CHINESE JOURNAL OF PHYSICS VOL. 47, NO. 3 JUNE 2009

An Experimental Study on the Hall Insulators

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(Received August 22, 2008)

We have studied the Hall insulators (HIs) in a gated two-dimensional GaAs electron system containing self-assembled InAs quantum dots. It is shown that the semicircle law can become invalid in the quantum Hall (QH) liquid, so that the quantized Hall plateau is absent at the insulator-quantum Hall (I-QH) transition. The appearance and breakdown of the semicircle law in the insulating phase can both be observed when the QH liquid is destroyed by disorder. From our study, the quantized HI is not necessarily accompanied by the I-QH transition.

PACS numbers: 71.10.Hf, 73.20.Fz, 73.20.Jc

At low temperatures, localization effects due to quantum interference [1] play an important role in determining the transport properties of disordered two-dimensional electron systems (2DESs). According to the theory of localization, a non-interacting ,disordered 2DES of infinite size is an insulator at zero magnetic field, since all of its electronic states are localized [2]. Although we shall consider that experimentally only a 2DES of finite size and/or temperature is available, the insulating behavior due to the zero-field localization has been observed in samples with high enough disorder [3]. By applying a magnetic field B perpendicular to a 2DES, the localization effect is also important for the appearance of the integer quantum Hall effect (IQHE), in which the 2DES may pass through a series of integer quantum Hall (QH) states (or phases). At high magnetic fields, the series of integer QH states is terminated by a transition to the insulating phase. Kivelson, Lee, and Zhang [4] showed that a 2DES in the insulating phase behaves as a Hall insulator (HI) which is characterized by a finite Hall resistivity, $\rho_{xy} \sim B$.

In the global phase diagram (GPD) proposed by Kivelson, Lee, and Zhang [4], a boundary separating two phases corresponds to a magnetic-field-induced phase transition. The transition separating the QH liquid from the insulator is usually denoted as the insulator-quantum Hall (I-QH) transition. More recent experiments [5–7] on the I-QH transition between the insulating phase and the QH state of ν=1 showed that at high B the quantized Hall plateau is observed not only in the QH state, but also in the insulating phase. The quantization of the Hall resistivity ρ_{xy} in such a transition is due to the semicircle law, under which the longitudinal (σ_{xx}) and Hall (σ_{xy}) conductivities satisfy the following equation [8]:

$$(\sigma_{xy} - e^2/2h)^2 + {\sigma_{xx}}^2 = (e^2/2h)^2. \tag{1}$$

In Ref. [6] the quantized Hall plateau can be observed in the insulating phase, which is dubbed a quantized HI, even when the longitudinal resistivity ρ_{xx} is as high as $8h/e^2$. Recently such a quantized HI has been investigated based on a phase-incoherence network model [9], and it has been found that the quantized HI can occur only in the presence of a strong dephasing mechanism [10]. This suggests that the quantized HI behavior is dominated by the nearest-neighbor hopping processes [11]. According to some theoretical studies [10, 12, 13], the semicircle law should breakdown (i.e., the quantized HI is destroyed) at high B, where the localization length becomes much shorter than the dephasing length.

In the present work, we investigate the semicircle law in a 2DES. From our study, the semicircle law can become invalid in the QH liquid, so that the quantized Hall plateau is absent at the I-QH transition. Moreover, the quantized HI is not necessarily accompanied by the I-QH transition. For convenience, in the following we denote the HI which is characterized by a finite Hall resistivity, $\rho_{xy} \sim B$, as the classical HI, to distinguish it from the quantized HI.

