Quantum Hall liquid-to-insulator transition in $In_{1-x}Ga_xAs/InP$ heterostructures

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(Received 5 December 1996)

We report a temperature- and current-scaling study of the quantum Hall liquid-to-insulator transition in an $In_{1-x}Ga_xAs/InP$ heterostructure. When the magnetic field is at the critical field B_c, $\rho_{xx}=0.86h/e^2$. Furthermore, the transport near B_c scales as $|B-B_c|T^{-\kappa}$ with $\kappa=0.45\pm0.05$, and as $|B-B_c|I^{-b}$ with $b=0.23\pm0.05$. The latter can be due to phonon emission in a dirty piezoelectric medium, or can be the consequence of critical behavior near B_c, within which $z=1.0\pm0.1$ and $\nu=2.1\pm0.3$ are obtained from our data. [S0163-1829(97)03424-3]

The charge transport in a two-dimensional electron system (2DES) at low temperature (T) and high magnetic fields (B) exhibits a rich set of critical phenomena.[1] As an example we take the transition regions between two adjacent quantum Hall (QH) plateaus. In the QH states, the system exhibits dissipationless conductance, while in the transition regions separating two adjacent plateaus, the system dissipates. The first quantitative study of the transition between two integer quantum Hall liquid (QHL) states showed a T-scaling phenomenon.[2] The experiment was performed in an $In_{1-x}Ga_xAs/InP$ heterostructure. Specifically, the maximum value of the first derivative of the Hall resistance, ρ_{xy}, with respect to B $[(d\rho_{xy}/dB)^{\max}]$ scales as $T^{-\kappa}$ with $\kappa=0.42$. The minimum value of the third order derivative of ρ_{xy} was later found to scale as $T^{-3\kappa}$.[3] These scaling results imply that the transport coefficients near the critical magnetic field (B_c) are functions of a single scaling argument $|B-B_c|T^{-\kappa}$.[3,4]

Another example of critical behavior in the magnetotransport is found in low electron mobility samples.[5] These systems show standard QHL states such as $i=2$ and 1 (i is the Landau level filling factor) when B is smaller than a specific field, B_c. When $B>B_c$, the diagonal resistivity ρ_{xx} increases with decreasing T, which is characteristic of an insulating phase (IP). The operation of the T-scaling analysis with scaling argument $|B-B_c|T^{-\kappa}$, in the transition between the IP and the QHL, is to collapse all the T-dependent data onto one curve using κ as a parameter.[6,7] The κ value obtained from this scaling procedure[7], suggests that this transition may belong to the same universality class as the QH plateau-to-plateau transitions.

Recently, current- (I-) dependent measurements were made in $In_{1-x}Ga_xAs/InP$ heterostructures in the QH plateau-to-plateau transitions.[8] At a fixed bath T and when I is larger than a characteristic value, $(d\rho_{xy}/dB)^{\max}$ scales with I as $(d\rho_{xy}/dB)^{\max}\sim I^b$ with $b=0.21$. The effect of large I is to deliver external power to the 2DES, done at a rate faster than its cooling rate to the substrate. One can therefore cast I into an effective temperature T_e. Combining the I-scaling and the T-scaling results, one obtains $T_e\sim I^a$ with $a=0.5$. This new angle of view of the transitions, as will be shown later, allows the independent extraction of both ν, the localization exponent of the transition and z, the dynamical exponent.

In this paper we report an I-scaling study at the QHL-IP transition. The $In_{1-x}Ga_xAs/InP$ sample used for this study was grown by chemical vapor deposition and has an electron density 4×10^{10} cm^{-2} and mobility of 94 000 cm^2/Vs at 4.2 K. The sample was patterned into a standard Hall bar geometry with Ohmic contacts made by diffusing indium. Our measurements were performed using standard ac lock-in technique at a frequency of 5 Hz.

