Temperature induced transitions between insulator, metal, and quantum Hall states

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Abstract

We report the observation of temperature induced transitions between insulator, metal, and quantum-Hall behaviors for transport coefficients in the very dilute high mobility two-dimensional electron system in silicon at a magnetic field corresponding to Landau level filling factor $\nu = 1$. Our data show that as the temperature decreases, the extended states at $\nu = 1$ (above the Fermi level at higher temperature so that the system is insulating) sink below the Fermi energy, so that the quantum Hall effect occurs. As the extended states cross the Fermi level, the conductivity has a temperature dependence characteristic of a metallic system.

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In the study of two dimensional electron systems (2DES), there have been considerable interest in transitions between insulating and quantum Hall (QH) states. Thus far such transitions have only been observed as the magnetic field and/or the electron density are changed. However, in this paper we present experimental evidence that transitions between insulator, metal, and QH-like behaviors for transport coefficients can also be observed at fixed field and carrier density as the temperature is decreased. In particular, we have observed 2DES delocalization (insulator to metal transition) with decreasing temperature, whereas increasing localization is the usual consequence of lowering the temperature for a 2DES.

It was reported recently both for high-mobility silicon inversion layers [1] and for low-mobility GaAs/(Al,Ga)As heterostructures [2] that 2DES, strongly localized in zero magnetic field ($B = 0$), can nevertheless manifest the integer QH effect. References [1] discuss this magnetic-field-induced transition from a many-body point of view, whereas Refs. [2] ignore the effects of electron-electron interactions and consider the arguments of Khmelnitskii [7] and Laughlin [8] along with the global phase diagram proposed by Kivelson, Lee, and Zhang [9] as the basis for the insulator-QH transition. According to Refs. [7,8], extended states, which lie above the Fermi energy ($E_F$) at $B = 0$ (i.e. making the system insulating) decrease in energy as $B$ is increased [see inset in Fig. (a)] and may sink below $E_F$. At zero temperature, the diagonal conductivity ($\sigma_{xx}$) is zero except when extended states are at $E_F$. As long as $E_F$ lies below the lowest extended state, the Hall conductivity ($\sigma_{xy}$) is also zero and the system is insulating. For each band of extended states below $E_F$, $\sigma_{xy}$ increases by $e^2/h$, providing the next integer QH state. In high magnetic fields, the extended states approximately follow half-filled Landau levels with filling factors $\nu = n_s/(eB/c) = 1/2, 3/2, 5/2$ etc (here $n_s$ is the electron density, $e$ is the electron charge, $c$ is the speed of light, and $h$ is the Plank constant). If temperature is not zero, $\sigma_{xx}$ usually displays activated behavior except when there are extended states at $E_F$ with the activation energy equal to the energy difference between $E_F$ and the nearest extended state.

Magnetic-field-induced transitions between insulating and QH groundstates have also been investigated in very dilute high-mobility GaAs/(Al,Ga)As heterostructures in the ex-
treme quantum limit (see, e.g., Ref. [12] and references therein) and in Si inversion layers around \( \nu = 1, 2, \) and 6 (Ref. [4,5]). In some papers [1,4,13,15] the fact that the insulating state can be disrupted by integer or fractional QH resistivity minima was discussed in terms of the formation of a pinned electron solid melting at integer or fractional \( \nu \). However, the global phase diagram [9] can also explain magnetic-field-induced transitions between QH (at \( \nu = 1, 1/3, \) or 1/5) and insulating groundstates without invoking collective effects; though, recently observed direct transitions from \( \nu = 2/7 \) and 2/5 (Refs. [15,16]) and \( \nu = 6 \) (Ref. [6]) to insulating states are contradictions of the global phase diagram. At very low \( n_s \), the QH effect breaks down even at integer or fractional \( \nu \); nevertheless \( \rho_{xx} \) still has minima at these filling factors.