Our sample used in this study is a molecular beam epitaxial grown GaAs/AlGaAs quantum well. The following layer sequence was grown on a GaAs (100) substrate: 50 nm AlGaAs, 20 nm GaAs in which the 2.15 mono layer of InAs were capped by a 5 nm GaAs layer, and the self-assembled InAs quantum dots were formed, 40 nm undoped AlGaAs, 40 nm Si doped AlGaAs, and finally a 17 nm GaAs cap layer. In our system, the self-assembled InAs quantum dots act as scattering centers in the GaAs 2DES and provide the necessary disorder to observe I-QH transitions [14]. The sample was made into the Hall pattern by standard lithography and etching processes. An Au/Ni/Cr gate was evaporated on the surface that can vary both the carrier concentration and the mobility by changing the applied gate voltage. Magneto transport measurements were performed with a top-loading He^3 system with a superconductor magnet. A phase sensitive four-terminal ac lock-in technique was used with a driving current of 10 nA. In order to investigate the relation between the Hall resistivity ρ_{xy} in the IQHE and the insulator, a careful measurement of ρ_{xy} is necessary. The divergent longitudinal resistivity ρ_{xx} component would influence the determination of ρ_{xy}, while the sample exists the misalignment of the Hall contacts. In principle, the ρ_{xx} component can be removed by averaging two different magnetic field orientations, as the contribution of ρ_{xx} is symmetric in the magnetic field, as opposed to antisymmetric for ρ_{xy}. All of the ρ_{xy} measured in our system were obtained by averaging two opposite directions of the magnetic field. With the gate voltage $V_g = -0.1035$ V and -0.106 V, the carrier densities are 6.8×10^{10} cm^{-2} and 6.2×10^{10} cm^{-2}, and the mobilities are 2.6×10^3 cm^2/Vs and 1.8×10^3 cm^2/Vs at 0.3 K, respectively.

The magnetic field dependence of ρ_{xx} over the temperature range $T = 0.3$–1.51 K and ρ_{xy} at $T = 0.3$ K are presented for the gate voltage $V_g = -0.1035$ V, as shown in Fig. 1. When $B < B_{c1} = 1.37$ T and $B > B_{c2} = 1.83$ T, the system behaves as an insulator in the sense that ρ_{xx} increases as T decreases. The QH state at the filling factor $\nu = 2$ is observed, which has a pronounced minimum in ρ_{xx} from the corresponding Hall plateau in ρ_{xy}. The

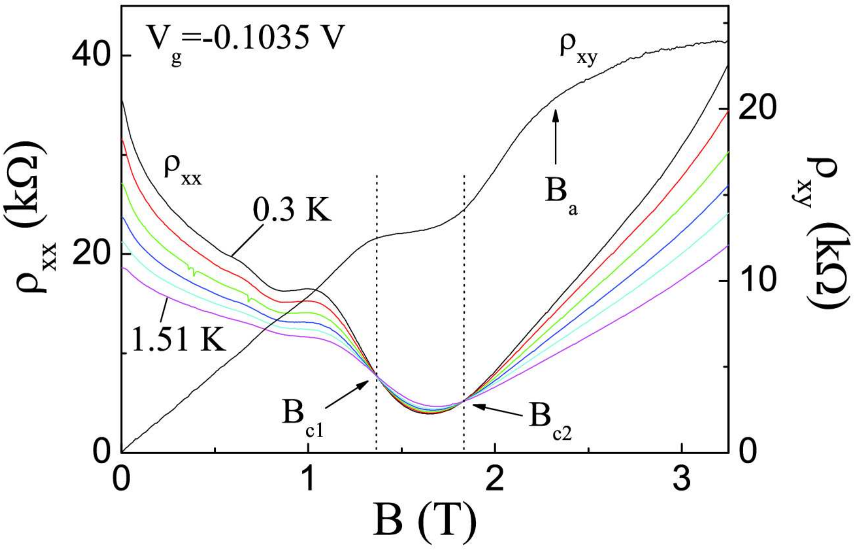

FIG. 1: The longitudinal (ρ_{xx}) and Hall (ρ_{xy}) resistivities as a function of the magnetic field B at $V_g = -0.1035$ V. The temperatures of ρ_{xx} are 0.3, 0.5, 0.68, 0.89, 1.13, and 1.51 K. The temperature of ρ_{xy} is 0.3 K. B_{c1} and B_{c2} are the two critical fields. The magnetic field B_a corresponds to the conversion of the Hall resistivity.

T-independent points in ρ_{xx} at B_{c1} and B_{c2} are observed, which could be used to identify the boundaries between the QH state and the insulator regions. Therefore, the system has the I-QH ($\nu = 2$)-I transitions, which are consistent with a GPD for a spin-degenerate 2DES. At the low-field insulator as shown in Fig. 1, the Hall resistivity follows the classical dependence on the magnetic field, $\rho_{xy} \sim B$, which is known as the classical HI. When the system enters the $\nu = 2$ QH state from the low-field insulator, ρ_{xy} remains nearly constant and is close to its quantized value of $h/2e^2$. In contrast to the previous reports [6, 7], we can observe that ρ_{xy} deviates from the quantized value of $h/2e^2$ before entering the high-field insulator rather than remaining quantized at the I-QH transition. From our experimental results, we can find that ρ_{xy} may not necessarily be quantized at the I-QH transition.

It is known that the QH state could disappear, and then the system is always in the insulating phase at all magnetic fields when the effective disorder is high enough [14, 16, 17]. Changing the applied gate voltage is equivalent to varying the effective disorder. By increasing the effective disorder, Fig. 2 shows the curve of ρ_{xy} at $T = 0.3$ K and the curves of ρ_{xx} at the temperature range from 0.3 to 1.11 K at $V_g = -0.106$ V. At the minima of $\rho_{xx}(B)$ for different temperatures, as shown in the inset of Fig. 2, ρ_{xx} increases with decreasing T, and thus the QH liquid is destroyed. Hence the system is an insulator at all magnetic fields. Upon increasing the magnetic field, ρ_{xy} increases linearly with the magnetic field and then is quantized at the value of $h/2e^2$ in the vicinity of $\nu = 2$, which indicates the appearance of quantized HI. At $B \sim 1.31$ T, the system undergoes a direct crossover from the classical HI to the quantized HI without passing through the QH liquid.

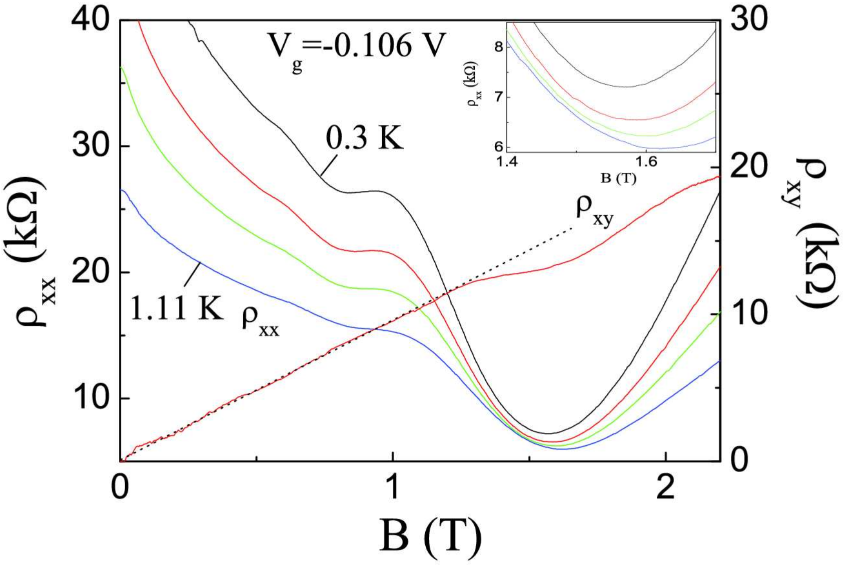

FIG. 2: The longitudinal (ρ_{xx}) and Hall (ρ_{xy}) resistivities as a function of the magnetic field B at $V_g = -0.106$ V. The temperatures of ρ_{xx} are 0.3, 0.5, 0.69, and 1.11 K. The temperature of ρ_{xy} is 0.3 K. The dotted line corresponds to a linear fit to the low-field classical Hall insulator. The inset shows a zoom-in of the longitudinal resistivities $\rho_{xx}(B)$ near the minimum of $\nu = 2$.

Therefore, the quantized HI can appear in the absence of an I-QH transition.

In order to obtain further understanding of our results, we study the T-driven flow diagram [15]. Figure 3 (a) and (b) are for $V_g = -0.1035$ V and -0.106 V, respectively. As proposed by Murzin *et al.* [16], we considered the conductivities per spin $\sigma'_{ij} \equiv \sigma_{ij}/2$ to construct such a flow diagram. At the magnetic fields where $\rho_{xy} \sim h/2e^2$, the T-driven flow lines are closed to the theoretical semicircle mentioned by Eq. (1) at both gate voltages. However, the directions of the T-driven flow lines in such a regime are opposite in Fig. 3 (a) and (b), because the system is in the $\nu = 2$ QH state and insulating phase, respectively. It is expected that in the lowest QH state and insulating phase, the T-driven flow lines are toward (e^2/h,0) and (0,0), respectively. Since no transition occurs at $V_g = -0.106$ V, in Fig. 3 (b) there is no unstable point near which the flow directions are different at its two sides. In contrast to the work of Wei, Tsui, and Pruisken [15], our study shows that there is no unstable point in the flow diagram under the destruction of the critical point which is T-independent in ρ_{xx}.

