Quantum Hall transitions in the presence of Landau levels mixing in n-InGaAs/InAlAs structures

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Abstract. We provide a systematic measurement of the longitudinal ρxx and Hall ρxy resistivities of quantum Hall transition in a two-dimensional electron system In0.9Ga0.1As/In0.81Al0.19As with strong spin-orbit coupling. For half-integer filling factors the linear temperature dependence of the effective quantum Hall effect plateau-to-plateau transition width ∆B(T) is observed in contrast to scaling behavior for systems with short-range disorder. The recent prediction that the width of transition region remains finite when extrapolated to zero temperature, resulting from Landau level mixing, is more preferable. The shift of the transition point in magnetic field with the temperature is found to originate from the mixing between Landau levels due to the inelastic scattering.

1. Introduction
The critical behavior near extended states in the quantum Hall effect is a subject of great interest [1-50]. The integer quantum Hall effect (QHE) demonstrates universal scaling behavior [1-4] in accordance with a single delocalized quantum critical point (Ec) [5-12] between two adjacent plateau states. Near the quantum critical point, the localization length ξ diverges as a power law ξ(E) ∼ |EF − Ec|−γ [6, 7], with EF being the Fermi energy and γ the localization length exponent. Physical quantities such as conductance follow the one-parameter scaling law as a function of the scaling variable (L/ξ)1/γ ~ L^1/γ|EF − Ec|, L being the system length. However, for experiments done at finite temperature, the effective system length for coherent transport is determined by a finite length scale Lφ ~ T−p/2 representing the dephasing effect [1, 7] due to inelastic scattering. T is the temperature and the parameter p is known as the inelastic-scattering exponent. Thus the scaling parameter for finite temperature systems appears to be T−κΔE with κ = p/2γ [1-7].

It has experimentally been found that the half width ∆B of the ρxx peak between adjacent Hall plateaus and the slope dρxy/dB of the Hall resistance ρxy show a power-low behavior ∆B ~ Tκ and dρxy/dB ~ Tκ. While some experimental works starting with [2] find κ as universal and equal =0.42, independent of material and Landau level number, in other reports the universality of κ is questioned [13-26].

The crossing of spin-split Landau levels with the same number and different spin index leads to interesting physics. When Landau levels are mixing, the interaction of electrons in different Landau levels complicate this problem and draw into question whether the above universality of scaling behavior is unchanged [23-26]. On the one hand, based on different models and calculation approaches, many theoretical works [23, 24] reach the conclusion that Landau level mixing will not change the universality of the quantum Hall phase transition. However, Xiong et al. give a striking and fundamentally different prediction that a narrow band of extended states is formed near each Landau level center due to interband mixing and leads to nonscaling behaviors [25, 26]. On the other hand, up to now the focus has been mainly theoretical with a lack of systematic studies on the experimental side. There are only a few experiments on one special case of Landau level mixing: the Landau levels associated with opposite spin orientations are not resolved [29-31]. Thus, a unified picture is
still lacking for quantum Hall phase transition in the presence of Landau level mixing. In contrast to earlier experiments, here we measure the transition directly in the spin resolved Landau level mixing regime.

2. Experimental details
Semiconductor heterostructures with an InAlAs/InGaAs/InAlAs quantum well and metamorphic buffer of varied composition In$_x$Al$_{1-x}$As were grown by molecular-beam epitaxy using a RIBER Compact 21 system at the Institute of Functional Nuclear Electronics of the National Research Nuclear University “MEPhI”. InP substrates (Wafer Technology Co.) with (100) orientation were used. The layer sequence and parameters of the sample are given in the [49]. Electron density n=6.8·10$^{15}$ m$^{-2}$, mobility μ = 20 m$^2$/V·s.

The composition profile (indium concentration x) in the In$_x$Al$_{1-x}$As metamorphic buffer was technologically specified as linear; a superlattice was introduced into the heterostructure to suppress dislocation growth into the active region. The metamorphic buffer was completed with an inversion step with linearly decreasing x to prevent elastic-strain penetration into the active region. Then a thick In$_x$Al$_{1-x}$As pseudo-substrate layer was grown as the substrate for subsequent active layers of the In$_x$Ga$_{1-x}$As quantum well (QW), an In$_x$Al$_{1-x}$As spacer layer, a 6-layer of dopant Si, an In$_x$Al$_{1-x}$As barrier layer, and an undoped In$_x$Ga$_{1-x}$As protective layer. The sample on the InP substrates contained a pseudomorphically strained QW whose lattice parameter exceeded that of the barrier layers. Silicon was used as the donor impurity and the Si-atom concentration was 1.5·10$^{12}$ cm$^{-2}$.

