Evidence for a quantum Hall insulator in an InGaAs/InP heterostructure

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Abstract

We study the quantum critical behavior of the plateau–insulator (PI) transition in a low mobility $In_{0.53}Ga_{0.47}As$/InP heterostructure. By reversing the direction of the magnetic field (B) we find an averaged Hall resistance ρ_{xy} which remains quantized at the plateau value h/e^2 throughout the PI transition. We extract a critical exponent $\kappa' = 0.57 \pm 0.02$ for the PI transition which is slightly different from the established value 0.42 ± 0.04 as previously obtained from the plateau–plateau transitions. © 2002 Elsevier Science B.V. All rights reserved.

One of the fundamental issues in the field of two dimensional electron gases is the nature of the transitions between adjacent quantum Hall plateaus. By measuring the resistance tensor of low mobility $In_{0.53}Ga_{0.47}As$/InP heterostructures, Wei et al. [1,2] demonstrated that the quantum Hall steps become infinitely sharp as $T \to 0$, indicating that the transitions between adjacent quantum Hall plateaus (plateau–plateau (PP) transitions) represent a sequence of quantum phase transitions (QPT). Both the maximum slope in the Hall resistance with varying B, $(\partial\rho_{xy}/\partial B)_{max}$, and the inverse of the half-width of the longitudinal resistance between two adjacent quantum Hall plateaus, $(\Delta B)^{-1}$, have been shown to follow

the power law $T^{-\kappa}$ as T approaches absolute zero, independent of Landau level index. Here, $\kappa = p/2\nu$ where p denotes the exponent of the phase breaking length ℓ_φ at finite T (i.e. $\ell_\varphi \sim T^{-p/2}$) and ν is the critical index for the localization length ξ which is defined at zero T.

In order to probe the QPT, it is essential to carry out experiments on samples where the dominant scattering mechanism is provided by short-ranged random potential fluctuations [3]. Like in $In_{0.53}Ga_{0.47}As$/InP, this produces the widest range in T where quantum criticality is accessible experimentally. At the same time, little is known about the effects of macroscopic sample inhomogeneities which generally complicate experiments on the QPT. The problem of sample inhomogeneities was recently addressed by van Schaijk et al. [4] who investigated the plateau–insulator (PI) transition in the lowest Landau level. The data were

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taken from the same $In_{0.53}Ga_{0.47}As/InP$ heterostructure which was previously used in the study of the PP transitions [2].

Following the analysis by van Schaijk et al. one can extract different exponents κ and κ' from the transport data on the PI transition, dependent on the specific quantity one considers. For example, the longitudinal resistance ρ_{xx} was shown to follow the empirical law $\rho_{xx}(v,T) \propto \exp(-\Delta v/v_0(T))$. Here, $\Delta v = v - v_c$ represents the filling fraction v of the lowest Landau level relative to the critical value $v_c \approx \frac{1}{2}$. This law was originally used to describe the PI transition for different GaAs/AlGaAs samples with $v_0 = \alpha T + \beta$, and was advocated as describing a new transport regime [5]. In our InGaAs/InP sample, however, the ρ_{xx} curves exhibit a power law behavior such that $v_0(T) \propto T^{\kappa'}$ with an experimental value $\kappa' = 0.55 \pm 0.05$ [4].

The numerical value of the exponent κ' differs by more than the experimental error from the established "universal" value 0.42 ± 0.05 that was previously extracted from the resistance data on PP transitions [1,2]. In an attempt to understand the difference, van Schaijk et al. pointed out that a different exponent ($\kappa \approx 0.42$) for the PI transition is obtained by considering the temperature dependence of the Hall conductance, $(\partial \sigma_{xy}/\partial B)_{\min} \propto T^{-\kappa}$. It was shown that the different exponents κ and κ' are related to one another according to equation [4]

$$\kappa = \kappa' - \frac{d \ln(\sigma_{xx}^{*2} + 1/4)}{d \ln T}, \tag{1}$$

where σ_{xx}^{*} is the maximum value of σ_{xx} in units e^2/h.

