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Probing the onset of strong localization and electron–electron interactions with the presence of a direct insulator–quantum Hall transition

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ABSTRACT

We have performed low-temperature transport measurements on a disordered two-dimensional electron system (2DES). Features of the strong localization leading to the quantum Hall effect are observed after the 2DES undergoes a direct insulator–quantum Hall transition on increasing the perpendicular magnetic field. However, such a transition does not correspond to the onset of strong localization. The temperature dependences of the Hall resistivity and Hall conductivity reveal the importance of the electron–electron interaction effects for the observed transition in our study.

1. Introduction

When a strong magnetic field B is applied perpendicular to the plane of a two-dimensional electron system (2DES), Landau quantization may cause the formation of Landau bands. It is now well established that Landau quantization can modify the electrical properties of a two-dimensional (2D) system. With increasing B, usually Landau quantization may give rise to Shubnikov–de Haas (SdH) oscillations with amplitude [1–5]

$$\Delta\rho_{xx}(B,T) = 4\rho_0 \exp(-\pi/\mu B) D(B,T) \quad (1)$$

in the longitudinal resistivity ρ_{xx} before the appearance of the integer quantum Hall effect (IQHE) [1,6] at a low temperature T. Here, ρ_0 is expected to be the longitudinal resistivity ρ_{xx} at $B = 0$ while there may exist deviations [7], μ is the quantum mobility, and $D(B,T) = 2\pi^2 k_B m^* T/\hbar eB \sinh(2\pi^2 k_B m^* T/\hbar eB)$ with m^*, k_B, and $\hbar$ being the effective mass, Boltzmann constant, and reduced Plank constant. It is worth mentioning that the SdH theory is derived based on Landau quantization without considering the strong localization effects induced by the quantum interference. On the other hand, it is believed that both extended and localized states arising from such effects are key ingredients for describing the IQHE, in which the magnetic-field-induced transitions [8–12] are good examples of quantum phase transitions. Such transitions occur as the Fermi energy passes through the extended states of Landau bands. In the global phase diagram (GPD) [8] of the quantum Hall effect, all the magnetic-field-induced transitions are regarded as equivalent though they are divided into two types, plateau–plateau (P–P) transitions and insulator–quantum-Hall (I–QH) transitions [12].

There has been much interest in the IQHE at low magnetic fields [13–18]. A thorough understanding of the low-field IQHE should provide important information regarding the I–QH transition [8,10,11,19]. In particular, whether a direct transition from the insulating regime (denoted by symbol 0) to a $\nu \geq 3$ QH state can occur is an interesting, fundamental yet unsettled issue in the field of 2D physics [13–15,20–23]. Experimental and theoretical evidence for such a direct phase transition has been reported [13–15, 20–22]. On the other hand, it was argued by Huckestein [16] that the observed direct I–QH transition is not a real quantum phase transition, but a crossover from a weak-localization regime to a strong-localization regime in which Landau quantization becomes dominant. Within Huckestein's model, the onset of strong localization which causes the formation of a QH state should correspond to the direct I–QH transition. We note that, in such a model,

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both weak localization and electron–electron interactions are considered as correction terms to the classical Drude conductivities. It is well known that electron–electron (e–e) interactions could play an important role in the metal–insulator transition (MIT) [24]. Moreover, in the seminal work of Dubi et al. [25], various transitions such as I–QH, MIT, and percolation transitions [26,27] can be explained within a unifying model. Therefore, it is interesting to probe electron–electron interaction effects with the presence of an I–QH transition. Moreover, the effect of Landau quantization and onset of strong localization are fundamental issues regarding the direct I–QH transition.

In this communication, we report magneto transport measurements on a disordered 2DES. With increasing B, the strength of the strong localization increases such that we can observe the well-developed QH state of $\nu = 2$. However, the direct I–QH transition observed at $B \sim 2.29$ T is not due to the onset of strong localization because the SdH formula is valid when $B < 4.76$ T. The T-dependences of the Hall resistivity ρ_{xy} and Hall conductivity σ_{xy} show the importance of e–e interactions for such a transition in our study.