The sample is made in the form of a double Hall bar. Longitudinal $\rho_{xx}$ and Hall $\rho_{xy}$, magnetoresistances were measured simultaneously in magnetic fields up to 9 T and temperatures from 1.8 K to 30 K using Quantum Design standard set up and in magnetic fields up to 12 T and temperatures from 0.4 K to 1.6 K using $^3$He Oxford Instruments system. Measurements were carried out on the equipment of the Collaborative Access Center ”Testing Center of Nanotechnology and Advanced Materials” of the Miheev Institute of Metal Physics of the Ural Branch of the Russian Academy of Sciences.

3. Magnetotransport results and discussion
3.1. Longitudinal and Hall resistances at magnetic fields
Figure 1 shows the magnetotransport measurements of our sample under perpendicular magnetic fields up to $B$=9.0 T at $T$=1.8-10.0 K. A well-developed Landau quantization at the integer quantum Hall regime is observed: well pronounced Shubnikov-de Haas oscillations in $\rho_{xx}$, and quantized plateaus in $\rho_{xy}$. In the magnetic structure, sharp quantum Hall steps are clearly seen for both even and odd filling factors up to $\nu$=11 (at $T$=1.8 K, fig.1). At the same time, in the case of the ordinary heterostructures, odd plateaus are resolved only up to $\nu = 3$. This indicates enhanced spin splitting of Landau levels in the sample due to the spin-orbit interactions.

In Figure 2 we represent a half-width of $\rho_{xx}$ peaks defined as the interval $\Delta B$ in $B$ between the extreme in $d\rho_{xx}/dB$ and the point where $d\rho_{xx}/dB$ is equal to zero. The experimental information was analyzed from the low- and the high-field sides of transition point. These two types of a half-width of $\rho_{xx}$ peaks correspond to originally different gaps in LL spectrum. $\Delta B$ is a measure for the fraction of Landau-level states, which contribute to the conduction at finite $T$. It can be seen that experimental data for 3-4 transition are in a good agreement for both conditions $B>B_c$ and $B<B_c$. Measured data for 4-5 and 5-6 transitions are slightly diverges when temperature increases. However, the slope remains the same. It is clearly seen that for odd numbers of QHE plateaus the scaling regime completes earlier than for even ones. Calculated values of critical exponent are in complete accord with the experimental findings obtained in [49], where we measured $\Delta B$ of $R_{xx}$ curve as a function of temperature.

We find that $\Delta B$ vanishes according to both the power law $T^\kappa$ in the temperature interval from $\sim 3$ K to 10 K and the linear dependence $\alpha T + \beta$ at $T< (6+8)$ K. The $\kappa$ values are, within the estimated confidence interval, distinctly different from that typically associated with an Anderson-type transition, namely, $\kappa = 0.42$ [2-4], but they correlate well with experimental results for systems with large-scale impurity potentials [3, 4, 15-19]. Figure 3 shows the evolution of $B_c$ with $T$ varying. $B_c$ was determined as the position of $d\rho_{xy}/dB$ maximum for appropriate transition at fixed $T$. It can be seen that $B_c$ tends to a fixed value at low temperature limit.
3.2. The width of the extended state band
According to the standard scaling theory [1], the Hall $\rho_{xy}$ and the longitudinal $\rho_{xx}$ resistivities will have power-law behaviors with temperature: the former has a slope at the critical point as $d\rho_{xy}/dB_{c}\sim T^{-\kappa}$, while the latter has a half-width of the transition region as $\Delta B \sim T^\gamma$. In terms of this conception the transition regions between adjacent QHE plateau and the width of appropriate $\rho_{xx}$ peaks should become narrower and narrower as the temperature approaches zero.