Notice that for an ideal sample σ_{xx}^{*} is expected to be universal and, hence, κ and κ' are identically the same. In a real experiment, however, σ_{xx}^{*} usually depends weakly on T. Moreover, a different absolute value is generally found by performing different runs of the same experiment or by reversing the field B. Eq. (1) therefore tells us that the differences in the observed exponents κ and κ' must be the result of macroscopic inhomogeneities in the sample.

In this paper, we further investigate the inhomogeneity problem and extend the high B results of van Schaijk et al. [4] in several ways. We are specifically interested in answering the question of universality of the critical exponents, as well as the critical conductance σ_{xx}^{*}. For this purpose, we study the effect of reversing the direction of the B field on the PP
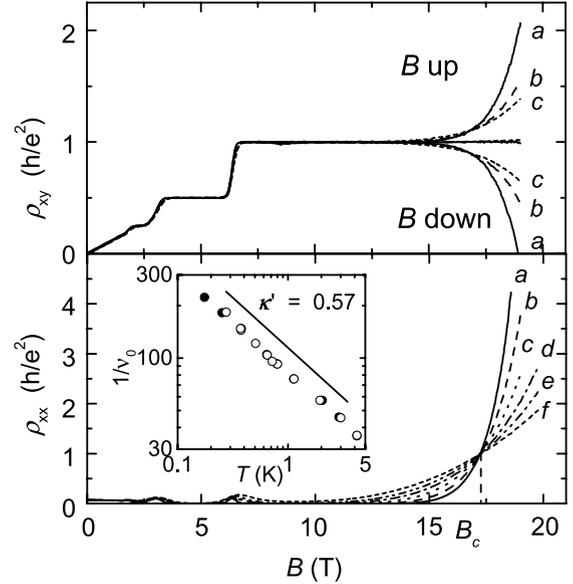

Fig. 1. ρ_{xx} and ρ_{xy} for a low mobility $In_{0.53}Ga_{0.47}As/InP$ heterojunction ($n = 2.2 \times 10^{11}$ cm^{-2}, $\mu = 16000$ cm^2/Vs) with varying B for up and down field directions. Labels a,b,...f correspond to temperatures 0.37, 0.62, 1.2, 1.9, 2.9 and 4.2 K. B_c (=17.2 T) is the critical field for the plateau–insulator (PI) transition. The ρ_{xx} curves have been normalized to $\rho_{xx}(B_c) = h/e^2$. Averaging over both field directions indicates that the Hall resistance remains quantized beyond B_c. Inset: $1/v_0$ versus T for the PI transition indicating a critical exponent $\kappa' = 0.57 \pm 0.02$. Closed symbols are data from positive field directions, open symbols denote negative field directions.

and PI transitions, in general, and on Eq. (1), in particular.

Our sample and experimental setup are identical to those described in Ref. [4]. The measurements were carried out in a Bitter magnet ($B < 20$ T) using a plastic dilution refrigerator. The magnetotransport coefficients ρ_{xx}, ρ_{xy} and the current I were measured simultaneously by using a standard AC technique with a frequency of 13 Hz and an excitation current of 5 nA.

Fig. 1 shows the results for sweeps in both directions of the B field for different values of T. Upon reversing the direction of B at constant T, we find that the ρ_{xx} data for the PI transition remain unchanged. The ρ_{xy} data, however, are strongly affected and the results for opposite B fields display a symmetry about the plateau value $\rho_{xy} = h/e^2$. By averaging the ρ_{xy} data over the B directions we obtain a Hall resistance

that remains quantized also beyond the critical field $B_c (=17.2$ T) of the PI transition. This indicates that the sequence of QPT's terminates in a so-called quantum Hall insulating phase.