2. Experimental details

Sample LM4645, a delta-doped quantum well with additional modulation doping, is used in this study. The following layer sequence was grown on a semi-insulating GaAs (100) substrate: 500 nm GaAs, 80 nm $Al_{0.33}Ga_{0.67}As$, 5 nm GaAs, Si delta-doping with a concentration of 3×10^{11} cm^{-2}, 15 nm GaAs, 20 nm $Al_{0.33}Ga_{0.67}As$, 40 nm Si-doped $Al_{0.33}Ga_{0.67}As$ with a doping concentration of 10^{18} cm^{-3}, and finally a 10 nm GaAs cap layer. Experiments were performed in a top-loading He^3 cryostat equipped with a superconducting magnet. Four-terminal magneto resistivities were measured using standard ac phase-sensitive lock-in techniques. The magnetic field is applied perpendicular to the plane of the 2DES.

3. Results and discussion

Fig. 1 shows the longitudinal and Hall resistivities (ρ_{xx} and ρ_{xy}) as a function of magnetic field B at various temperatures T. For $2.54 \text{ T} \leq B \leq 4.76$ T, magneto-oscillations in ρ_{xx} are observed. In order to further study these oscillations, we plot their amplitudes as a function of $1/B$, as shown in Fig. 2. As shown in this figure, there is a good fit to Eq. (1), and thus these magneto-oscillations are ascribed to SdH oscillations. From the observed SdH oscillations, the carrier density of the 2DES is measured to be 4.38×10^{15} m^{-2}. According to the fit shown in Fig. 2, the quantum mobility is estimated to be ≈ 0.19 m^2/Vs. Since the SdH theory is derived based on Landau quantization without considering strong localization effects, it is believed that high-field strong localization effects leading to the IQHE are not significant for $B \leq 4.76$ T. The resistance peak at around 6 T appears to move with increasing B. This movement cannot be described within the standard SdH theory, and the measured amplitudes at $B = 4.76$ T can be affected by this movement. Hence the data points at $B = 4.76$ T in Fig. 2 are given in open symbols whilst it can be fitted to Eq. (1).

The Hall slope at low B increases with decreasing T, and we can see from Fig. 1 that the curves of ρ_{xy} at $T = 0.33$ K and $T = 1.242$ K do not collapse into a single curve when B is smaller than 4 T. Such a change in the Hall slope does not result from a change in n since n determined from the SdH oscillations is T-independent over the whole measurement range. As will be described later, such T-dependent ρ_{xy} can be ascribed to electron–electron interactions.

As shown in the inset to Fig. 1, for $7.6 \text{ T} \leq B \leq 10.6$ T, we can see a well-quantized $\nu = 2$ Hall plateau with corresponding vanishing resistivity. Therefore the strong localization effect which gives rise to the formation of the quantum Hall state should occur with increasing B.