Shimshoni and Auerbach [9] have proposed one explanation for the quantization of ρ_{xy} in the insulating regime. They showed that a quantized HI can be explained by a network model of puddles when the dephasing length is smaller than the puddle size. Based on such a model, the phenomenon of a quantized HI is not necessarily accompanied by an I-QH transition. Our study is consistent with their theoretical interpretation associated with a strong dephasing mechanism [9].

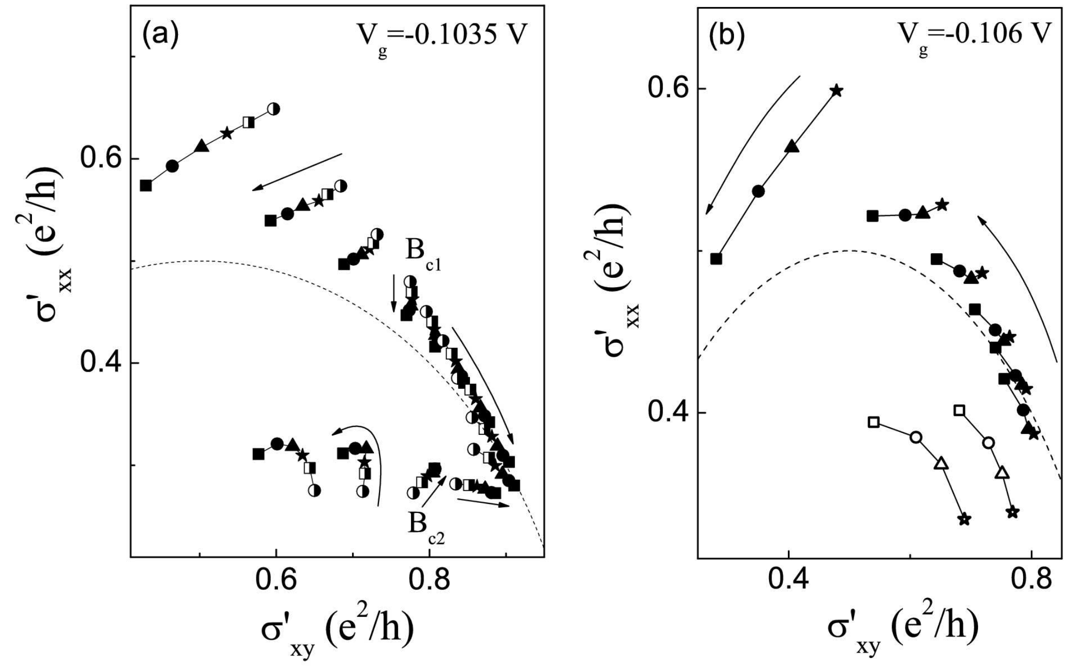

FIG. 3: The temperature-driven flow diagrams (a) for the insulator-quantum Hall ($\nu = 2$)-insulator transitions near the two critical points (B_{c1} and B_{c2}) at $V_g = -0.1035$ V, and (b) near the quantized Hall insulator at $V_g = -0.106$ V. The dashed lines show the theoretical semicircle lines. The arrows indicate the directions of the flow lines from high to low temperatures.

The behavior of the Hall resistivity in the insulating phase is a subtle effect and a number of theoretical studies [4, 9–13] have proposed different behaviors of ρ_{xy} under various restrictions. In order to obtain further information on the underlying physics in the Hall insulator regime, we study the B dependence of the measured ρ_{xx} in the high-field regime. Theoretically, the B dependence of ρ_{xx} in the strongly localized regime follows the law of $\ln \rho_{xx} \propto B^2$ because of the shrinkage of the electron wave functions [18, 19]. Figure 4 shows the B dependence of ρ_{xx}, $\ln \rho_{xx}$ vs B^2, around the high-field insulator regime at $T = 0.3$ K for the gate voltage $V_g = -0.1035$ V. At $B_a = 2.31$ T shown in Fig. 4, the curve has an apparent change in the slope. And we can observe a characteristic shown in Fig. 1, that $\rho_{xy}(B)$ also has a change in the slope at such a magnetic field. So theoretical and experimental studies are required to further investigate this unsettled issue.