The phenomenon of a quantum Hall insulator has been observed on a set of qualitatively different heterostructures and quantum wells, such as Ge/SiGe [6] and GaAs/AlGaAs [7]. However, these samples do not show any evidence for a QPT at the lowest available T. In this case, the data on the PP and PI transitions can be explained by semi-classical reasoning in transport theory [8]. The effect of reversing the B field on the transport data of the PI transition can qualitatively be understood as being the result of a macroscopic misalignment of the Hall bar contacts [6,9]. This kind of picture is in many ways too simple, however, and it is more appropriate to think in terms of macroscopic sample inhomogeneities such as electron density fluctuations, inhomogeneous current distributions, etc. which cannot be excluded from the experiment in general.

Notice that once the quantization of ρ_{xy} throughout the PI transition is accepted, the difference in κ and κ' is no longer an issue. The ρ_{xx} data, with varying values of T (Fig. 1), now display a true critical fixed point at the critical field strength B_c. Therefore, contrary to van Schaijk et al. we must conclude that the critical index of the PI transition is not given by κ but rather by κ' which is independent of the direction of B.

Next, we can make use of the renormalization theory of the quantum Hall effect and remove the remaining experimental uncertainties in the geometrical factor L/W of the sample. Here, L and W stand for the length and width of the Hall bar, respectively. This factor is important since it determines the absolute value of ρ_{xx} and, hence, the correct value of the conductances σ_{xx} and σ_{xy}. In our sample the physically measured width W of the Hall bar channel is 650 ± 20 μm, while the average distance between the middle of longitudinal contacts (L) is 1066 ± 25 μm. Naively, one would expect the value of $L/W \approx 1.64$. However, since the channels for the contacts themselves have widths of 350 ± 10 μm, the error in the absolute value of the geometrical factor is in the order of 10–15%.

An obvious criterion for fixing the value of L/W is obtained by demanding that the critical resistance $\rho_{xx}(B_c)$ be normalized at $\rho_{xx}(B_c) = h/e^2$ such that the
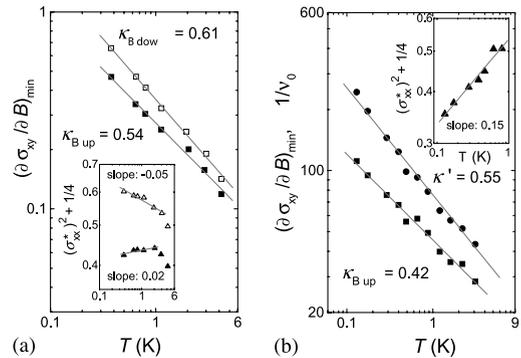

Fig. 2. (a) Field direction dependence of the critical exponent κ determined from the minimum slope of σ_{xy} with varying B. Subtracting the correction factor according to Eq. (1) gives the correct value of $\kappa' = 0.57 \pm 0.02$ for both field directions. (b) Similarly, measurements by van Schaijk et al. [4] give the same value of κ' for the PI transition. Closed symbols are positive B directions, while open symbols denote negative fields.

PI transition occurs precisely at a half integral value of the Hall conductance, $\sigma_{xy} = \frac{1}{2}$, as it should be. The value of L/W (=1.55), obtained in this way, differs from a directly measured value by 6% which is within the experimental error. It must be noted that since there is no notable temperature dependence of the density in our data, one can easily identify $\rho_{xx}(B_c)$ as the crosspoint of all ρ_{xx} curves. In systems where a slight temperature dependence of the electron density results in a shift of B_c towards higher fields, this method of determining B_c and thereby fixing the geometrical factor is less successful.

As a result of the averaging procedure over the directions of B, our data not only display particle–hole symmetry and scaling, but also follow the statement of duality [7,10]. It is important to remark that the same averaging procedure has previously been studied in detail for the PP transitions but the results are generally somewhat different from those obtained in this paper. A detailed study linking the PP and PI transitions will be published elsewhere [11].