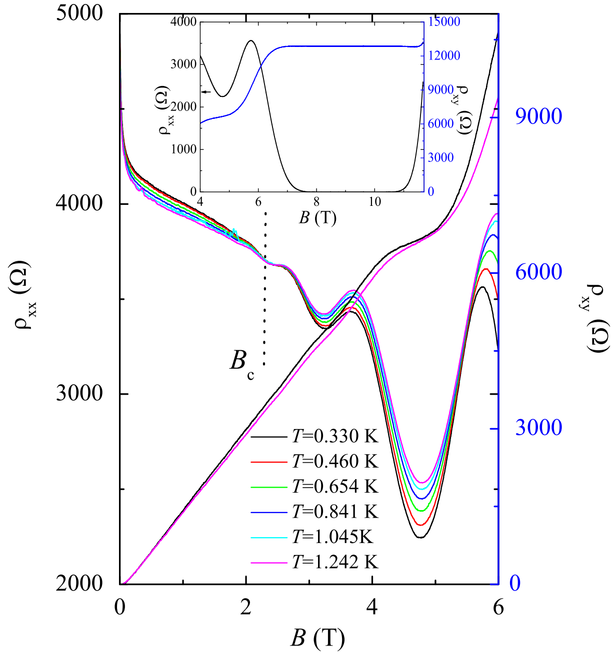

Fig. 1. Longitudinal resistivity ρ_{xx} measurements as a function of magnetic field B at various temperatures T. The Hall resistivity measurements at the lowest and highest temperatures are shown so as to highlight its weak T-dependence. The inset shows both ρ_{xx} and ρ_{xy} measurements in the high-field regime at the lowest temperature $T = 0.33$ K.

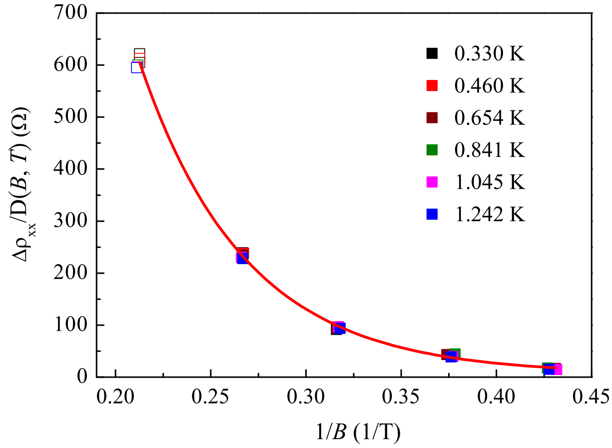

Fig. 2. $\Delta\rho_{xx}/D(B, T)$ as a function of $1/B$ at various temperatures T, where $\Delta\rho_{xx}$ represents the amplitude of SdH oscillations. The solid curve corresponds to a fit to Eq. (1).

In order to further study the strong localization effect in our system, we follow the seminal work of Shahar [12] as described as follows. First, as shown in Fig. 3, we convert the measured ρ_{xx} and ρ_{xy} into σ_{xx} and σ_{xy} by matrix inversion:

$$\sigma_{xx} = \frac{\rho_{xx}}{\rho_{xx}^2 + \rho_{xy}^2}, \tag{2}$$

$$\sigma_{xy} = \frac{\rho_{xy}}{\rho_{xx}^2 + \rho_{xy}^2}. \tag{3}$$

Using the following equations, we then obtain the conductivity of the topmost Landau level by subtracting from the conductivity data the contribution of the lowest, full Landau level.

$$\sigma_{xx}^t = \sigma_{xx}, \tag{4}$$

$$\sigma_{xy}^t = \sigma_{xy} - \frac{2e^2}{h}. \tag{5}$$

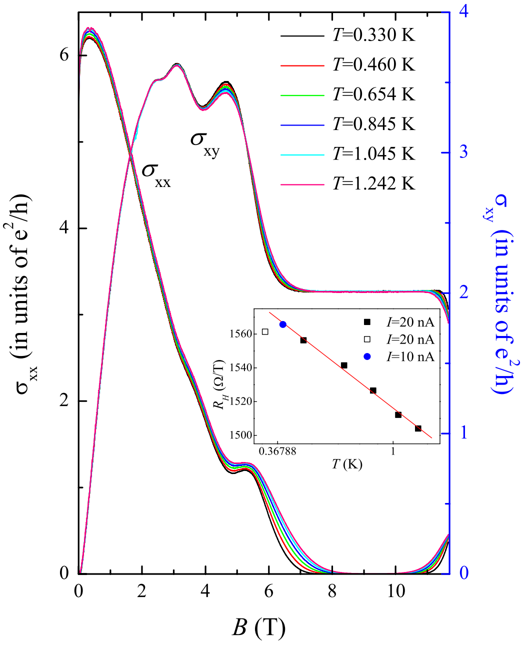

Fig. 3. Converted (a) $\sigma_{xx}(B)$ and (b) $\sigma_{xy}(B)$ at various temperatures T ranging from $T = 0.33$ K to $T = 1.242$ K. Inset: semilogarithmic plot of Hall slope R_H as a function of $\ln T$. The linear fit to the full symbols is discussed in the text.