It has been reported by our previous study [17] that Shubnikov-de Haas oscillations can be observed in the low-field insulator. In the present study, we also find that the minimum in ρ_{xx} corresponding to the filling factor $\nu = 4$ can appear in the low-field insulator, as shown in Fig. 1. The T-driven flow line shown in Fig. 3 (a) at B_{c1}, which is at the critical point, starting from high temperatures at $\sigma'_{xy} \approx 0.77e^2/h$, terminates at the lowest temperatures very close to the theoretical semicircle at the same σ'_{xy} rather than at the top of the semicircle. From the flow diagrams, the T-driven flow lines deviate from the

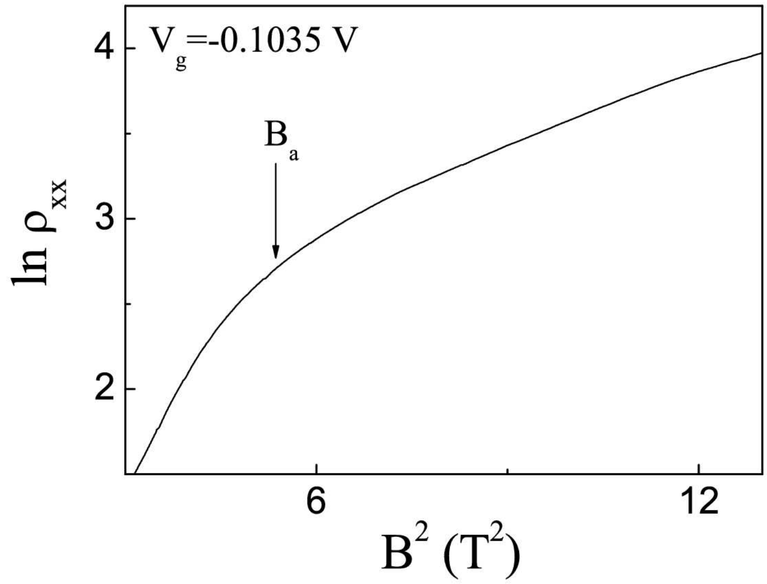

FIG. 4: The logarithm of ρ_{xx} as a function of the square of the magnetic field B near the high-field insulator at $T = 0.3$ K for $V_g = -0.1035$ V.

theoretical semicircle at both gate voltages, while ρ_{xy} begins to deviate from its quantized value. So the appearance and breakdown of the semicircle law are observed. Moreover, the T-driven flow line shown in Fig. 3 (a) at B_{c2}, in which the flow directions are opposite on both its sides, could still be corresponding to an unstable point, although it deviates from the theoretical semicircle.

In conclusion, we have performed a magnetotransport study on a gated two-dimensional GaAs electron system containing self-assembled InAs quantum dots. The quantization of the Hall resistivity could deviate from the plateau value of the nearby QH state at the I-QH transition. While the QH liquid is destroyed by strong enough disorder, the system can exhibit a quantized HI. The system undergoes a direct crossover from the classical HI to the quantized HI without passing through the QH liquid. The appearance and breakdown of the semicircle law can be observed both in the QH state and in the insulating phase. From our study, the quantized HI is not necessarily accompanied by the I-QH transition.

Acknowledgements

This work was funded by the NSC, and the MOE program for Promoting Academic Excellence of Universities (89-N-FA01-2-4-3), Taiwan. The work at Cambridge was supported by the EPSRC, United Kingdom. Gil-Ho Kim. acknowledges financial support from the Korea Science and Engineering Foundation (KOSEF) grant funded by the Korea government (MOST) (No. ROA-2007-000-10032-0). We thank Y.-H. Chiu, J.-R. Juang, M.-G. Lin, H.-S. Wang, and T.-M. Chen for their experimental help, and E. Shimshoni for fruitful discussions.

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