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Quantum Hall liquid-insulator and plateau-to-plateau transitions in a high mobility 2DEG in a HgTe quantum well

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The present work reports the results of a study of the magnetic field induced Quantum Hall liquid-insulator transition and the plateau-to-plateau transition in a high mobility two-dimensional electron gas in a HgTe quantum well. The applicability of the universal scaling models (such as the universal critical exponent description and the semicircle model) for the description of these transitions is analyzed. We come to the conclusion that neither of these descriptions is completely adequate for the system under study.

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The quantum-Hall effect provides a remarkable opportunity to study the transitions between the insulating and metallic states in two dimensional electron systems. In the case of a medium or high mobility 2D electron system the insulating state is reached when the lowest Landau level crosses and moves above the Fermi level. In this case we have a transition from the QH liquid state, characterized by the filling factor $\nu = 1$, to an insulator state [1 – 4]. In samples of very high mobility, the transition to an insulating behavior can occur from the fractional QH states, such as $\nu = 1/3$ [5]. Experimentally, these transitions exhibit the following features: the transition occurs at a certain critical magnetic field B_c and is characterized by a universal value of the diagonal resistivity component ρ_{xx} which is close to h/e^2. Indeed, such behavior has been observed in different types of 2D electron systems: in AlGaAs/GaAs, InGaAs/InP, and Ge/SiGe heterostructures. Theoretically the transitions observed in these works are analyzed using different types of scaling models, such as the universal critical exponent approach (see, for example, review [6]) and the semicircle diagram model [7,8]. It is significant, that according to these models both the QH liquid-insulator transition and the plateau-to-plateau transition in any given sample should be described by similar semicircle relations and have the same critical exponent.

Recently, owing to the advances in the MBE technology of narrow gap semiconductors a high mobility 2DEG in HgTe quantum wells has become available for diverse experimental investigations [9 – 11]. The 2DEG in HgTe is characterized by a highly specific energy spectrum with an inverted band structure, low effective mass ($m_{\text{eff}} = 0.02 m_0$) and, consequently, a large Landau level separation. These facts together with a scattering potential dominated by a long range scattering component due to a large screening length make this system attractive for the study of the applicability of the universal scaling descriptions of the metal-insulator transitions in the QHE regime.

In the present paper the magnetic filed induced QH liquid – insulator transition and the plateau-to-plateau transition in a high mobility 2DEG in HgTe quantum well have been studied for the first time. A comparative analysis of the applicability of different universal models of these transitions has been performed. It shows that neither of these models will give a satisfactory description of these transitions in our samples. Moreover, in some of the samples we have observed neither the critical magnetic field nor the universal value of $\rho_{xx} \approx h/e^2$ supposed to correspond to these transitions.

The samples used in the present work were CdTe/HgTe/CdTe quantum wells having two different widths (d): d = 16 nm (sample N330) and d = 21 nm (sample N331). The quantum wells were grown on a GaAs substrate by means of a modified MBE method (for more details see [12 – 14]). The schematic layer view of the samples is shown in the insert to fig.1. Samples N330 had a 2DEG with the electron density $N_s = 2.2 \cdot 10^{11}$ cm^{-2} and the mobility $\mu = 2.8 \cdot 10^5$ cm^2/Vs while the 2DEG in the N331