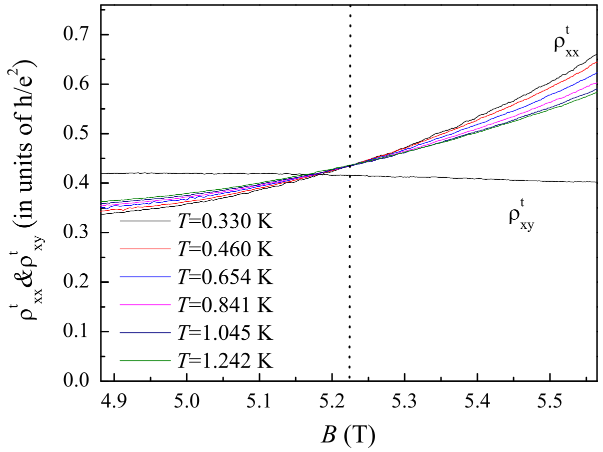

Fig. 4. Converted ρ^t_{xx} as a function of B at various temperatures T ranging from $T = 0.33$ K to $T = 1.242$ K. ρ^t_{xy} is at $T = 0.33$ K. The vertical dotted line denotes the magnetic field where ρ^t_{xx} is T-independent.

Finally, we convert σ^t_{xx} and σ^t_{xy} into the corresponding resistivities for the topmost Landau levels ρ^t_{xx} and ρ^t_{xy}. Such results are shown in Fig. 4. We can clearly see a clear crossing point in ρ^t_{xx} at around 5.2 T, which is denoted by a vertical dotted line. Such a T-independent point can be ascribed to the formation of the extended states under the existence of the localized states [12]. Since both extended and localized states are due to strong localization effects leading to the IQHE, such effects should become significant when $B \geq 5.2$ T in our system. On the other hand, at $B < 4.76$ T, the validity of the SdH formula reveals that the strength of strong localization is weak. Therefore, the onset of strong localization occurs when $B = 4.76$ T $\sim$ 5.2 T.

It has been pointed out that the strong localization occurs at the magnetic field $B \sim 1/\mu$, near which the localization length changes quickly [16]. As mentioned above, the mobility $\mu = 0.19$ m^2/Vs, and thus the onset of strong localization is expected when $B \sim 5.3$ T. Such a magnetic field is close to the estimation based on the SdH formula and the crossing point in ρ^t_{xx}. We note that the temperature-independent point in ρ^t_{xx} is close to the resistance quantum $\frac{h}{2e^2}$ as expected for the topmost Landau level [12]. In addition, as shown in Fig. 4, ρ^t_{xy} does not deviate much from the expected value $\frac{h}{2e^2}$ at the lowest temperature $T = 0.33$ K when $B < 5.2$ T.

We can see from Fig. 1 that the 2DES behaves as an insulator when $B < B_c \equiv 2.29$ T in the sense that ρ_{xx} increases with decreasing T. The longitudinal resistivity ρ_{xx} is almost independent of T at B_c. Since there is no QH state of the lowest integer filling factor 1 or 2 near B_c, the 2DES undergoes a direct I–QH transition at B_c [13,15]. The filling factor ν is about 8 near B_c, so the observed transition is a 0–8 transition [15,20]. If such a transition is due to the onset of strong localization [16], B_c should be within the range $B = 4.76$–5.2 T, as mentioned above. In our study, however, B_c is at a much lower magnetic field, $B = 2.29$ T. Therefore, the observed direct I–QH transition is not due to the onset of strong localization.