The value of $\gamma$ in the context of short-range potential and without regard to the e-e interaction was theoretically obtained to be 2.3 (see, for example, review [7, 46]). Afterwards, the generalized theory that takes into account the e-e interaction as well as spin-polarized and spin-degenerate electron states was constructed. In fact, this theory introduces special scaling parameter considering the renormalization of interaction constant and subsequently, new values of the critical exponents $\gamma$ and $\kappa$ were estimated to be 2.75 and 1.35, respectively.

There were the several bright experimental studies where the universal value of exponent $\kappa=0.42$ was established for heterostructures with short-range impurity potential [2-4, 15, 16, 27]. On the other hand, the universality of the exponent $\kappa$ was questioned in other series of experiments [13-21].

To clarify the influence of the interaction and spin effects on the universality of critical exponents values the idea to study the half-width of resistance (conductivity) peaks on the different (high-field and low-field) sides from the critical point was arose [22, 50]. The purpose was to separate the effects which are better seen and originated from the Zeeman and cyclotron gaps.

Meisels et al analyzed the longitudinal conductivity $\sigma_{xx}$ peak between adjacent IQHE states with respect to temperature and frequency scaling [50]. The critical behavior of $\sigma_{xx}$ was studied on the different sides of the peak width. The authors separated non-universal impurity-induced ($\kappa > 0.4$) effects from universal behavior ($\kappa \approx 0.4$) within the localization model of the QHE. It is reported that for $\nu < 1.5$ the presence of attractive impurities giving rise to at least a shoulder in the density of states (DOS) and this asymmetry in the DOS leads to a strong increase of the value of $\kappa$ ($\kappa > 1$) on the high-field side of the $\sigma_{xx}$ peak. All the higher-$\nu$ direct current peaks showed a tendency toward $\kappa = 0.2$, when the spin splitting was not resolved.

Some interesting effects were highlighted for peaks belonged to different spin direction [50]. For example, the temperature dependence of the spin-up peak widths was enhanced ($\kappa=0.3$) due to the overlap with the spin-down peaks which increases with temperature since the spin-split subbands become more equally occupied (reduced g-factor enhancement). Also such a growth of the spin-up peaks is probably due to the effect of spin-orbit scattering [47]. For the peaks $\nu=7/2$ (low-field), 11/2 (low-field), 5, 7, 9, the subbands
were more equally occupied (effective value of g-factor is closer to its bare value), then the temperature dependence was reduced (κ = 0.2).

![Figure 3](image-url)  
**Figure 3.** The temperature dependence of critical magnetic field $B_c$ of quantum phase transitions (log-linear plot) for the sample under study (with field variation $\Delta B$: for the transition 3-4 $\Delta B = 90$ mT, for the 4-5 – $\Delta B = 108$ mT, for the 5-6 – $\Delta B = 43$ mT).

Theoretically Xiong et al. claim that the strong inter-Landau band mixing can result a finite bandwidth which is compared to the spacing of two adjacent Landau bands [25, 26]. They proved convincingly that a narrow metallic region is formed near each Landau level center due to Landau level mixing [25]. The theory was developed further to include interband overlap [26]. They show that for clean samples the extended state in each Landau level remains a single point at zero temperature. In contrast, for dirty samples the extended state in each Landau level can form a narrow band instead of a single point.

In the work of Li Wang et al. [22] the Xiong’s theory [25, 26] was experimentally checked using exploration of the width of quantum Hall transition region in the presence of spin resolved LL mixing regime. The authors investigated a 24-nm wide single GaAs quantum well bounded on each side by Si δ-doped layers of AlGaAs. They discussed the half-width $\Delta B$ of $R_{xx}$ curve as a function of temperature and additionally the data was analyzed from low- and high-field sides of transition region. The value of $\kappa$ was calculated to be 0.72. The critical exponents in the left- and right-hand sides of transition region was extracted as $\kappa_l = 0.72$ and $\kappa_l = 0.75$. The experimental results demonstrated that the standard scaling behavior remains unchanged even with strong Landau level degeneracy. The authors concluded that their experiment may correspond to the case of clean samples, in Xiong’s terms, where the extended state in each Landau level remained a single point at zero temperature (mobility is high as the order of $10^5$ cm$^2$/V·s).

Let us discuss our results and compare them with the experimental findings of [22, 50]. It was mentioned in previous section that figured out values of critical exponent are in a good agreement with the experimental results obtained in [49], similar to Wang’s research, where estimated values of $\kappa$ are equal for two approaches within the experimental uncertainty. In the present work, the values of $\kappa$ are the same within the measurement accuracy for different types of gaps, in contrast to Meisels’s work [50].

In [17, 18] a transport regime distinct from the critical scaling behavior was reported to exist asymptotically close to the transition at very low temperatures. The effective transition width of GaAs/AlGaAs and InGaAs/InP samples appears to vary as $\alpha T + \beta$ rather than exhibiting $T^\kappa$ scaling behaviour. This means that at $T = 0$ the transition has a finite width.

To estimate the width of a band of delocalized states in our n-In$_{0.9}$Ga$_{0.1}$As/In$_{0.81}$Al$_{0.19}$As samples we have analyzed magnetoresistance data in transition region between the filling factors 3-4, 4-5, 5-6 QHE plateau. In figures 2 (inset) the $\Delta B(T)$ dependences on a linear scale for the investigated sample are presented. It is seen
that the data can be satisfactorily described by a power law $\Delta B \sim T^\beta$. On the other hand, the data are far more compatible with a linear dependence $\Delta B(T) = \alpha T + \beta$ with $\beta = 0.16$ T, $\alpha = 1.65$ K for 3-4 transition, $\beta = 0.17$ T, $\alpha = 3.1$ K for 4-5 transition and $\beta = 0.12$ T, $\alpha = 3.3$ K for 5-6 transition.

As pointed out the ratio $\beta/\alpha$ defines a temperature $T^*$ that is found to be characteristic of the material system. $T^*$ turned out to be close to 0.5 K for InGaAs/InP samples and 50 mK for GaAs/AlGaAs samples [17, 18]. For Ge/GeSi samples studied in [21] the characteristic temperature is about 2.5 K (2.3–2.8 K).

What a reason for the linear $\Delta B(T) = \alpha T + \beta$ dependence? The most natural reason for the linear $\Delta B(T)$ dependence, namely, the thermal broadening of a quantum critical phase transition, is suggested and confirmed by calculation in [19]. It is shown there that the thermal broadening Fermi-Dirac distribution function $f(E)$ gives the linear increase of $\Delta B(T)$.

The authors [21] think that the answer to the main question about the finite $T \to 0$ width of QHE transitions may be found in the works treating the influence of Coulomb interactions on the screening of smooth disorder potential [33, 34]. The theory includes screening within the Thomas –Fermi approximation appropriate for smooth disorder.

When Landau levels are mixing, the interaction of electrons in different Landau levels with the same number and oppositely directed spins complicate this problem, especially in the case of nanostructures with strong spin-orbit interactions [25, 26, 38, 39, 47]. Particularly the half-width of the transition region can have a linear dependence with temperature $\Delta B = \alpha T + \beta$, which remains finite even when the temperature $T$ approaching zero.

For comparing both theoretical predictions, we have plotted two different fits in Fig. 2. It is obvious that in the measurable regime the power law and linear fits are both good, where the fitting parameters are $\kappa = (0.60$–0.76) and $\beta = (0.12$–0.16)$T$ in two the methods, respectively. The deviation between the two fits lies within the experimental uncertainty. In other words, it is difficult to find the obvious evidence to support the two separated critical points prediction even in the presence of strong Landau level mixing.

Thus, our experiment may correspond to the presence of a band of delocalized states, as a consequence of strong mixing and overlapping Landau levels with the same number and opposite spin directions.

3.3. The temperature dependence of critical magnetic field $B_c$ of quantum phase transitions

The behaviors of critical magnetic field $B_c$ for all the three transitions are summarized in Fig.3, which provides a possible verification of the scaling theory. In both the 3 \to 4 and 4 \to 5 plateau-plateau transitions, the critical fields $B_c$ rapidly moves from the low temperature value 1.0-1.8K with field variation $\Delta B_c = (43.0$–$108.0)$ mT at 20.0 K for different transitions. However, for 5 \to 6 transition, the critical fields $B_c$ is much smoother when increasing the temperature, with the field variation as low as $B = 43$ mT at 20.0 K.