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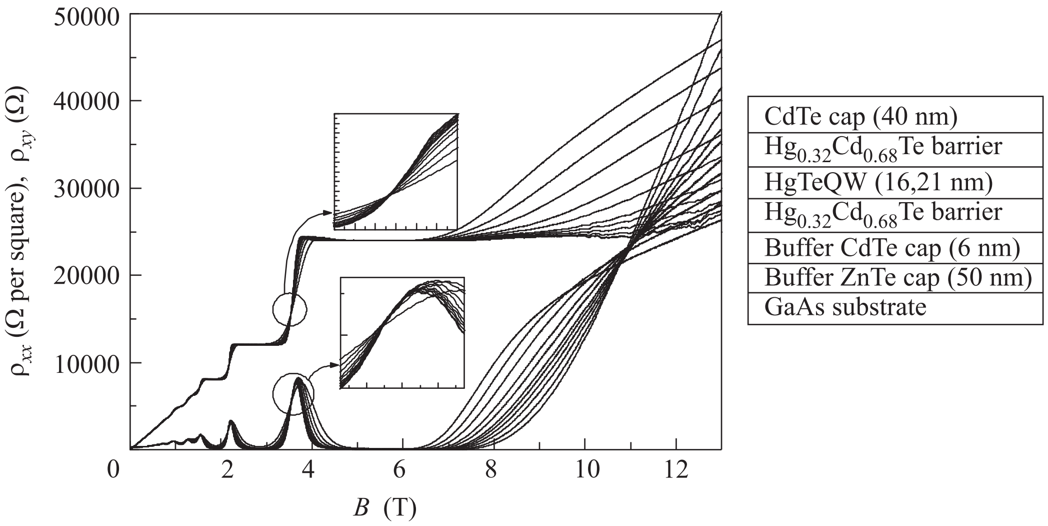

Fig.1. The longitudinal and the Hall resistance versus magnetic field in a 21 nm wide QW sample (N331). The traces (from bottom to top) are taken at temperatures $T = 0.3$; 0.4; 0.5; 0.6; 0.7; 0.8; 1; 1.2; 1.6; 2 and 3 K. On the right, the schematic layer view of the samples is show. The magnified areas correspond to the plateau-to-plateau (2-1) transition

samples had electron density $N_s = 1.4 \cdot 10^{11}$ cm^{-2} and the mobility $\mu = 1.5 \cdot 10^5$ cm^2. It should be noted that the indicated mobility represent the highest values achieved so far for the corresponding electron densities in HgTe QWs. Before, the highest mobility values at similar electron density values did not exceed few tens of thousand cm^2/Vs [10]. In order to study the transport properties of the layers they were photolithographically processed with a consequent wet chemical etching into 50 μm wide Hall bars with the distance between the four voltage probes on each side 100, 250 and 100 μm. Ohmic indium contacts to the Hall bars were formed by thermal bonding. Magnetotransport measurements were carried out in magnetic fields up to 17 T and temperatures from 50 mK to 3 K using standard lock-in techniques with the current value $(1-10)$ nA to exclude electron heating. Four samples with the QW width 16 nm and four with QW width 21 nm were investigated.

Fig.1 presents the typical results obtained in our samples with a wider QW. The figure shows the $\rho_{xx}(B)$ and the Hall resistivity $\rho_{xy}(B)$ in the temperature range $(0.3-3)$ K and in magnetic fields up to 13 T. Beginning at $B \approx 2$ T one can see the ordinary QHE features, such as wide plateaux in the ρ_{xy} and corresponding wide minima in the ρ_{xx}. At $B_c \approx 10.9$ T a behavior resembling a magnetic field induced QH liquid-insulator transition (1-0) that corresponds to the Fermi level crossing the lowest Landau level is observed at low temperatures, $T < 1.6$ K. The transition is characterized by a critical magnetic field $B_c = 10.9$ T and a corresponding critical diagonal resistivity value $\rho_{xx} = 0.9h/e^2$. At the same time the Hall resistivity has a sort of plateau on the insulator side of the transition at the lowest temperatures. Thus, at a first glance, for $T < 1.6$ K this transition in our 21 nm HgTe QW samples manifests the three main features, observed earlier in AlGaAs/GaAs and Ge/SiGe structures: 1) a certain critical magnetic field, 2) ρ_{xx}^c of about h/e^2, 3) a plateau in ρ_{xy} on the insulator side of the transition. For $T > 1.6$ K a deviation of the $\rho_{xx}(B)$ curves from the critical point is observed. To see how well the universal scaling models can describe our data we first try the semicircle model. According to this model our quantum Hall liquid – insulator transition (1-0) as well as the preceding plateau-to-plateau transition (2-1) at $B \approx 3.5$ T should both be described by a simple expression [7, 8]

$$\left(\sigma_{xy} - \frac{2n+1}{2}\frac{e^2}{h}\right)^2 + \sigma_{xx}^2 = \left(\frac{e^2}{2h}\right)^2, \qquad (1)$$

