Transport properties of 2D-electron gas in a n-InGaAs/GaAs DQW in a vicinity of low magnetic-field-induced Hall insulator–quantum Hall liquid transition

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The resistivity ($\rho$) of low mobility dilute 2D-electron gas in a n-InGaAs/GaAs double quantum well (DQW) exhibits the monotonic “insulating-like” temperature dependence ($d\rho/dT < 0$) at $T = 1.8 − 70$K in zero magnetic field. This temperature interval corresponds to a ballistic regime ($k_B T \tau/\hbar > 0.1 − 3.5$) for our samples, and the electron density is on a “insulating” side of the so-called $B = 0$ 2D metal-insulator transition. We show that the observed localization and Landau quantization is due to the $\sigma_{xy}(T)$ anomalous $T$-dependence.

Keywords: 2D-electron gas; ballistic regime; quantum phase transition.

1. Introduction

The coexistence of so-called two-dimensional (2D) ”metallic” and ”insulating” phases, identified in n-Si-MOSFET’s by Kravchenko and Pudalov[1,2], is still a subject of considerable interest and controversy. While the effectively ”metallic” and ”insulating” character of phases is observed experimentally in many 2D-systems, the microscopic origin of the both phases, particularly in vicinity of the metal-insulator transition (2D-MIT), is a mystery yet.

Recently there has been a great renewal of interest to the low magnetic-field-induced Hall insulator–quantum Hall liquid (HI-QHL) transitions[3,4,5,6]. According to the scaling theory of localization in noninteracting 2D-systems in zero magnetic field, at low temperatures only the localized states should exist. In the presence of strong perpendicular magnetic field the Landau quantization becomes important. The ”fate” of electronic states from being extended at strong magnetic field to being localized at $B = 0$ was at first explained by Laughlin and Khmelnitski[7].
It was argued that to be consistent with the scaling theory, the extended states should "float up" indefinitely in energy in the limit of $B = 0$. An alternative to this "floating-up" picture is that the extended states could be destroyed by increasing disorder or with decreasing magnetic field they merge, forming a metallic state in $B = 0$.

To date, an interesting but unsettled issue is whether the observed direct transitions from an insulating state in $B = 0$ to a conducting ones for high Landau-level filling factor ($\nu > 3$) are genuine quantum phase transitions (QPT). Hackenstein claimed that there is no any QPT. The low field transitions to the quantum Hall effect (QHE) states with $\nu \geq 3$ are only crossovers from quantum corrections regime to Landau quantization (LQ) after $\omega c \tau > 1$. Kim et al. and Huang et al. made an attempt to overcome the Hackenstein’s doubt about the QPT truth in their recent papers.

They observed the crossover from the low-field localization to QHE that covers a wide range of magnetic fields. With increasing $B$, Shubnikov-de Haas oscillations (SHO) appear at $B_s$, $\rho_{xx} = \rho_{xy}$ at $B_a$ and $\rho_{xx}$ becomes $T$-independent at $B_c$ ($B_s < B_a < B_c$). Thus the observed well-defined critical points of $\rho_{xx}(B,T)$ don’t correspond to the crossover from localization to LQ when $\rho_{xx} = \rho_{xy}$. Experimental data in the vicinity of the critical point $B_C$ show good scaling behaviour confirming that HI–QHL transition is a genuine QPT.

On the other hand, it is argued that such a low-field transition is not a phase transition, but can result from the interplay of the classical cyclotron motion and the electron-electron interaction quantum correction $\delta \sigma_{ee}$ to the Drude conductivity in the diffusive regime ($k_B T/\hbar < 1$).

The HI–QHL transition in low magnetic fields was investigated by different authors on the "insulating" side of the 2D- MIT ($B = 0$) or on the "metallic" side one, but in the diffusive regime, where resistivity have an "isolating-like" behaviour due to weak localisation or ee-interaction effects. We call the phase "insulating", when $\rho_{xx}$ diverges as $T \to 0 (d\rho/dT < 0)$ as opposed to the quantum Hall liquid phase, where $\rho_{xy} \to h/\nu e^2$ and $\rho_{xx} \to 0$ with vanishing $T$. The boundary is then simply the $B$-field, where the $\rho_{xx}(B,T)$ dependence changes direction ($d\rho/dT > 0$).

In this report we observed the HI–QHL transition at the relatively high temperatures (ballistic regime) in the low mobility dilute 2D-electron gas confined within GaAs/n-InGaAs/GaAs DQW. The transport in the vicinity of quantum phase transition is discussed. We have shown that the appearence of different critical points ($B_s, B_a, B_c$) is possibly caused by the anomalous temperature dependence of $\sigma_{xy}(B,T)$.