In Fig. 1 we plot ρ_{xx} as a function of B for six T's between 300 and 730 mK, measured with $I=1$ nA. The sample exhibits well developed QHL states at filling factor $i=2$ and 1, illustrated by a vanishing ρ_{xx} around $B=0.8$ and 1.6 T. There is a particular $B_c=2.6$ T, below which ρ_{xx} decreases

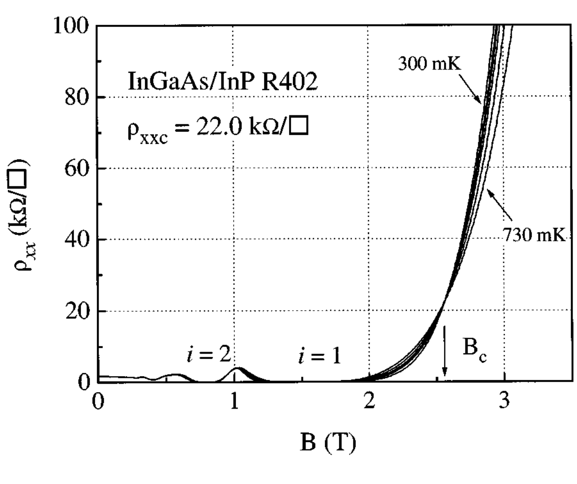

FIG. 1. Diagonal resistivity ρ_{xx} versus B, with $I=1$ nA at $T=300$, 390, 450, 510, 600, 730 mK.

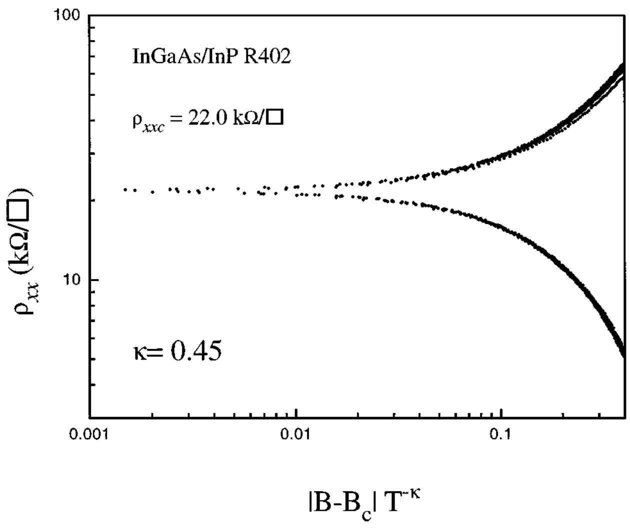

FIG. 2. ρ_{xx} versus $|B-B_c|T^{-\kappa}$ with the parameter κ adjusted to be 0.45 ± 0.05 to collapse the data points at different T's.

and above which it increases as T decreases. This B_c can be interpreted[5,9,10] as the critical B separating the transport into the QHL at $B< B_c$, and the IP at $B> B_c$. The value of ρ_{xx} at B_c is 22 k$\Omega/\square$, close to h/e^2, which is consistent with the results of Shahar *et al.*[5] and others.[7] In their papers, they show that $\rho_{xx}(B_c)\sim h/e^2$ is universal at the QHL-IP transition.

In Fig. 2 we replot a portion of the data in Fig. 1 close to B_c. It shows ρ_{xx} as a function of the T-scaling variable $|B-B_c|T^{-\kappa}$, where κ is used as a fitting parameter adjusted to give the best collapse of all data points at different T's onto a single curve. The upper curve is for $B> B_c$, while the lower for $B< B_c$. We obtain $\kappa=0.45\pm0.05$,[11] consistent with the results of Ref. 7. Our result of κ is also consistent with that obtained from the QH plateau-to-plateau transitions.[2] This illustrates that the sample is in the T-scaling regime in the T range studied.