where $n = 0$ for the QH liquid-insulator transition (1-0) and $n = 1$ for the plateau-to-plateau transition (2-1). Earlier a good agreement has been reported of the semicircle model with the experimental data obtained in AlGaAs/GaAs and Ge/SiGe systems, [15]. Fig.2 shows the results of a similar comparative analysis for both the plateau-to-plateau (2-1) and the QH liquid-insulator (1-0) transitions from the data presented in fig.1. Unlike [15], we do not find a good agreement of the semicircle model with the experiment. First, one can see a considerable tilt of the experimental $\sigma_{xx}(\sigma_{xy})$ curves corresponding to the (2-1) transition with respect to the theoretical curve as well as a significant temperature dependence of the curves corresponding to the (1-0) tran-

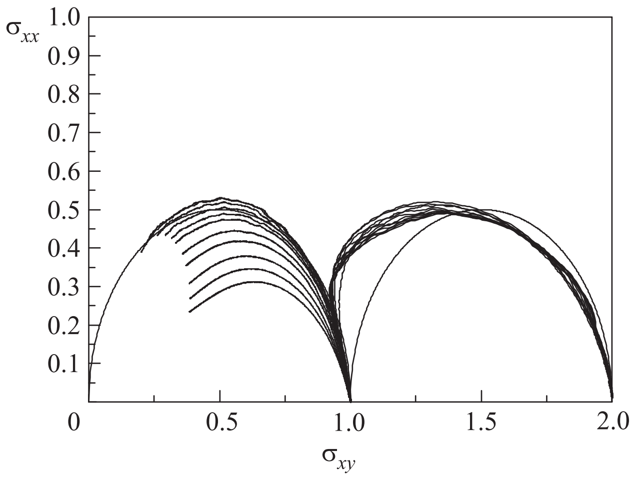

Fig.2. Longitudinal conductivity σ_{xx} versus Hall conductivity σ_{xy} calculated using the data for N331 sample shown in Fig.1. The bold traces represent the σ_{xx} versus σ_{xy} relation as expected form the "semicircle" theoretical model (see Eq.(1) in the text)

sition (in the plot the lower temperature traces lie closer to the theoratical dependence, than those corresponding to the higher temperatures).

We have also performed an analysis of the data in Fig.1 based on the critical exponent description, [6]. According to this approach between any two QH liquid states there exists only one extended state at the critical energy E_c. As the Fermi energy approaches this critical energy, the localization length is supposed to diverge following a power law $|E - E_c|^{-\eta}$ with a universal critical exponent η. The extended state can also be accessed by sweeping B, in which case the localization length $\xi \sim |B - B_c|^{-\eta}$. In order to extract the critical exponent value from experimentally measured quantities one has to invoke the finite size scaling theory according to which the resistance tensor scales as $R_{mn} = R_{mn}(L/\xi)$ for a sample of finite size L. The phase coherence length sets the effective sample size and from its temperature dependence of the $T^{-p/2}$ form one obtains $R_{mn} = R_{mn}(|B - B_c|T^{-\eta})$, the scaling function of both the longitudinal resistance ρ_{xx} and the Hall resistance ρ_{xy}. Approaching zero temperature, the derivative of the Hall resistance ρ_{xy} taken at B_c diverges as a power law $(d\rho_{xy}/dB)_{B=B_c} \sim T^{-\kappa}$, while the half width for the longitudinal resistance ρ_{xx} vanishes as $\Delta B \sim T^{\kappa}$, where the exponent is expressed as $\kappa = p/2\eta$. The first experiment on the 2D electrons confined at the interface of InGaAs/InP heterostructures has given $\kappa = 0.42$ [2]. Further experiments with $GaAs/Al_{0.32}Ga_{0.68}As$ structures confirmed this result [16]. Considering $p = 2$ [6], the exponent η is found to be 2.4, a value obtained independently by subsequent theoretical calculations [6]. However, further experiments raised doubts about the universality of the critical exponent. So, in a silicon metal-oxide semiconductor field-effect transistor (MOSFET) κ was found to range from 0.16 to 0.65 while in GaAs/AlGaAs heterostructures it varied from 0.28 to 0.81 [6] or was completely indeterminable [17]. These latter measurements have shown that the critical exponent behavior can be sample specific or there may even be transitions characterized by different κ in a single sample.

