On the low-field insulator-quantum Hall conductor transitions

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We studied the insulator-quantum Hall conductor transition which separates the low-field insulator from the quantum Hall state of the filling factor $\nu=4$ on a gated two-dimensional GaAs electron system containing self-assembled InAs quantum dots. To enter the $\nu=4$ quantum Hall state directly from the low-field insulator, the two-dimensional system undergoes a crossover from the low-field localization to Landau quantization. The crossover, in fact, covers a wide range with respect to the magnetic field rather than only a small region near the critical point of the insulator-quantum Hall conductor transition.
Insulator-quantum Hall conductor (I-QH) transitions have attracted much attention recently [1-10]. These transitions occur when two-dimensional (2D) systems enter quantum Hall states from the insulating state. According to selection rules in the global phase diagram (GPD) suggested by Kivelson, Lee, and Zhang [1], in the integer quantum Hall effect (IQHE) such transitions are between the quantum Hall state of the filling factor \( \nu=1 \) and the insulating state. To enter any integer quantum Hall state from the insulating state, therefore, a 2D system must pass through \( \nu=1 \) quantum Hall state. However, I-QH transitions between \( \nu \geq 3 \) quantum Hall states and the insulating state are observed [2-5]. It is shown by Hanein et al. [11] that the low-field I-QH transitions separating the integer quantum Hall liquid from the low-field insulator, in fact, can be linked to the 2D metal-insulator transition [12], which occurs at a zero magnetic field and is also inconsistent with the GPD.

For convenience, denotes the I-QH transition between the insulating state and the quantum Hall state of the filling factor \( \nu \) as 0-\( \nu \) transition [1,3,5] (Usually the insulating state is denoted by the number “0”). Song et al. [2] claimed that the low-field 0-\( \nu \) transition with \( \nu \geq 3 \) are phase transitions contradicting to the GPD, and the numerical studies [13] show that such transitions can be due to that extended states are destroyed by the disorder at low fields. On the other hand, Huckestein [6] claimed that there is no contradiction and the low-field 0-\( \nu \) transitions with \( \nu \geq 3 \) are only crossovers from weak localization to Landau quantization rather than phase transitions. Huckestein argued that under finite temperatures and/or finite sizes, Landau quantization is important if \( B>1/\mu \) and hence from the Drude model the crossover should occur when

\[
\frac{\rho_{xy}}{\rho_{xx}} \sim (\mu B) \sim 1, \quad \text{(1)}
\]

where \( \mu \) is the mobility. Such arguments can explain why Eq. (1) holds at the critical point of the low-field 0-\( \nu \) transitions with \( \nu \geq 3 \) [2,6]. However, Huang et al. [5] and
Sheng et al. [7] showed that such low-field I-QH transitions can have properties of phase transitions.

To further study the low-field I-QH transition inconsistent with the GPD, we performed a magneto-transport study on the gated 2D GaAs electron system containing self-assembled InAs quantum dots. We identified a crossover from the low-field localization to Landau quantization when the 2D system enters \( \nu=4 \) quantum Hall state directly from the low-field insulator. The point at which \( \rho_{xy}/\rho_{xx}\sim 1 \), is within the crossover as expected. However, such a crossover covers a wide range with respect to the magnetic field rather than only a small region around the critical point of the 0-4 transition. In addition, in our study the critical point of the 0-4 transition is not the point at which \( \rho_{xy}/\rho_{xx}\sim 1 \).

