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Probing two-dimensional metallic-like and localization effects at low magnetic fields

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ABSTRACT

The metallic-like regime characterized by Shubnikov–de Haas (SdH) oscillations is investigated between localization-induced weak insulator and quantum Hall liquid in a gated two-dimensional GaAs electron system containing InAs dots. Multiple SdH crossing points are observed in the longitudinal resistivity before the appearance of the critical point of a plateau transition with increasing perpendicular magnetic field. In conductivities, however, there is no corresponding crossing in the metallic-like regime because of the T-dependent Hall slope under electron–electron interaction, which provides an explicit way to distinguish SdH crossing points from the critical point in our study.

Considerable efforts have been made to understand the quantum Hall (QH) transport of two-dimensional electron systems (2DESs) in a perpendicular magnetic field B. Theories based on localization effects have been successfully developed for such systems at high enough B, but more studies are still necessary to clarify the low-field transport mechanisms. Most 2DESs are metallic rather than being insulators at low magnetic fields although only the insulating state is expected as the QH liquid is terminated with decreasing B[1]. To understand the low-field metallic behaviors and zero-field metal phase [2,3], finite size (temperature) effects [1,4] and/or electron–electron (e–e) interaction [3] are discussed in the literature. Recently, there are reports on magneto-oscillations in the metallic-like regime with low-field Landau quantization [5,6]. Such oscillations can follow the Shubnikov–de Haas (SdH) formula [6], and survive under an insulating background [7–10]. While the insulator–quantum Hall (I–QH) transitions are expected to shrink to a single transition point in B as temperature T approaches zero, the coexistence indicates that the crossover from the low-field insulator to QH liquid may cover a wide range of B[11]. In addition to the transition point, there can exist multiple T-independent crossing points in the metallic regime, which follow the SdH formula [6]. The 2DESs, in fact, can undergo the transition from the QH states of arbitrary integer filling factors ν directly to the low-field insulator while only the QH state of the lowest integer is allowed to be adjacent to the insulating state in the global phase diagram (GPD) suggested in Refs. [1,4–6,11–13]. Such a transition is denoted as the direct I–QH transition.

In order to improve our understanding on the low-field transport properties of 2DESs, we investigate the crossover from the insulator to QH liquid in a gated GaAs-based 2DES containing self-assembled InAs dots. We take the benefit from the fact that such a 2DES has been investigated in Ref. [6]. The sample is a molecular beam epitaxial grown AlGaAs/GaAs heterostructure. The following layer sequence was grown on a GaAs (1 0 0) substrate: 50 nm AlGaAs, 20 nm GaAs in which 2.15 mono-layers of InAs were capped by a 5 nm GaAs layer, self-assembled InAs quantum dots were formed, 40 nm undoped AlGaAs, 40 nm Si doped AlGaAs, and finally 17 nm GaAs cap layer. In our case, a 2DES is formed near the interface of the AlGaAs/GaAs heterojunction. It has been proved that such a GaAs 2DES containing InAs quantum dots is suitable for studying I–QH transitions [8]. The device was made into a Hall pattern by standard lithography and etching processes and a NiCr/Au gate was evaporated on the surface. The experiments were performed in a He^3 cryostat at temperatures ranging from 0.25 to 1.6 K. Four-terminal magnetoresistivities were measured using standard AC phase-sensitive lock-in techniques with a current of 10 nA.

With decreasing B, the 2DES leaves the QH liquid to become an insulator, where the longitudinal resistivity ρ_{xx} increases with decreasing T. Just as reported in our previous study [6], multiple T-independent crossing points expected in the SdH formula can

