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Evidence for a Quantum Hall Insulator in an InGaAs/InP Heterostructure

D.T.N. de Lang, L. A. Ponomarenko, A. de Visser

Van der Waals-Zeeman Instituut, Universiteit van Amsterdam, Valckenierstraat 65, 1018 XE Amsterdam, The Netherlands

C. Possanzini, S.M. Olsthoorn

High Field Magnet Laboratory, University of Nijmegen, 6525 ED Nijmegen, The Netherlands

A.M.M. Pruisken

Institute for Theoretical Physics, University of Amsterdam, 1018 XE Amsterdam, The Netherlands

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We study the quantum critical behavior of the plateau-insulator (PI) transition in a low mobility $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{InP}$ 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 (and possibly more accurate than) the established value 0.42 ± 0.04 as previously obtained from the plateau-plateau (PP) transitions.

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 $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{InP}$ heterostructures, Wei *et al.* [1,2] demonstrated that the quantum Hall steps become infinitely sharp as $T \rightarrow 0$, indicating that the transitions between adjacent quantum Hall plateaus (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 $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{InP}$, 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 taken from the same $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{InP}$ 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 exponential law [5]

$\rho_{xx}(\nu, T) \propto \exp(-\Delta\nu/\nu_0(T))$. Here, $\Delta\nu = \nu - \nu_c$ represents the filling fraction ν of the lowest Landau level relative to the critical value $\nu_c \approx \frac{1}{2}$ and $\nu_0(T) \propto T^{\kappa'}$ with an experimental value $\kappa' = 0.55 \pm 0.05$.

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 the equation [4]

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

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 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 car-

ried out in a Bitter magnet ($B < 20\text{T}$) 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.

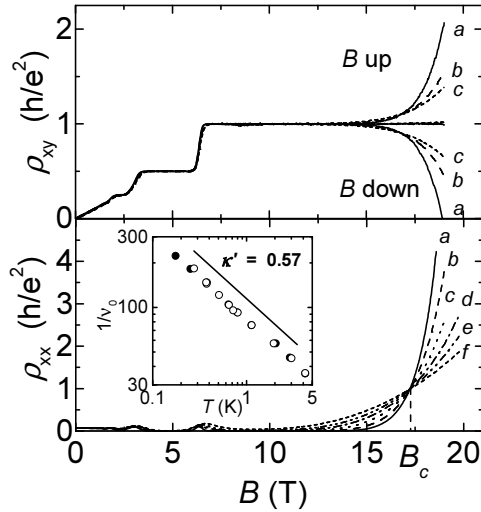


FIG. 1. ρ_{xx} and ρ_{xy} for a low mobility $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{InP}$ heterojunction ($n = 2.2 \times 10^{11} \text{cm}^{-2}$, $\mu = 16000 \text{cm}^2/\text{Vs}$) with varying B for up and down field directions. Labels a, b, \dots, f correspond to temperatures 0.37, 0.62, 1.2, 1.9, 2.9 and 4.2 K. B_c ($= 17.2 \text{T}$) 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: $1/\nu_0$ 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.

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 ($= 17.2 \text{T}$) 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 $\text{GaAs}/\text{AlGaAs}$ [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} .

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 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 , obtained in this way, differs from a directly measured value by 8% which is quite reasonable.

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. 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 $(\sigma_{xx}^*)^2 + 1/4$ 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 2b 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.

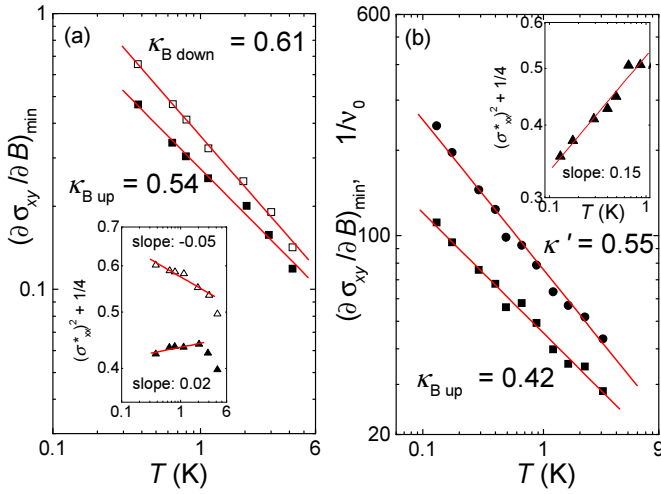


FIG. 2. (a) Field direction dependence of the critical exponent κ determined from the minimum slope of σ_{xy} with varying B . Subtracting the correction factor according to Eq. 1 gives the correct value of $\kappa' = 0.57 \pm 0.02$ for both field directions. (b) Similarly, measurements by van Schaijk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

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. However, 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.

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