We then study the effect of I at the QHL-IP transition. Figure 3(a) shows the I dependence of the ρ_{xx} versus B traces in the neighborhood of B_c at $T=0.3$ K, for $I=50$, 100, 150, and 200 nA. When $I\leqslant 50$ nA, the data overlap that of $I=1$ nA. We notice that these I-dependent data are similar qualitatively to the T-dependent data shown in Fig. 1. This implies that the role of I is to heat up the 2DES and the transport at each I is as if there is an effective temperature T_e which is larger than the bath T.[8] The facts that the transport shows T scaling with a single variable $|B-B_c|T^{-\kappa}$, and that I appears to be mapped onto a T_e, lead us naturally to analyze the I-dependent data using a modified single variable $|B-B_c|I^{-b}$. The result is shown in Fig. 3(b), in which the parameter $b=0.23\pm0.05$ results in the collapse of the transport data.[11]

Combining the T-scaling and the I-scaling analysis, we arrive at the conclusion that $T_e\sim I^a$ with $a=0.51\pm0.05$. This result is the same as that in the QH plateau-to-plateau transitions,[8] indicating the universal nature of this phenomenon. One possibility of this apparent universality of the exponent a is that the T_e controlled by I is determined by the electron-phonon interaction via piezoelectric coupling in

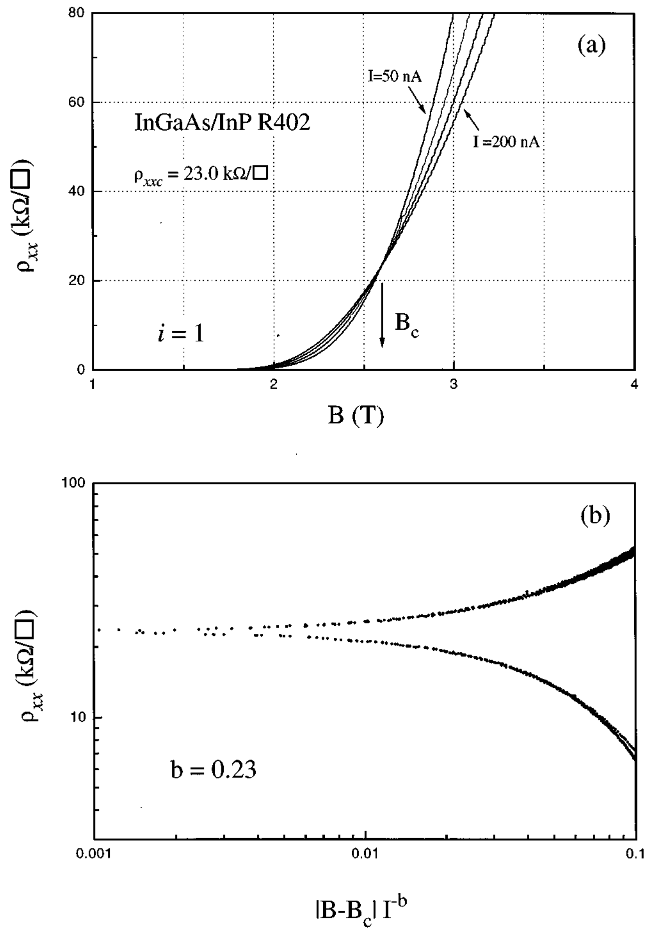

FIG. 3. (a) ρ_{xx} versus B at $T=300$ mK for $I=50$, 100, 150, and 200 nA. (b) ρ_{xx} versus $|B-B_c|I^{-b}$ with the parameter b adjusted to be 0.23 ± 0.05 to collapse the data points at different I's in (a).

III-V compound semiconductors. This mechanism gives rise to $a=0.5$ in the dirty limit.[12] One way to check this explanation is to study the high B transport of the 2DES in Si material where deformation-potential coupling dominates the electron-phonon interaction and may result in a different a.

