Destruction of the quantum Hall effect with increasing disorder

J. E. Furneaux, S. V. Kravchenko, Whitney E. Mason, and G. E. Bowker

Laboratory for Electronic Properties of Materials and Department of Physics and Astronomy,
University of Oklahoma, Norman, Oklahoma 73019

V. M. Pudalov

Institute for High Pressure Physics, