with this sample, in that system ρ_{xx} at B_c is also temperature independent to within experimental error and all curves collapse into a single one in the scaling plot. We thus conclude that the phase transition has the properties of a genuine phase transition rather than just a crossover from one conduction regime to another.

This work was supported by the National Science Council and Ministry of Education of the Republic of China.

*Email address: yhchang@phys.ntu.edu.tw

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