Our results fall in line with these observations. Indeed, we find that it is impossible to characterize our data by a single value of critical exponent κ. Fig.3a,b show the ρ_{xx} plotted versus $|\nu - \nu_c|T^{-\kappa}$ both for the quantum Hall liquid-insulator transition (1-0) and the plateau-to-plateau transition (2-1). Commonly, the traces corresponding to different temperatures should all collapse to a single curve when κ has the value of the universal critical exponent. In our cases the closest we can come to such a collapse is for $\kappa = 0.45$. However, as can be seen from Fig.3a,b, even for this value of κ the traces do not merge into a single curve very well. Another way of determining the critical exponent κ is by plotting the values of $\ln(d\rho_{xy}/dB)_{B=B_c}$ (the derivative at the transition point) as a function of $\ln(T)$. According to the theory the points should fall on a straight line whose slope will give the critical exponent value. As one can see in Fig.3c for our plateau-to-plateau transition (2-1), the general scatter of points corresponding to $\ln(d\rho_{xy}/dB)_{B=B_c}$ taken at different temperatures is too large to allow a reliable linear fit. Moreover, there is a noticeable saturation as the temperature decreases in contrast to the theoretical prediction. The straight line in Fig.3c is a guide to the eye corresponding to the general slope of the dependence at higher temperature that gives $\kappa = -0.42$. Thus, we come to the conclusion that the 2DEG in a HgTe QW does not belong to the group of 2D systems in which the QHE effect can be described by universal scaling theories.

Our experimental data obtained in narrower 16 nm HgTe QWs strengthens this conclusion even further. Figure 4 shows the typical $\rho_{xx}(B)$ and $\rho_{xy}(B)$ curves obtained in one of our N330 samples in the temperature range 50 mK – 1.2 K and in magnetic fields up to 17 T. In contrast to the N331 samples the N330 data is characterized by the absence of any critical point in $\rho_{xy}(B)$ or $\rho_{xx}(B)$ at magnetic fields where either the plateau-to-plateau (2-1) or the QH liquid-insulator (1-0) transitions are expected. What we observe is a few separate intersections of the $\rho_{xx}(B)$ curves accompanied at low temperatures by a certain flattening out of the $\rho_{xy}(B)$