Here we consider the \( \nu = 1 \) integer QH effect at the border of it’s existence, at very low \( n_s \). There is definitely no electron solid for these conditions. We report experimental evidence for transitions from insulating to metallic and QH types of behavior of transport coefficients at constant filling factor \( \nu = 1 \) as the temperature is varied. We will define a system as insulating if its conductivities exhibit insulator-like temperature behavior, i.e., \( d\sigma_{xx}/dT, d\sigma_{xy}/dT > 0 \) with \( \sigma_{xy} < \sigma_{xx} < e^2/h \). Similarly we define “metallic” behavior as \( d\sigma_{xx}/dT, d\sigma_{xy}/dT < 0 \). Finally, a QH state is characterized by \( \sigma_{xy} \rightarrow e^2/h \) and \( \sigma_{xx} \rightarrow 0 \) as the temperature is lowered. The observed transitions from insulating behavior can be explained by assuming that at \( \nu = 1 \), the lowest band of extended states, which lies above the Fermi energy at high temperature as expected for an insulator, drops as the temperature is lowered. The system behaves as a metal as it passes through the Fermi level, and finally displays the QH effect after the band of extended states sinks below \( E_F \).

Two samples from wafers with different mobilities have been studied: Si-14, which has a maximum mobility \( (\mu_{\text{max}}) \) of \( 1.9\times10^4 \) cm\(^2\)/Vs, and Si-22, which has \( \mu_{\text{max}} = 3.5\times10^4 \) cm\(^2\)/Vs. The samples are rectangular with a source to drain length of 5 mm, a width of 0.8 mm, and an intercontact distance of 1.25 mm. Resistances were measured using a four-terminal low-frequency (typically 8 Hz) AC technique using cold amplifiers with input resistances \( > 10^{14} \) \( \Omega \) installed inside the cryostat. The output of these amplifiers was connected to a
standard lock-in amplifier. Great care was taken to ensure that all data discussed here were 
obtained where the $I - V$ characteristics are linear.

The dependencies of $\rho_{xx}$ and $\rho_{xy}$ (both are in units of $h/e^2$) on magnetic field for three 
different temperatures are shown in Fig. 1 (a). At the highest temperature, $\rho_{xx}(B)$ is flat 
up to $B \approx 4$ T and lies well above $h/e^2$. As the temperature decreases, minima near integer 
filling factors $\nu = 1$ and 2 and maxima at intermediate filling factors $\nu \sim 1.5$ and 2.7 appear. 
The Hall resistance is almost $T$-independent; at low temperature, narrow QH plateaux start 
to develop near $\nu = 1$ and 2 [17]. Note that as the temperature is decreased from 1.82 K 
to 942 mK, $\rho_{xx}$ at $\nu = 1$ decreases while remaining larger than $\rho_{xy} = h/e^2$; this corresponds 
to $d\sigma_{xx}/dT < 0$ characteristic of a metallic state and reflects delocalization with decreasing 
temperature, whereas $\rho_{xx}$ increases at $B = 0$, indicating an insulating groundstate. At still 
lower temperature, $\rho_{xx}$ at $\nu = 1$ sinks below $\rho_{xy} = h/e^2$ penetrating into the QH region.