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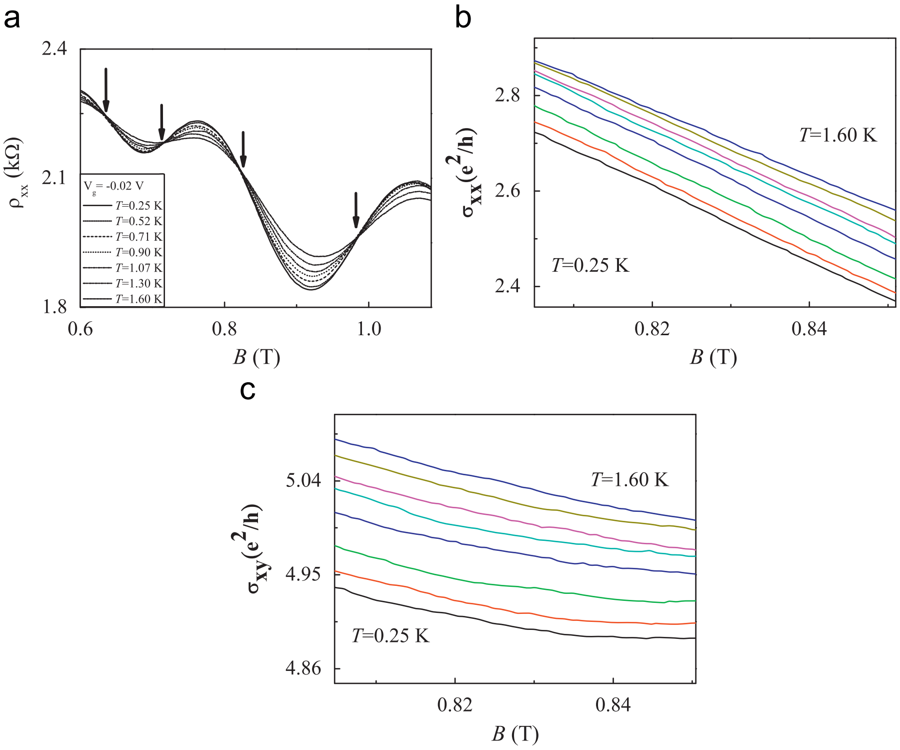

Fig. 1. The curves of (a) the longitudinal resistivity ρ_{xx} at B=0.6–1.1 T and (b) the longitudinal and Hall conductivities σ_{xx} and (c) σ_{xy} at B=0.805–0.85 T at various temperatures. For Fig. 1(b) and (c), from top to bottom: T=1.60, 1.30, 1.07, 0.90, 0.71, 0.52, 0.36, and 0.25 K. The arrows indicate the crossing temperature-independent points.

be observed in ρ_{xx} between the QH liquid and low-field insulator when the Hall slope increases with decreasing T because of the e–e interaction [14]. The four T-independent points of the 2DES under the gate voltage $V_g = -0.02$ V are marked by arrows in Fig. 1(a).

By decreasing the gate voltage, as reported in Ref. [6], in ρ_{xx} we can observe a T-independent point that cannot be taken as the crossing point in SdH formula. Such a point is the direct I–QH transition separating the low-field insulator directly from the ν=4 QH state. In our study, there is also no T-independent point in σ_{xx} or σ_{xy} corresponding to this transition point because ρ_{xy} increases with decreasing T. Our group [23] has reported that the direct I–QH transition can follow temperature scaling when there are no clear magneto-oscillations. However, it should be one-parameter scaling [24] rather than two-parameter scaling [17,25–29] because the Hall resistivity is not a function of the scaling parameter. More studies are still necessary to clarify whether the scaling, if it exists, is for ρ_{xx} or for σ_{xx}.

Between adjacent QH states, there exists a critical magnetic field where both the longitudinal and Hall conductivities σ_{xx} and σ_{xy} are T-independent [15,16]. Hence both ρ_{xx} and the Hall resistivity ρ_{xy} are expected to be T-independent at the critical magnetic field. Fig. 2 shows the curves of ρ_{xx} and ρ_{xy} between the QH states of ν=2 and 4 at $V_g = -0.02$ V, and we can identify the critical magnetic field as marked by the vertical line from the T-dependences of ρ_{xx} and ρ_{xy}. The four crossing points in Fig. 1(a), however, have no corresponding T-independent point in ρ_{xy}. Converting the resistivities to conductivities, there is no corresponding T-independent point in σ_{xx} and σ_{xy} [17]. Figs. 1(b) and (c) show the curves of σ_{xx} and σ_{xy} as B=0.805–0.85 T, and there is no crossing point while there exists a T-independent point in ρ_{xx} at B=0.84 T. Therefore, it is clear in our study that the T-independent crossing points in Fig. 1(a) are different from the critical points separating different QH states.