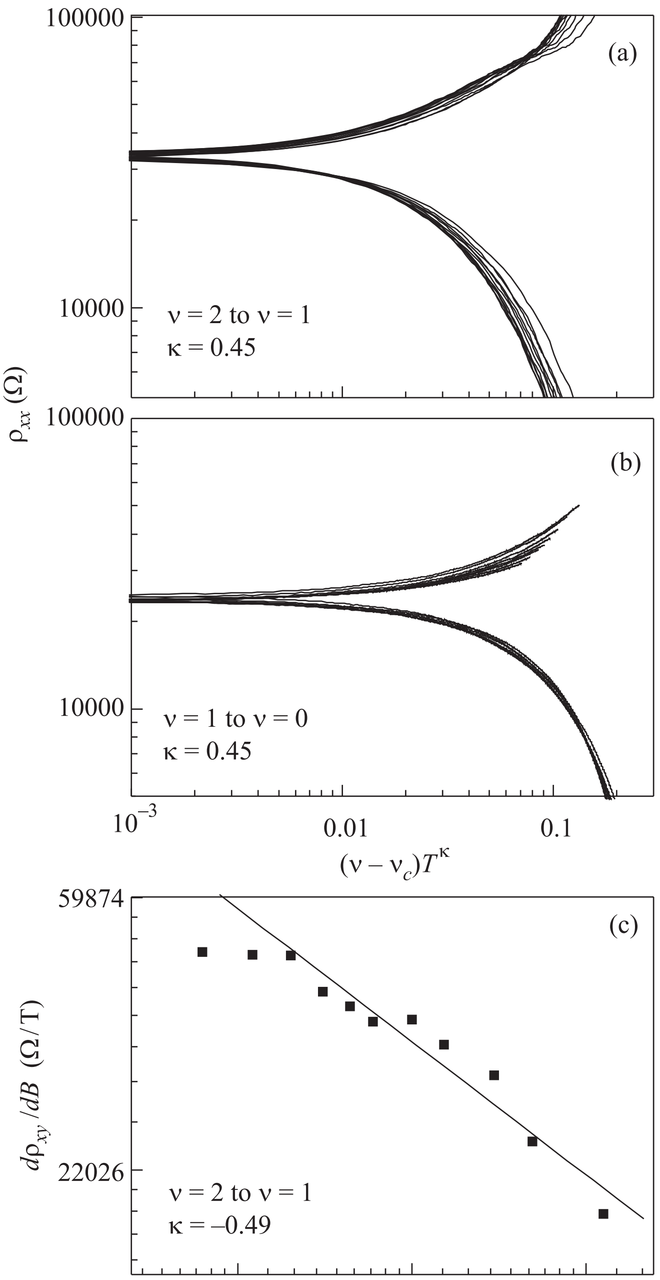

Fig.3. Scaling analysis of the ρ_{xx} (the data from Fig.1) versus $|\nu - \nu_c|T^{-\kappa}$ with $\kappa = 0.45$ for (a) – plateau-to-plateau (2-1) transition and (b) – QH liquid-insulator (1-0) transition; (c) – $(d\rho_{xy}/dB)_{B=B_c}$ vs T for the (2-1) transition. The straight line is a guide for the eye corresponding to $\kappa = 0.49$

in magnetic fields corresponding to the expected QH liquid-insulator transition. For the plateau-to-plateau (2-1) transition there is no crossing point at all (see the insert) either for $\rho_{xx}(B)$ or for $\rho_{xy}(B)$. All one observes is a certain narrowing of the $\rho_{xx}(B)$ peak and a widening of the $\rho_{xy}(B)$ plateau as the temperature decreases.

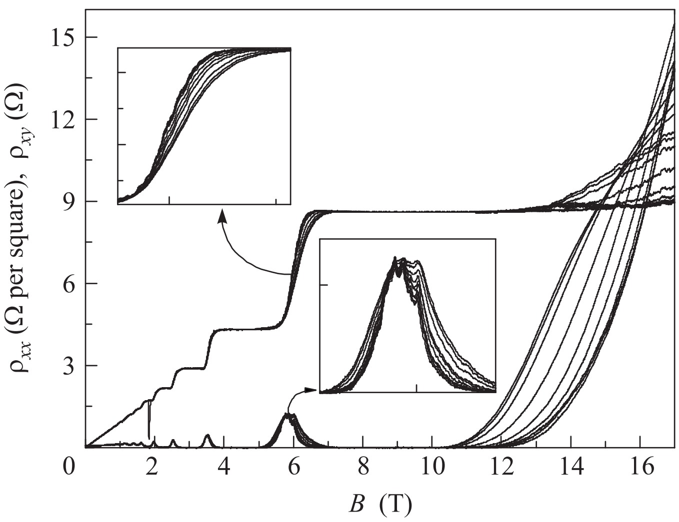

Fig.4. The longitudinal and the Hall resistance versus magnetic field in a 16 nm wide QW sample (N330). The traces (from bottom to top) are taken for temperatures in the range from 60 mK to 1.1 K. The magnified areas correspond to the plateau-to-plateau (2-1) transition

To conclude, the integral QHE behavior in the 2DEG in a HgTe QW is found to be in disagreement with the existing universal scaling theories. The possible reasons for this may be as follows: 1) a strong interaction of the conduction and the valence bands in a HgTe QW because of their affinity, 2) a nontrivial long range scattering potential, 3) a contribution of electron-phonon interaction, which can be significant even at low temperatures. In any case further investigations on a larger variety of HgTe samples will be required to explain the observed discrepancies between theory and experiment.

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