Before proceeding further, we must demonstrate that the observed metallic-like decrease 
in $\rho_{xx}$ near $\nu = 1$ is a fundamental effect of the whole 2DES and not an artifact of special 
current paths such as, e.g., edge currents [18]. Furthermore, in principle the current dis-
tribution in a 2DES at low temperatures can be inhomogeneous. If this is the case, it is 
difficult to draw conclusions about the behavior of $\sigma_{xx}$ using $\rho_{xx}$ data. To check these points 
and to obtain information about $\sigma_{xx}$ directly, we have measured the impedance between the 
2D channel and the metallic gate using an $RC$ bridge. The real part of the bridge imbal-
ance signal is proportional to inverse $\sigma_{xx}$ averaged over the sample area. The magnetic field 
dependence of the signal proportional to $\sigma_{xx}^{-1}$ is shown in Fig. 1 (b). One can see that it is 
qualitatively similar to $\rho_{xx}(B)$ as expected for the case of $\rho_{xx} > \rho_{xy}$. [For “normal”, high-$n_s$ 
QH effect, where $\rho_{xx} < \rho_{xy}$, the dependence is qualitatively different: at integer filling factors 
$\nu = 1$ and 2, $\sigma_{xx}^{-1}$ has extreme maxima instead of minima, see Fig. 1 (b) inset]. Again, as the 
temperature is lowered, $\sigma_{xx}$ increases at $\nu = 1$, showing metallic behavior, and decreases at 
$B = 0$, showing insulating behavior. The similarity of the independently determined $\rho_{xx}(B)$ 
and $\sigma_{xx}^{-1}(B)$ shows that the current distribution can be considered homogeneous and that 
we can therefore calculate $\sigma_{xx}$ and $\sigma_{xy}$ from the data for $\rho_{xx}$ and $\rho_{xy}$. 

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Figure 2 shows the temperature dependence of $\rho_{xx}$ at $\nu = 1$ for four different electron densities. For the lowest $n_s$, $\rho_{xx}(T)$ always lies above $h/e^2$ and monotonically increases as the temperature is decreased showing an activated temperature behavior (see inset). On the other hand, for the highest electron density, $\rho_{xx}$ always lies below $h/e^2$ and monotonically decreases as the temperature is decreased below $T \approx 3$ K showing QH type of behavior. But for the two middle $n_s$, $\rho_{xx}(T)$ are nonmonotonic, increasing exponentially at high temperatures (see inset) and decreasing at lower ones. This nonmonotonic behavior implies, as shown below, temperature induced transitions from insulator-like to metallic and QH types of behavior.

The temperature dependencies of $\sigma_{xx}$ and $\sigma_{xy}$, computed from the data for $\rho_{xx}$ and $\rho_{xy}$, are shown in Fig. 3. Figure 3 (a) shows temperature behavior of $\sigma_{xx}$ and $\sigma_{xy}$ for the case of “ordinary”, “high-$n_s$” QH effect. Diagonal conductivity, which is always less than $e^2/2h$, monotonically decreases, and $\sigma_{xy}$, which is always higher than $e^2/2h$, monotonically increases as the temperature is decreased. Neither metallic nor insulator-like behavior is observed at $n_s \gtrsim 1.3 \times 10^{11}$ cm$^{-2}$ for any temperature. However, at slightly lower electron density [Fig. 3 (b)], both components of conductivity are no longer monotonic functions of $T$:

(i) at $T \gtrsim 2.5$ K (to the left of the first vertical dotted line), $\sigma_{xy} < \sigma_{xx} < e^2/h$ and both diminish with diminishing $T$ which is characteristic for an insulating state. Furthermore, according to Khmelnitskii [2], $\sigma_{xy}$ in units of $e^2/h$ is a “counter” of the number of bands of extended states below $E_F$, and because $\sigma_{xy} \ll e^2/2h$ at $T \gtrsim 2.5$ K, there are no extended states below $E_F$ which confirms an insulating state in this temperature region.

(ii) at $1 \lesssim T \lesssim 2.5$ K (between the two vertical dotted lines), both $\sigma_{xx}$ and $\sigma_{xy}$ increase with decreasing $T$, indicating “metallic” behavior. Both also reach $e^2/2h$, the value expected for an extended state ($\sigma_{xx}^0 \sim \sigma_{xy}^0 = e^2/2h$ at $\nu = 1/2$ and $T = 0$ [19]).

(iii) below $T \approx 1$ K (to the right of the second dotted line), $\sigma_{xx}$ again tends to zero as $T \to 0$ while $\sigma_{xy}$ approaches $e^2/h$. The value of $\sigma_{xy}$ now corresponds to one band of extended states below $E_F$; this is a QH state.
At even lower $n_s$ [Fig. 3 (c)], both $\sigma_{xx}(T)$ and $\sigma_{xy}(T)$ change their slope from “insulator-like” to the “metallic” at $T \approx 1$ K but $\sigma_{xy}$ always remains $< e^2/2h$ and the QH conditions are never obtained for this $n_s$. Finally, for the lowest $n_s$ [Fig. 3 (d)], both $\sigma(T)$ decrease monotonically down to the lowest temperatures while $\sigma_{xy} < \sigma_{xx} < e^2/h$; for this $n_s$, the system always remains insulating. In summary, for $n_s \gtrsim 1.3 \times 10^{11}$ cm$^{-2}$ we have observed that the system remains in the QH state regardless of temperature. For $n_s = 9.5 \times 10^{10}$ cm$^{-2}$, we have observed three different types of behavior at $\nu = 1$: insulator-like at higher temperatures, metallic at intermediate, and QH at $T \to 0$. For lower $n_s = 8.6 \times 10^{10}$ cm$^{-2}$, we have observed a transition from insulating to metallic types of behavior without a further transition to QH behavior. For even lower $n_s = 8.1 \times 10^{10}$ cm$^{-2}$, the system remains insulating.

We can understand this effect phenomenologically by examining the position of the energy of the lowest extended state at $T = 0$. According to Refs. [7,8], this is

$$E_c = \frac{1}{2} h\Omega_c \left[ 1 + (\Omega_c \tau)^{-2} \right],$$

(1)

where $\Omega_c$ is the cyclotron frequency and $\tau$ is the relaxation time. Therefore, at constant $B$ ($\Omega_c = \text{const}$), $E_c$ increases with decreasing $\tau$, i.e., with increasing disorder. Our data show that at $\nu = 1$, the effect of temperature is qualitatively similar to the effect of disorder: with decreasing temperature, the energy of the lowest band of extended states decreases. At high $T$, there are no extended states below the Fermi energy, and conductivity is due to temperature activation to the nearest extended state. At lower temperatures, the band of extended states crosses the Fermi level, and we observe a metallic state with characteristic metallic temperature dependencies for both diagonal and Hall conductivities. At still lower temperatures, the band of extended states sinks below the Fermi energy, $\sigma_{xy}$ approaches $e^2/h$, and the system enters the QH regime.

Summarizing, we have studied the temperature dependent behavior of the very dilute 2D electron system in silicon at fixed filling factor $\nu = 1$. We have obtained experimental evidence that at $\nu = 1$, the energy of the lowest band of extended states decreases relative
to the Fermi energy as the temperature is decreased. As a result, this band passes through
the Fermi energy, causing transitions from insulator-like to metal-like and metal to QH-like
temperature dependencies of transport coefficients. The first of these transitions reflects
delocalization with decreasing temperature; this is in sharp contrast to “normal” situation
in which lowering the temperature makes a 2DES more localized.

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FIGURES

FIG. 1. (a) Diagonal and Hall resistivity of sample Si-14 in units of $h/e^2$ vs magnetic field at three temperatures and $n_s = 9.1 \times 10^{10}$ cm$^{-2}$. The inset schematically shows the expected behavior of extended states in a magnetic field [7,8]; (b) Inverse $\sigma_{xx}$ of sample Si-22 obtained by impedance measurements vs magnetic field at two temperatures and $n_s = 7.8 \times 10^{10}$ cm$^{-2}$. The inset shows a “conventional” $\sigma_{xx}(B)$ for higher electron density, $n_s = 1.56 \times 10^{11}$ cm$^{-2}$.

FIG. 2. Temperature dependence of diagonal resistivity of Si-14 at $\nu = 1$ for four electron densities. Inset shows activated temperature dependence of $\rho_{xx}$ at higher temperatures for the same sample.

FIG. 3. Temperature dependence of diagonal and Hall conductivities for sample Si-14 at $\nu = 1$ for four different $n_s$. Open symbols correspond to $\sigma_{xy}$, closed - to $\sigma_{xx}$. Vertical dotted lines approximately separate different kinds of temperature behavior.