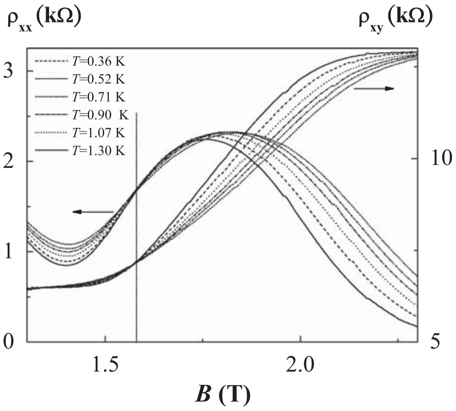

Fig. 2. Longitudinal and Hall resistivities ρ_{xx} and ρ_{xy} between the quantum Hall states of the filling factors ν=4 and 2. The vertical line indicates the critical point separating these two states.

In this study, oscillations following the SdH formula are observed in the low-field insulator when there exists a clear direct I–QH transition. On the other hand, such a formula can hold true in the QH liquid [18,19]. More studies are necessary to clarify the condition for SdH formula [20–22].

It is well known that from the SdH oscillations, a parameter ρ_0 that is expected to be close to the zero-field resistivity of the 2DES can be determined by [30]

$$\Delta\rho_{xx} = 4\rho_0 \exp[-\pi/(\mu_q B)][X/\sinh X]. \quad (1)$$

Here $\Delta\rho_{xx}$ is the amplitudes following the SdH formula, μ_q the quantum mobility, and $X=(4\pi^3 km{*}T)/(heB)$ with $m{*}$, k, h, and e as the effective mass of electron, Boltzmann constant, Planck constant, and electron charge, respectively. Fig. 3 shows the determined ρ_0, the longitudinal resistivity ρ_c at the 0–4

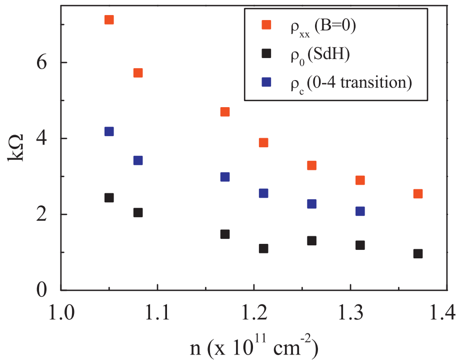

Fig. 3. Zero-field resistivities ρ_{xx} and ρ_0 determined from the SdH oscillations, and ρ_c at the 0–4 transition as a function of carrier density n at T=0.25 K.

transition, and the measured zero-field resistivity as a function of n at the lowest measurement temperature of ~0.25 K. Due to the presence of weak localization and e–e interactions, the zero-field resistivity is the highest one as expected. Near the 0–4 transition, weak localization effect is strongly suppressed and the resistivity decreases from its zero-field value. Interestingly, we can see that all three values show a similar trend. That is, ρ_{xx} decreases with increasing n. In our study, ρ_0 is lower than ρ_c. We note that quantum corrections [31] may be important for ρ_c and there are reports on deviations of ρ_0 [22]. More studies are required to understand the underlying physics of this interesting effect.

In conclusion, we investigate the magneto-transport properties of the two-dimensional GaAs electron system with self-assembled InAs dots. In the metallic-like regime between the low-field insulator and quantum Hall liquid, multiple crossing points are observed in the longitudinal resistivity ρ_{xx}, of which the oscillations follow the Shubnikov–de Haas formula. In both the longitudinal and Hall conductivities σ_{xx} and σ_{xy}, however, there is no corresponding crossing because of the T-dependent Hall slope under the electron–electron interaction. There is also no crossing in conductivities at the direct insulator–quantum Hall transition while ρ_{xx} is T-independent at the transition point. In our study, therefore, we can distinguish these T-independent points from the critical points separating different quantum Hall states by converting the resistivities to conductivities.

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