As an important check on the consistency of our data, we next extract the exponent κ and the σ_{xx}^* (Eq. (1)) for each field direction independently, using the measured ρ_{xy} in order to calculate σ_{xx}. Fig. 2a shows the results for κ obtained from the slope of σ_{xy} for both directions of the B field. The insets show the data for $(\sigma_{xx}^*)^2 + \frac{1}{4}$ versus T on a log–log scale.

Following Eq. (1) we obtain $\kappa' = 0.56$, independently of the direction of B, which agrees very well with the result $\kappa' = 0.57 \pm 0.02$ as obtained directly from the T dependence of the ρ_{xx} data.

The data from Ref. [4] are shown in Fig. 2b. Notice that a different value for κ was found but the results for κ' are the same as ours. Comparing the results of Figs. 2a and b we see that the value of κ is generally different for different field directions and different experimental runs. The numerical value of κ' remains constant in all cases, however. This clearly indicates that κ' represents the true critical index.

In conclusion, we have measured and analyzed the PI transition of a low mobility sample that exhibits scaling. The numerical value of the critical exponent is estimated at 0.56 ± 0.02. This upsets the "established" value of 0.42 ± 0.04 which was extracted from the PP transitions and previously believed to be universal. We attribute the different results for the PP and PI transitions to the macroscopic sample inhomogeneities which have a different effect on the qualitatively different transport data of these transitions.

Nonuniversal behavior of κ has been reported in the literature before [12]. However, it is important to remark that the complications due to inhomogeneities, as addressed in this work, are not at the basis of the lack of universality of κ found in the transport data taken from AlGaAs/GaAs heterostructures [12]. In that case, the different values that have been measured for κ, as well as the linear T law proposed by Shahar et al. [5] that has been extracted from the PI transition, are the result of the long-range potential fluctuations that are known to complicate the observation of the quantum critical phenomenon [8].

At the same time, more work on higher quality samples is obviously necessary in order to narrow down the experimental uncertainties in the numerical value of the critical indices.

References

[1] H.P. Wei, D.C. Tsui, M. Paalanen, A.M.M. Pruisken, Phys. Rev. Lett. 61 (1988) 1294;
A.M.M. Pruisken, Phys. Rev. Lett. 61 (1988) 1297.

[2] S.W. Hwang, H.P. Wei, L.W. Engel, D.C. Tsui, A.M.M. Pruisken, Phys. Rev. B 48 (1993) 11416.

[3] H.P. Wei, S.Y. Lin, D.C. Tsui, A.M.M. Pruisken, Phys. Rev. B 45 (1992) 3926.

[4] R.T.F. van Schaijk, A. de Visser, S. Olsthoorn, H.P. Wei, A.M.M. Pruisken, Phys. Rev. Lett. 84 (2000) 1570.

[5] D. Shahar, M. Hilke, C.C. Li, D.C. Tsui, S.L. Sondhi, J.E. Cunningham, M. Razeghi, Solid State Commun. 107 (1998) 19.

[6] M. Hilke, D. Shahar, S.H. Song, D.C. Tsui, Y.H. Xie, D. Monroe, Nature 395 (1998) 675.

[7] D. Shahar, D.C. Tsui, M. Shayegan, E. Shimshoni, S.L. Sondhi, Solid State Commun. 102 (1997) 817.

[8] A.M.M. Pruisken, B. Škorić, M.A. Baranov, Phys. Rev. B 60 (1999) 16838.

[9] M. Furlan, Phys. Rev. B 57 (1998) 14818.

[10] S. Kivelson, D.H. Lee, S.C. Zhang, Phys. Rev. B 46 (1992) 2223.

[11] D.T.N. de Lang, L. Ponomarenko, A. de Visser, A.M.M. Pruisken, to be published.

[12] S. Koch, R.J. Haug, K.v. Klitzing, K. Ploog, Phys. Rev. B 46 (1991) 1596.