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From localization to Landau quantization in a two-dimensional GaAs electron system containing self-assembled InAs quantum dots

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We have studied insulator–quantum Hall–insulator (I-QH-I) transitions in a gated two-dimensional GaAs electron gas containing InAs quantum dots. In this system Shubnikov–de Haas oscillations are observed in both the low-field and high-field insulating regimes, showing that Landau quantization and localization *can* coexist. A phase diagram is constructed based on our experimental results, and we see that the critical points of the I-QH-I transitions *do not* correspond to crossover from localization to Landau quantization. Moreover, good scaling behavior is observed on both sides of low- and high-field I-QH transitions.

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Recently there has been a great renewal of interest in magnetic-field-induced transitions in the integer quantum Hall effects.[1–6] According to the scaling theory of localization, in zero magnetic field there are only localized states in a noninteracting two-dimensional (2D) system at low temperatures. In the presence of a strong perpendicular magnetic field the Landau quantization becomes important, causing the formation of Landau levels in a 2D system. The picture of extended states at the Landau-level centers and localized states between Landau levels provides a simple explanation for the quantum Hall effect. The evolution of electronic states from being extended at a strong magnetic field B to being localized at $B=0$ was first explained by Laughlin[7] and Khmelnitskii.[8] It is argued that to be consistent with the scaling theory, the extended states could float up in energy as the magnetic field is reduced. An alternative to this floating-up picture is that the extended states could be destroyed by decreasing the magnetic field or increasing the disorder.[9,10]

To date, an interesting but unsettled issue is whether the observed direct transitions from an insulating state to a high Landau-level filling factor $\nu \geqslant 3$ (Refs. 11–14) are genuine quantum phase transitions. Experimental[11–14] and numerical studies[15] show that such transitions are quantum phase transitions. On the other hand, it is argued that such low-field transition[11–14] is not a phase transition, but can be identified as a crossover from localization to a strong reduction of the conductivity when Landau quantization becomes dominant.[16] Although in the vicinity of a quantum phase transition, it is expected that scaling behavior should occur,[17] inter-Landau level mixing of opposite chirality might affect the scaling behavior.[18]

It is widely accepted that in order to observe insulator–quantum Hall (I-QH) transitions, one needs to deliberately introduce disorder so as to experimentally realize a highly-disordered 2D system. Depositing self-assembled InAs quantum dots in the GaAs well has proved to be a reliable way to controllably introduce short-range repulsive scattering in the two-dimensional electron gas[5] (2DEG). The strain fields due to the self-assembled InAs quantum dots cause strong scattering experienced by the 2DEG, providing the necessary disorder to observe I-QH transitions.[5] In this paper, we report magnetotransport measurements on a gated GaAs electron system containing self-assembled InAs quantum dots. Our results show that Shubnikov–de Haas (SdH) oscillations are observed in both the low-field and high-field insulating regimes, showing that Landau quantization and localization *can* coexist. A phase diagram is constructed based on our experimental results, and we see that the critical points of the I-QH transitions *do not* correspond to crossover from localization to Landau quantization. Moreover, good scaling behavior is observed on both sides of low- and high-field I-QH transitions.

Figures 1(a) and 1(b) show a cross sectional schematic illustration of the sample structure and the corresponding band diagram, respectively. 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 (ML) of InAs. A cap layer of GaAs was grown at 530 °C, before the substrate temperature was raised to 580 °C for the remainder of the growth. In our system, the self-assembled InAs dots act as short-range scattering centers

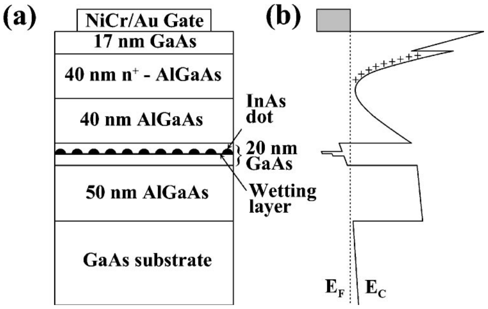

FIG. 1. (a) The cross section of the sample structure. (b) Schematic diagram of the conduction band.