2. Experimental set-up

We used $n$-type modulation doped GaAs/n-InGaAs/GaAs DQW samples. Here we present the data obtained for one of samples with the following parameters at low temperatures: the electron density $n_s = 2.3 \times 10^{11}\text{cm}^{-2}$ and the mobility of
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3. Experimental results and discussion

1. Fig.1 shows a set of resistance versus temperature dependences. For the first time the insulating-like behavior \((d\rho/dT < 0)\) of the resistance dependence in a whole temperature interval up to \(T \approx 70\,K\) \((T/T_F \approx 0.65)\) is observed. For the material of our samples, this temperature interval corresponds to a ballistic regime \((k_B T \tau/\hbar > 0.1)\). There exist a few theoretical models to explain the apparent insulating \(\rho(T)\) behaviour of the 2D metallic state at high temperatures \((T < T_F)\). A simple non-interacting picture for the apparent insulating behaviour of metallic 2D systems at high \(T\) is the \(T\)-dependent scattering of a non-degenerate electron gas. On the other hand, for the degenerate electron gas, the temperature-dependent screening and electron-electron interaction effects play important quantitative roles in determining the type of resistivity temperature dependence and producing the effective insulating-like behaviour.

This dependence could be quantitatively described by three contributions\(^{14}\)

\[
\rho(T) = \rho_D(T) + \delta\rho_{WL}(T) + \delta\rho_{eei}(T),
\]

where \(\rho_D(T)\) is the Drude resistance, \(\delta\rho_{WL}(T)\) and \(\delta\rho_{eei}(T)\) are the weak localization and interaction contributions, respectively. Now, that we have experimentally determined \(\rho_D(T) = \sigma^{-1}_D(T)\) from analysis of \(\sigma_{xy}(B,T)\) (see below), we are in a position to extract the bare \(\delta\rho_{WL}(T) + \delta\rho_{eei}(T)\), according to Eq. \(^{11}\). by sub-

Fig. 1. Resistivity for sample 3982b at \(B_\perp = 0\) vs temperature. Difference between the experimental results and those deduced from \(\sigma_{xy}(B,T)\) resistivity is shown in the inset.

Fig. 2. Four-terminal resistivity measurements of \(\rho_{xx}(B)\) and \(\rho_{xy}(B)\) at \(T = 2 \div 70\,K\).

1.16 \times 10^4 \, \text{cm}^2/\text{Vs} \,(k_F l_F = 10.6)\). Four-terminal longitudinal \((\rho_{xx})\) and Hall \((\rho_{xy})\) resistivity measurements were carried out in a “Quantum Design” equipment using a standard low frequency (10 Hz) lock-in technique in a wide temperature interval (1.8-300K) and in tilted magnetic fields up to 9.0T. A \(\leq 1\,\mu\text{A}\) driving current through Hall bar was chosen to avoid heating effects.
tracting the Drude resistance from the measured zero-field resistance (Fig. 1). The obtained two corrections show logarithmic temperature dependence (see inset on Fig.1) Origin of the temperature dependences of Drude resistance and quantum corrections will be analysed elsewhere 15.

2. In Figs. 2-4 we plot the measurement data of longitudinal magnetoresistivity $\rho_{xx}(B, T)$ and $\rho_{xy}(B, T)$ and magnetococonductivity $\sigma_{xx}(B, T)$, $\sigma_{xy}(B, T)$ over the temperature range $T = 1.8 - 50.0K$. Fig.2 shows the well expressed SHO in $\rho_{xx}(B, T)$ and of QHE plateaus in $\rho_{xy}(B, T)$. Pronounced minima in $\rho_{xx}(B, T)$ traces observed at filling factors $v = 2, 4, 6$, which are accompanied by QHE plateaus in $\rho_{xy}(B, T)$ at corresponding magnetic fields, are used for evaluation of the carrier density. The temperature-independent magnetic field positions of SHO minima allow us to make an important assertion that the carrier density for this sample up to $T \approx 50K$ is unchanged and therefore such an unusual temperature dependence of resistivity is not due to the carrier density change. In the low magnetic fields perpendicular to the 2DEG ($B_{\perp}$) the negative magnetoresistance (NMR) on $\rho_{xx}(B, T)$ was observed. The so-called temperature independent ($T_{\text{ind}}$) point is seen (Fig. 3a) at some $B_{\text{cr}}$. At temperatures $T > 6.0K$ this point begins to "wash out". May be at this value of magnetic field we have $\omega_c\tau = 1$? 10, 11 But why doesn’t this point coincide with the point where $\rho_{xx}(B, T) = \rho_{xy}(B, T)$ (see Fig.3a)? We think that this lack of coincidence is connected with the beginning of the transition from diffusive to ballistic regime.