Figure 1 shows the sample structure that was grown by molecular-beam epitaxy on a GaAs (100) substrate and consists of a 20 nm wide GaAs/Al\(_{0.33}\)Ga\(_{0.67}\)As quantum well that is modulation doped on one side using a 40 nm spacer layer. The growth of the GaAs quantum well was interrupted at its center, and the wafer was cooled from 580 °C to 525 °C. The shutter over the indium cell was opened for 80 sec, allowing growth of 2.15 monolayers of InAs capped by a 5nm GaAs layer, and self-assembled InAs quantum dots were formed. The alloy Au/Ni/Cr was deposited onto the surface to serve as the front-gate. In this study, we set the gate voltage \( V_g=-0.07 \) V. Magneto transport measurements were performed with a top-loading He\(^3\) system at temperatures (\( T' \)'s) ranging from 0.52 to 1.6 K in a 15 T superconductor magnet. A phase sensitive four-terminal ac lock-in technique was used with a current of 10 nA. At low temperatures, the sample behaves as an insulator in the sense that the longitudinal resistivity \( \rho_{xx} \) increases as the temperature \( T \) decreases when the magnetic field \( B=0 \). From the low-field Hall measurement and SdH oscillations, the carrier concentration \( n=1.08 \times 10^{11} \text{ cm}^{-2} \).
Figure 2 shows the curve $\rho_{xy}(B)$ at the temperature $T=0.52$ K and the curves of $\rho_{xx}(B)$ at $T=0.52$-1.60 K when the gate voltage $V_g=-0.07$ V. At low magnetic fields, $\rho_{xx}$ increases as $T$ decreases and the 2DES behaves as an insulator. With increasing $B$, SdH oscillations [14] appear when $B > B_s=0.48$ T and $\rho_{xx}$ becomes $T$-independent at the magnetic field $B_c=0.89$ T. The $T$-dependences, in fact, are different on the both sides of $B_c$, and quantum Hall plateaus corresponding to $\rho_{xy}=\hbar/2e^2$ and $\hbar/4e^2$ are observed when $B > B_c$. Therefore, $B_c$ is the critical magnetic field of the I-QH transition to separate the low-field insulator from the quantum Hall liquid, and we can identify $\nu=4$ and 2 quantum Hall states from the corresponding Hall plateaus. [1] In the observed I-QH transition, the 2DES enters the $\nu=4$ quantum Hall state directly from the low-field insulator and hence such a transition is a low-field 0-4 transition, which is inconsistent with the GPD.

In Fig. 2, at higher $B$ the 2DES exhibits features of Landau quantization, including both the SdH oscillations and quantum Hall effect while at lower $B$ it behaves as an insulator due to the low-field localization. Since SdH oscillations and the low-field insulator can be identified when $B > B_s=0.48$ T and $B > B_c=0.89$ T, respectively, the region where $B_s < B < B_c$ correspond to the crossover from low-field localization to Landau quantization. The observations of SdH oscillations in the low-field insulator have also been reported by Smorchkova et al. [15] and Kim et al. [16]. Because we also observed the low-field 0-4 transition, we can examine how the 2DES enters quantum Hall state of $\nu\geq 3$ directly from the low-field insulator in such a crossover. The inset in Fig. 2 shows the curves of $\rho_{xx}$ and $\rho_{xy}$ when $B_s < B < B_c$. We can see that the magnetic field $B_a$, at which Eq. (1) holds, is in the crossover between the magnetic fields $B_s$ and $B_c$ and hence this crossover do occur when $\mu B \sim \rho_{xy}/\rho_{xx} \sim 1$ as argued by Huckestein [6]. However, the critical magnetic field $B_c$ of the 0-4 transition does not correspond to $B_a$, and the crossover region covers 0.41 T in $B$ rather only a
small region near $B_a$ (or $B_c$). From our study, therefore, a 2D system undergoes a crossover from low-field localization to Landau quantization when it enters a quantum Hall state of $\nu \geq 3$ directly from the low-field insulator. Such a crossover, however, can cover a wide range in $B$ rather than a small region near the critical point. At the critical field $B_c$, in fact, in our study the ratio $\rho_{xy}/\rho_{xx}$ is about 1.5 and is larger than 1. We note that as reported by Hilke et al. [17] the criterion $\rho_{xy}/\rho_{xx} \sim 1$ does not hold at the critical point.

In conclusion, we observed a low-field insulator-quantum Hall conductor transition inconsistent with the GPD in the two-dimensional GaAs electron system containing self-assembled InAs quantum dots. To enter a quantum Hall state of $\nu \geq 3$ directly from the low-field insulator, in our study the two-dimensional system undergoes a crossover from the low-field localization to Landau quantization. The point at which $\rho_{xy}/\rho_{xx} = 1$ is located within the crossover as expected. However, such a crossover can cover a wide range with respect to the magnetic field rather than only a small region around the critical point of the I-QH transition. In addition, the point at which $\rho_{xy}/\rho_{xx} \sim 1$ is not the critical point of the I-QH transition.

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Figure Captions

Fig. 1. The structure of the sample.

Fig. 2. The curves of $\rho_{xx}(B)$ at $T = 0.52 - 1.60$ K. The curve $\rho_{xy}(B)$ at $T=0.52$ K.

The inset shows the curves between the magnetic $B_s$ and $B_c$. 
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Fig. 2

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