Such a variation of $B_c$ can be expected from the irrelevant finite size correction at high temperature [36]. Also, the absence of the independent temperature percolation point ($B_c(T)$) may be due to scattering events [37]. The magnetic-field shift $B_c(T)$ (or energy shift $E_c(T)$) of the saddle point for increasing temperature can be explained by the increase of the scattering between electrons moving along percolation lines belonging to the highest Landau level ($N=1$) or the $N=2$ electrons rotating along closed loops around the potential hills. This shift due to Landau-level mixing of delocalized states, named “weak levitation,” has been predicted recently [38, 39].

The authors [38, 39] employed a two-channel version of Chalker-Coddington network model [6], which was previously used to study a spin-split Landau level. Electrons move along unidirectional links that form closed loops in analogy with semiclassical motion on contours of constant potential. Nodes correspond to regions in space where two classical contours approach one another, i.e., nodes are saddle points in the potential. At nodes, tunneling must complement the semiclassical motion so that scattering at nodes couples states on neighboring links. The assumption that each link carries current only in one direction implies that the wave packets are sufficiently localized in the transverse direction, i.e., the magnetic length is small in comparison with the spacing of nodes or with the correlation length of the potential fluctuations. The network model is therefore a strip whose width has half-integer number of links with two channels per link and scattering of states on two neighboring links is allowed at quarter part of nodes.

In [38, 39] was shown how the the energy of the delocalized state are gone upward from the position $h\omega_c(n + 1/2)$ due to Landau level mixing, $\omega_c$ is the cyclotron frequency, $n=0, 1, 2,...$. This shift is relatively small in a smooth potential even when the peaks in the density of states corresponding to different Landau level are not well resolved.

Up to now it is considered a single-particle picture of delocalization. The authors completely neglected the effects of screening caused by electron-electron interactions. At the same time, in a smooth potential the
electron-electron interactions drastically affect the distribution of electrons within the plane. In fact, when the potential is smooth enough, the equipotentials are separated by incompressible strips [40, 41]. In this situation, one should speak not about the energy position of delocalized state but rather about the critical filling factor at which delocalization occurs. It was argued in [37] that by replacing equipotentials with edge excitations, the many-electron problem can be effectively reduced to the Chalker-Coddington model [6, 7]. In the framework of this scenario the theory [42] predicts that the critical filling factor is larger than $n + 1/2$ due to Landau level mixing.

We attribute the behaviors of critical magnetic field $B_C$ for all the three transitions to the large spin-orbital interaction effect in the n- InGaAs/InAlAs nanostructures, which has been known in this system [43-45]. The Landau levels are spin non-degenerate due to the Zeeman splitting, and the Landau levels with filling factor $2n - 1$ and $2n$ are also strongly coupled due to the spin-orbital coupling effect. Because the Landau energy is larger than the Zeeman splitting energy, the inter-level coupling between the third and fourth plateau is more effective than the other two transitions, which causes a shorter localization length $\xi$, weakens the irrelevant finite size correction [5-7], and leads to a higher precision of the critical $B_C$. Moreover, although in the theoretical aspect the spin-orbital coupling effect can lead to delocalized states, the large magnetic field change the system to the unitary class [46], which only contains delocalized states at the center of Landau levels.

As mentioned above the specific peculiarity of studied structures is the presence of strong spin-orbit interaction, which affects the spin splitting of Landau levels. In [47, 48] was considered the case where the electronic system with a smooth potential disorder and strong spin-orbit interaction in the two mode conditions widened Zeeman Landau level much overlap. It turned out that the spin-orbit interaction causes changes in the percolation grid, which leads to an increase of the dissipative conductivity at finite $T$, when the Fermi level lies between the energies of two delocalized states at the centers of the widened Zeeman Landau levels.

4. Conclusion
In conclusion, we have measured the temperature dependences of the longitudinal $\rho_{xx}$ and Hall $\rho_{xy}$ resistivities in the region of quantum Hall transition. We focus on the two Zeeman Landau levels mixing case. For half-integer filling factors the linear temperature dependence of the effective quantum Hall effect plateau-to-plateau transition width $\Delta B(T)$ is observed in contrast to scaling behavior for systems with short-range disorder. Our experiment may correspond to the presence of a band of delocalized states, as a consequence of strong mixing and overlapping Landau levels with the same number and opposite spin directions.

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