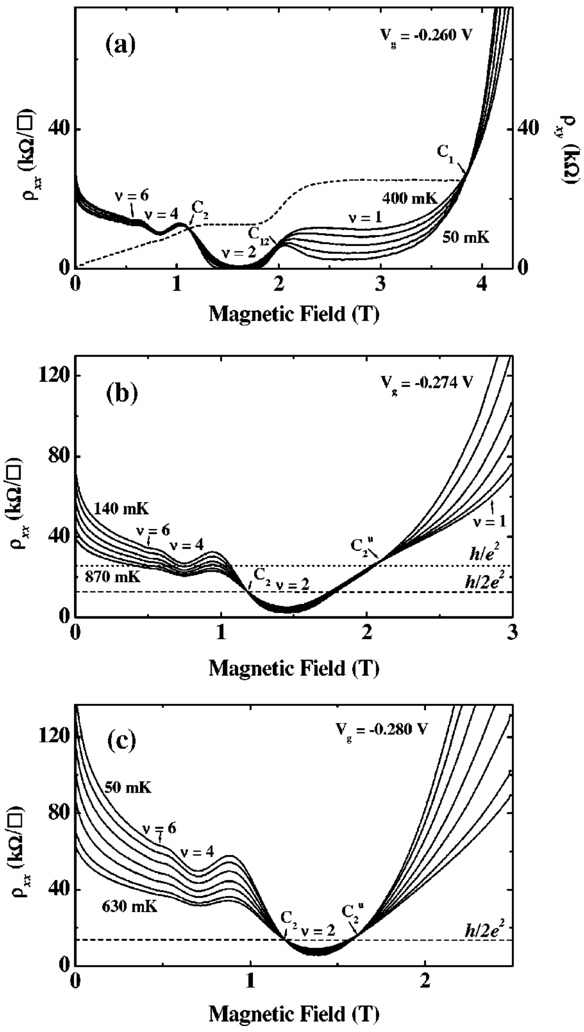

FIG. 2. (a) ρ_{xx} as a function of magnetic field at temperatures 50, 140, 220, 300, and 400 mK. The dotted line shows ρ_{xy} at $T=300$ mK. (b) ρ_{xx} as a function of magnetic field at temperatures 140, 220, 300, 400, 590, and 870 mK. The dotted and dashed lines correspond to $\rho_{xx}=h/e^2$ and $\rho_{xx}=h/2e^2$, respectively. (c) ρ_{xx} as a function of magnetic field at temperatures 50, 140, 220, 300, 400, 590, and 630 mK. The dashed line corresponds to $\rho_{xx}=h/2e^2$.

in the GaAs 2DEG and provide the necessary disorder to observe I-QH transitions. Four-terminal longitudinal (ρ_{xx}) and transverse (ρ_{xy}) resistivity measurements were performed using an excitation current of 2 nA. The 2D carrier density n is varied by applying a negative gate voltage V_g to a gate covering the Hall bar. The ability of electrons to screen out the disorder potential decreases as n is lowered, and therefore V_g can be regarded as a means of varying the effective disorder of the sample, an important parameter in the study of I-QH transitions.[4]

Figures 2(a)–2(c) show longitudinal magnetoresistivity measurements $\rho_{xx}(B)$ over the temperature range $T=50$–870 mK at three different V_g. As V_g is made more negative, the effective disorder within our system increases. Figure 2(a) shows measurements of longitudinal resistivity ρ_{xx} and Hall resistivity ρ_{xy} traces over the temperature range $T=50$–400 mK at $V_g=-0.260$ V. Pronounced minima in $\rho_{xx}(B)$ traces are observed at filling factors $\nu=1$ and $\nu=2$, which are accompanied by QH plateaus in $\rho_{xy}(B)$. The temperature-independent ρ_{xx} at a particular magnetic field and gate voltage V_g is used to identify the boundaries between different QH liquid at filling factor $\nu=1$ and $\nu=2$ and insulating phase. The quantum Hall-insulator transitions are identified by a temperature-independent ρ_{xx} at $B=1.11$ and 3.84 T (labeled C_2 and C_1), respectively. For $B<B_{C2}$, ρ_{xx} increases with decreasing temperature, and hence the sample is always in the insulating phase. Note that the minima in ρ_{xx} corresponding to the filling factors $\nu=4$ and $\nu=6$ are clearly observed.

Figure 2(b) shows well-defined transition points at $V_g=-0.274$ V. We can see temperature-independent points in ρ_{xx} at $B=1.18$ and 2.10 T (labeled C_2 and C_2^u), at which $\rho_{xx}=h/2e^2$ (dashed line) and ρ_{xx} is slightly higher than h/e^2 (dotted line), respectively. $\rho_{xx}(B)$ traces have well developed minima at filling factor $\nu=2$. The $\nu=1$ SdH minimum is barely resolved as indicated by an arrow. With increasing T, ρ_{xx} at $\nu=1$ decreases, characteristics of an insulating phase. The traces of the longitudinal resistivity ρ_{xx} of the sample at $V_g=-0.280$ V and temperature between 50 to 630 mK are shown in Fig. 2(c). From this figure we could find that at $B=1.22$ and 1.59 T, ρ_{xx} are temperature-independent crossing points. These are the critical magnetic fields, C_2 and C_2^u, where the QH transitions take place 0-2-0 with spin-degenerate state. At C_2, ρ_{xx} has a value of $h/2e^2$ and at C_2^u, ρ_{xx} is slightly higher than $h/2e^2$.