The Hall resistance in a low magnetic fields ($\rho_{xy}(B, T)$) is also strongly temperature dependent. Before analyzing the role of the quantum corrections in the diffusive ($k_B T \tau/\hbar \ll 1$) and ballistic ($k_B T \tau/\hbar > 0.1$) regimes in a behaviour of the resistance temperature dependence in a $B = 0$ shown in Fig.1, let us estimate the possible contribution from other temperature dependent factors.

Observation of SHO, QHE and an "insulator-QH transition" in the insulating regime of low density 2D-electrons is somewhat remarkable, since it was originally believed that the insulating behavior of $\rho(T)$ at $B = 0$ in this temperature range is related to the non-degenerate nature of the low density hole gas 11. Note that if the insulating $\rho(T)$ at $T < T_F$ has a classical origin, as in Ref.1,2, it would be unlikely for the sample to show a negative magnetoresistivity and the "insulator-QH transition" as in Fig.2 because the classical Drude magnetoresistivity is zero. At present, it is unclear if a more elaborated semi-classical model can reproduce the insulating-like $T$-dependent zero field resistivity and an "insulator- QH transition" at high $T$ at the same time.

3. Let us pay attention to a temperature dependence of the magnetococonductivity $\sigma_{xy}(B, T)$ (Fig.4). It is well known that classical part of $\sigma_{xy}(B, T)$ should be temperature independent at such a degeneracy of electron gas ($T_F/T \approx 2 - 50$). All contradictions are resolved if we suppose that the electron mobility for our case is temperature dependent: $\mu(T)$ 15, 16. An analysis of the temperature dependence of the magnetococonductivity $\sigma_{xy}(B, T)$ allows us to find it. According to the Drude
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theory, \( \sigma_{xy}(B) \) have a maximum at \( \mu B = 1 \) (or \( \omega_c \tau = 1 \)) and this value is equal to \( \sigma_D/2 \), where \( \sigma_D \) is Drude conductivity. Doted lines in Fig. 1 represent \( \sigma_D^{-1}(T) \), deduced from \( \sigma_{xy} \) maximum amplitude, and \( \rho(T) = (e n \mu(T))^{-1} \), where \( \mu(T) \) is obtained from \( \mu B = 1 \). It is seen that these dependences are close to the experimental ones (solid line). However this poses a question: if the conventional Drude theory is applicable, what is the reason of the mobility temperature dependence? We attribute the \( T \)-dependence of the mobility and hence the Drude conductivity to the \( T \)-dependence of \( \tau(T) \).\footnote{17}

Then we extracted the temperature dependence of \( \sigma_D(T) \) due to \( \mu(T) \) from the experimental dependence \( \sigma_{xy}(B,T) \) and \( \sigma_{xx}(B,T) \). After that we calculated the resistivity tensor component \( \rho^*_{xx}(B,T) \) using the new \( \sigma^*_{xx}(B,T) \) and the calculated \( \sigma^*_{xy}(B) \).\footnote{15,16} The result of this procedure is presented at Fig.3b. It is seen very well now that \( T_{ind} \) point coincides with the point where \( \rho_{xx}(B,T) = \rho_{xy}(B,T) \) and its ”washing out” considerably decreases (Fig. 5).

In summary, we have presented the studies of ”isulating-like” transport properties of the low mobility 2DEG in a n-InGaAs/CaAs DQW in a wide temperature interval \( T = 1.8 \div 70 \text{K} \) (diffusive and ballistic regimes). The presence of anomalous temperature dependence of \( \sigma_{xy}(B,T) \) challenges the conventional understanding of low magnetic-field-induced Hall insulator – quantum Hall liquid transitions.

![Fig. 3. (a) \( \rho_{xx}(B,T) \) and \( \rho_{xy}(B,T) \). There is a \( T_{ind} \)-point, where \( \rho_{xx}(B,T) \) traces cross itself in a \( B_{cr} \). (b) corrected \( \rho^*_{xx}(B,T) \) and \( \rho^*_{xy}(B,T) \). At the critical point \( B_{cr}^* \): \( \rho^*_{xx}(B_{cr}^*,T) = \rho^*_{xy}(B_{cr}^*,T) \).](image-url)
Fig. 4. Converted conductivities $\sigma_{xx}(B, T)$ and $\sigma_{xy}(B, T)$ at varies temperatures $T = 2 \div 70$K.

Fig. 5. Temperature dependence of initial and corrected $\rho_{xx}(T)$ in a $B_{cr}$.

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