It has been shown that by converting the measured ρ_{xx} and ρ_{xy} into longitudinal and transverse conductivities σ_{xx} and σ_{xy}, one can provide further information on the I–QH transition [11,28]. Fig. 3 shows converted σ_{xx} and σ_{xy} as a function of B. We can see that σ_{xy} is T-independent over a wide range of magnetic field (0 T $\leq B \leq$ 2.8 T), spanning from the insulating region to the QH-like regime. On the other hand, as shown in the inset to Fig. 3, the Hall slope R_H shows an approximately $\ln T$-dependence. The deviation from the linear fit through the full symbols can be ascribed to current heating. As the current is decreased from 20 to 10 nA (full circle in blue), we are able to restore the $\ln T$-dependence at low T [23]. The observed $\ln T$-dependence of R_H does not result from a change in n since n determined from the SdH oscillations is T-independent over the whole measurement range. Therefore, the observed T-independent σ_{xy}, together with the $\ln T$-dependent ρ_{xy}, can be ascribed to electron–electron interaction, and we note that the corrections resulting from such an interaction have been discussed in the literature [29]. Our experimental result therefore supports the direct I–QH transition not always being due to the onset of strong localization when the e–e interaction is significant.

Interestingly, whilst there is a crossing field at B_c in ρ_{xx}, there is no corresponding crossing point in σ_{xx} [30]. The reason for this is that ρ_{xy} shows a logarithmic dependence on T. Therefore, according to Eq. (2), there is no corresponding crossing point in σ_{xx} even when there exists a T-independent point in ρ_{xx}.

To further study the direct I–QH transition and onset of the strong localization leading to the IQHE, we have re-analyzed the data published in [23], where the studied sample is almost identical except there is a different delta-doping concentration of 5×10^{11} cm^{-2}. There also exists a crossing point in ρ^t_{xx} when $B \sim 1/\mu$, near which the onset of strong localization is expected. The direct I–QH transition, however, appears at a much lower magnetic field, $B < 1/(2\mu)$, and does not correspond to the onset of strong localization. Tilted-field measurements show that the sample studied in [23] is two dimensional, such that the direct I–QH transition and features of Landau quantization only depend on the perpendicular component of the applied B.

It has been reported that in some cases when ρ_{xx} approaches zero and strong localization effects may occur, the large resistance oscillations can still be well approximated by the conventional SdH formula [17,18]. In this case, rising background resistance [17] needs to be introduced, while such background resistance does not occur in our system. In our system, the amplitudes of the resistance oscillations are a lot smaller than the non-oscillating background when $B \leq 4.76$ T, under which the resistance minima are much bigger than zero.

Based on the tight-binding model, Nita et al. [31] have predicted that resistance oscillations can cover the I–QH transition.

There also exists experimental evidence for this prediction [32]. We note that, in this case, the e–e interaction effects are not significant since ρ_{xy} is nominally T-independent. It may be possible that the existence of e–e interactions may dictate the observation of SdH-like oscillations spanning from the insulating regime to the QH-like regime.

4. Conclusion

In conclusion, we have performed magneto transport measurements on a weakly disordered 2DES. With increasing magnetic field, the 2DES undergoes a direct 0–8 I–QH transition at a crossing field B_c. For $B > B_c$, magneto-oscillations governed by the conventional Shubnikov–de Haas theory are observed. Since strong localization effects are not considered in the SdH theory, our results explicitly demonstrate that the direct I–QH transition does not correspond to the onset of strong localization. The observed nominally T-independent σ_{xy} spanning from the insulating regime to the SdH regime, together with the observed logarithmic T-dependent Hall slope, demonstrates that electron–electron interactions, rather than the weak localization effects, are the dominant mechanism near the direct I–QH transition in our study.

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