The T- and I-scaling results can also be interpreted in the framework of critical phenomena, which lets us relate the experimental parameters κ and b to the microscopic critical exponents. Within this framework, the electron localization length ξ diverges at B_c according to $\xi\sim|B-B_c|^{-\nu}$, where ν is the universal localization exponent. If l is the cutoff length scale within which the quantum interference can take place, the transport coefficients then scale with the dimensionless parameter l/ξ.[4] Moreover, it is found that at the quantum critical point the electron coherence time τ_c, diverges as $\tau_c\propto\xi^z$, where z is the dynamical exponent.[13] The effect of finite T and finite E (or equivalently, finite I), is to introduce new cutoff length scales, l_ϕ and l_E, respectively. The uncertainty in time associated with the energy fluctuations of the electron about the Fermi energy is $1/k_BT$ for the case of finite T, and $1/eEl_E$ for finite E. One can obtain $l_\phi\sim T^{-1/z}$ and $l_E\sim E^{-1/(z+1)}$ (see Ref. 1). As a result, when $B\sim B_c$, the transport coefficients are functions of the dimensionless parameters,

$$l_\phi/\xi \sim (|B-B_c|T^{-1/z\nu})^\nu, \quad (1)$$

$$l_E/\xi \sim (|B-B_c|E^{-1/(z+1)\nu})^\nu. \quad (2)$$

We therefore identify the experimental scaling parameters κ and b as $\kappa = 1/z\nu$ and $b = 1/(z+1)\nu$. From our experimental data of κ and b, we obtain $z = 1.0 \pm 0.1$ and $\nu = 2.1 \pm 0.3$, which are comparable to the numerical and other experimental results.[1,14] Our measurement therefore corroborates quantitatively the notion that the QHL-IP transition belongs to the same universality class as the QH plateau-to-plateau transition.

In summary, we have studied the T-dependent and I-dependent transport at the QHL-IP transition in an $In_{1-x}Ga_xAs/InP$ heterostructure. At $B = B_c$, $\rho_{xx} = 0.86h/e^2$. The scaling analysis results in $T_e \sim I^{0.51 \pm 0.05}$, in agreement with that of the QH plateau-to-plateau transition. This may be due to phonon emission in a dirty piezoelectric medium, or may be the consequence of scaling within which $z = 1.0 \pm 0.1$ and $\nu = 2.1 \pm 0.3$ are obtained from our data.

The work done at Princeton was supported by the NSF. H.P.W. acknowledges support by NSF Grant No. DMR-9311091.

[1] For a recent review, see, for example, S.L. Sondhi, S.M. Girvin, J. Carini, and D. Shahar, Rev. Mod. Phys. **69**, 315 (1997).

[2] H.P. Wei, D.C. Tsui, M. Paalanen, and A.M.M. Pruisken, Phys. Rev. Lett. **61**, 1294 (1988).

[3] H.P. Wei, S.W. Hwang, D.C. Tsui, and A.M.M. Pruisken, Surf. Sci. **229**, 34 (1990).

[4] A.M.M. Pruisken, Phys. Rev. Lett. **61**, 1297 (1988).

[5] D. Shahar, D.C. Tsui, M. Shayegan, R.N. Bhatt, and J.E. Cunningham, Phys. Rev. Lett. **74**, 4511 (1995).

[6] T. Wang, K.P. Clark, G.F. Spencer, A.M. Mack, and W.P. Kirk, Phys. Rev. Lett. **72**, 709 (1994).

[7] L.W. Wong, H.W. Jiang, N. Trivedi, and E. Palm, Phys. Rev. B **51**, 18 033 (1995).

[8] H.P. Wei, L.W. Engel, and D.C. Tsui, Phys. Rev. B **50**, 14609 (1994).

[9] H.W. Jiang, C.E. Johnson, K.L. Wang, and S.H. Hannahs, Phys. Rev. Lett. **71**, 1439 (1993).

[10] B.W. Alphenaar and D.A. Williams, Phys. Rev. B **50**, 5795 (1994).

[11] The error is obtained by finding the range of the parameter, which gives the best visual collapse of the data.

[12] E. Chow, H.P. Wei, S.M. Girvin, and M. Shayegan, Phys. Rev. Lett. **77**, 1143 (1996).

[13] P.C. Hohenberg and B.I. Halperin, Phys. Rev. **177**, 952 (1969).

[14] For a recent review, see, for example, D. Liu and S. Das Sarma, Phys. Rev. B **49**, 2677 (1994); B. Huckestein, Rev. Mod. Phys. **67**, 357 (1995).