We now turn to our main experimental findings. As clearly shown in Figs. 2(a)–2(c), for $B<B_{C2}$ we observe well-resolved minima in ρ_{xx} which correspond to $\nu=4$ and $\nu=6$ due to Landau quantization. For these two minima, ρ_{xx} decreases with increasing temperature T, showing insulating behavior. We note that spin-split SdH oscillations in the insulating phase have been observed in a magnetic 2DEG.[19] The observation of the SdH oscillations in the insulating phase is remarkable. In conventional SdH theory, a SdH minimum increases with increasing temperature T, in contrast to our results. Moreover, since the insulating behavior is due to localization and the observed SdH oscillations at $\nu=6$ and $\nu=4$ arise from Landau quantization, our results clearly show that localization and Landau quantization can coexist. It is worth mentioning that our experimental results are in line with the seminal work of Huckestein.[16] In this work, it is argued that the observed "transition" from an insulating state (0) to a high Landau-level filling factor ($\nu\geqslant 3$) can be ascribed to a crossover from localization to Landau quantization. In our system, we observe the well established 0-2-0 and 0-2-1-0 transitions, consistent with the global phase diagram and the work of Huckestein. Our results explicitly show that the crossover from localization to Landau quantization occurs over a wide range of magnetic field (≈ 0.6 T). Thus the observed well-defined critical points of ρ_{xx} do not correspond to the crossover from localization to Landau quantization when $\rho_{xx}\approx\rho_{xy}$.

By tracing the SdH minima at various filling factor and the temperature-independent points in ρ_{xx} as a function of gate voltage (and hence disorder), we are able to construct a

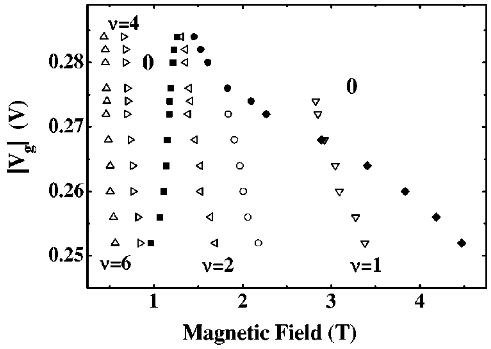

FIG. 3. The phase diagram determined from temperature-independent points and SdH minima in ρ_{xx} traces. Various transitions are marked: 0–2 (solid squares), 2–0 (solid circles), 2–1 (open circles), and 1–0 (full diamonds). Open triangles represent SdH minima at different filling factor $\nu=6,4,2$, and 1, respectively.

phase diagram, as shown in Fig. 3. The solid symbols corresponding to the temperature-independent critical points in ρ_{xx} represent the position of the phase boundaries in the gate voltage (disorder)-B field plane. Conventionally the symbol 0 corresponds to the insulating regime.[4–6] We see 0-2-0 transitions as in Ref. 3,5 between the gate voltage -0.285 V $<V_g\leqslant -0.276$ V and the diagram showing stronger spin splitting for $V_g>-0.274$ V. An insulating phase is observed at gate voltage $V_g<-0.285$ V in the high disorder and beyond the critical field C_1 and C_2^u in the high B field. Most importantly, we can clearly see that SdH minima corresponding to $\nu=6$ and $\nu=4$ are observed in the insulating phase in all cases. In our case, the SdH minima serve as a guide to the eye, and are not related to the phase boundaries. It is worth mentioning that the $\nu=1$ state can be observed both in the insulating phase and the QH state. We only observe a single series of SdH oscillations. Moreover, well-defined critical points of ρ_{xx} which correspond to I-QH transition are observed. All these results suggest that the observed SdH oscillations in the insulating phase, I-QH transitions and the scaling behavior are not due to the nonuniformity of our system. We have also studied a sample which contains one continuous layer of InAs, being below the critical coverage required for the onset of Stranski-Krastinow growth. We do not observe I-QH transitions and SdH oscillations in the insulting phase in this sample in which no self-assembled InAs dots are formed. At $T=1.6$ K, the resistivity of this sample is about ten times smaller than that of the sample containing self-assembled InAs quantum dots. This result clearly demonstrates that our sample which contains InAs dots is much more disordered than the sample with an InAs wetting layer. It is expected that the strain field emanating from the uniform InAs layer does not cause variation of the potential in the plane of the 2DEG. Therefore we believe that the scattering introduced by the self-assembled InAs dots provides the necessary disorder to observe the coexistence of Landau quantization and localization in our system.

