Magnetic-field-induced phase transitions in a Si/SiGe hole system

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Seminal theoretical work on the integer quantum Hall effect describes a two-parameter scaling [1] in which both the dissipative conductance \( \sigma_{xx} \) and the Hall conductance \( \sigma_{xy} \) vary with the sample length \( L \). The renormalisation-group function can be illustrated by flow lines. After successive length-scale transformation the flow lines are directed towards fixed points \((\sigma_{xx}, \sigma_{xy}) = (0,0)\) (in units of \( e^2/h \)) in which \( n = 0,1,2,... \) is the Landau level index. In addition to these “localization fixed points” which describe the localisation of the electron wavefunctions near the Fermi energy, there are “intermediate-coupling fixed points” on \( \sigma_{xy} = n + 1/2 \) which are related to transitions between quantum Hall states. Note that this theory was developed for zero temperature \( T = 0 \) and the length scale transformations are accomplished by varying the sample length \( L \). It has been shown that, in practice, the effective sample size can be varied by changing the temperature [2]. The studies of the “temperature-driven flow lines” in GaAs systems and more recently in Ge/SiGe systems [3] support the two-parameter scaling theory of Pruisken [1].

Recently there has been a great deal of interest in Si/SiGe hole systems. For example, at a Landau level filling factor \( \nu = 1.5 \), an insulating phase observed in such a system is not fully understood at present. It is called a “Hall insulator” since although \( \rho_{xx} \) approaches infinity, the Hall resistivity remains finite at approximately \( h/(2e^2) \). This magneto-driven transition within the global phase scheme of Kivelson, Lee and Zhang. Moreover, or a Si/SiGe hole gas, the observed quantum Hall states are off odd filling factors at low magnetic fields, indicating that spin-splitting is comparable with the spacing between adjacent Landau levels. This provides an interesting system for the study of magnetic-field-induced transitions in the quantum Hall effect. In this paper, we present low-temperature transport measurements on a Si/SiGe hole system. In particular we report a study of the temperature-driven flow lines in the vicinity of the “Hall insulator” regime. We also observe magnetic-field-induced phase transitions which correspond to the temperature-independent points in \( \sigma_{xx} \) as shown in figure 1.

The temperature-driven flow lines are complicated thus we divided our results into four parts as shown in Fig. 2(a)-(d). It is evident that \((\sigma_{xx}, \sigma_{xy}) = (1,0)\) for \( \nu \to 1 \), as illustrated by the \( T \)-driven flow lines as shown in Fig.2(a). Figure2 (b) and 2 (c) show the \( T \)-driven flow diagrams near the two critical points \( B_{B1} = 8.1 \) T and \( B_{B2} = 9.8 \) T, respectively. It is evident that \((\sigma_{xx}, \sigma_{xy}) = (0,0)\) as \( T \to 0 \) for the “Hall insulator” since \( \rho_{xx} \) approaches infinity whereas \( \rho_{xy} \) remains finite. We can clearly see that the directions of the flow lines in the “Hall insulator” are different from those near a quantum Hall state. \( B_{B2} \), labelled as full squares, is, in fact, the boundary of the “Hall insulator” as well as the intermediate-coupling fixed point. It is worth mentioning that near \( B_{B1} \), \( \rho_{xy} \) slowly varies at different temperatures. Thus, although \( B_{B1} \) corresponds to the boundary of the “Hall insulator” regime, the intermediate-coupling fixed point is estimated to be at around \( B = 8.2 \) T, \( \sim 0.1 \) T higher than \( B_{B1} \). To the right of this fixed point, the flow lines all show a “kink”. In contrast, to the left of the fixed point, the lines flow directly \((0,0)\) as \( T \to 0 \). The main finding is that, in contrast to a single intermediate-coupling fixed point between neighboring quantum Hall states previously predicted and observed, there are two intermediate-coupling points in a SiGe hole system. The reason for this is the existence of the “anomalous Hall insulator” near \( \nu = 1.5 \). Figure 2(d) shows the \( T \)-driven flow lines for 2<\( \nu <3 \). At around \( A_{2} \), the directions of the \( T \)-driven flow lines seem ambiguous. At present, the physical origin of this effect is not fully understood and awaits further experimental and theoretical investigations. Our new experimental results on \( T \)-driven flow lines, together with the pioneeering work on the “Hall insulator” urge further investigations in order to understand the physical origin of this “anomalous insulating state”.

References:
Figure 1. Conductivity $\sigma_{xx}$ and $\sigma_{xy}$ at various temperatures.

Figure 2 (a)-(d) Temperature-driven flow lines between 1 < $\nu$ < 3. The arrows indicate the directions of the flow lines (From high-T to low-T) and the full squares correspond to intermediate-coupling fixed points. The dotted line represents $\sigma_{xx}(\sigma_{xy})$ at $T = 0.3$ K.