It is known that in order to observe I-QH transitions, one needs to experimentally realize a highly-disordered 2D system. For example, in the pioneering work of Jiang *et al.*, no undoped spacer is used in order to ensure large random fluctuations of the impurity potential. In our work, we use a different method by depositing InAs quantum dots in the center of the GaAs quantum well. In this case, the self-assembled InAs dots act as scattering centers in the GaAs 2DEG. It is thus interesting to compare our results with those obtained from "conventional" disordered 2D systems. Compared with the work of Hughes *et al.*,[3] our system allows us to study the same I-QH-I (0-2-0) transition at much lower magnetic fields. Moreover, our system is of lower disorder compared with the work of Jiang *et al.*[1] and Wang *et al.*,[2] allowing us to observe the 0-2-1-0 transition when spin-splitting is resolved. In comparison with the other GaAs system which shows the 0-2-1-0 transition, we are able to see SdH oscillations in the insulating phase which is not observed in the system studied by Shahar *et al.*[4] In the work of Smorchkova and co-workers,[19] well-defined I-QH transitions are observed. They also observe the coexistence of Landau quantization and localization. However, there is a huge positive magnetoresistance at low fields ($B\approx 0.1$ T), in contrast to a negative magnetoresistance observed in our system. Moreover, since Smorchkova *et al.*[19] observe spin-split SdH oscillations, the spin effect is believed to play an important role in their system. In our system the coexistence of localization and Landau quantization is not related to spin splitting since we observe spin-degenerate SdH oscillations in the insulating phase.

It has been shown[2] that for the QH transitions, $\rho_{xx}=f[(B-B_c)T^{-\kappa}]$ near the transition points and

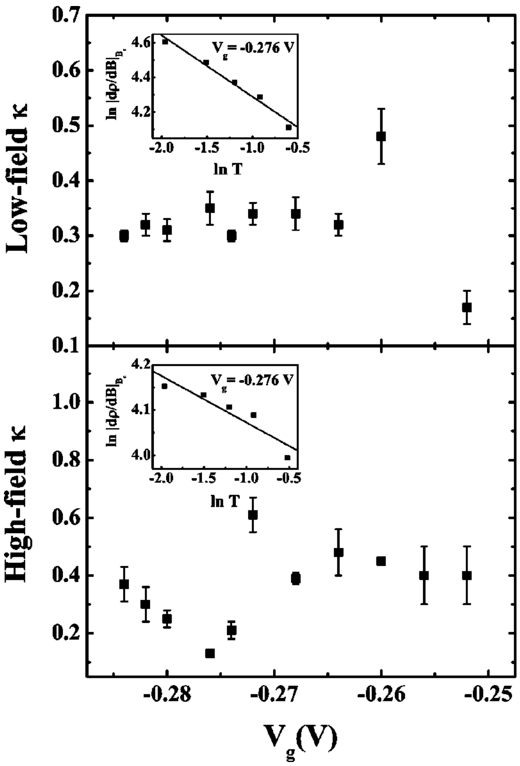

FIG. 4. Experimentally determined κ values for (a) low-field and (b) high-field transitions at different gate voltages. The insets show the scaling fits to obtain κ both in the low- and high-field regimes for $V_g=-0.276$ V.

$|d\rho_{xx}/dB|_{B=B_c} \propto T^{-\kappa}$, where κ denotes the critical exponent. By plotting $\ln|d\rho_{xx}/dB|_{B=B_c}$ vs $\ln T$, we could obtain κ. The insets to Fig. 4 show the scaling fits to obtain κ both in the low- and high-field regimes for $V_g = -0.276$ V. We note that in a spin-degenerate system and in a spin-split one, κ is expected to be 0.21 (Refs. 2,20,21) and 0.42 (Refs. 22,23), respectively. Figure 4 shows the determined κ for both the low- and high-field transitions at different gate voltages. For $V_g = -0.256$ V, the critical field occurs at a maximum in ρ_{xx}. In this case, $|d\rho_{xx}/dB|_{B=B_c} \rightarrow 0$ so that we cannot determine κ for the low-field transition. Except for $V_g = -0.252, -0.256$, and -0.260 V, the critical exponents are close to 0.3 for low-field transitions. For the high-field transitions, κ appears to show large deviation from the expected value for a spin-split case (0.42) at $V_g = -0.264$ V and $V_g = -0.272$ V. κ also shows large deviation from the expected value for a spin-degenerate case (0.21) at $V_g = -0.276$ V, $V_g = -0.282$ V, and $V_g = -0.284$ V.

In summary, we have presented low-temperature transport measurements on a gated GaAs electron system containing self-assembled InAs quantum dots. Our results show that SdH oscillations can occur in the insulting phase, showing that Landau quantization and localization can coexist. A phase diagram is constructed based on our experimental data and from which we see that the critical points in the I-QH transitions do not correspond to crossover points from localization to Landau quantization. Moreover, our experimental data show good scaling behavior in the vicinity of both the low- and high-field I-QH transitions. Our results challenge conventional understanding of Landau quantization and phase transitions in two dimensions and thus urge further studies in these two areas.

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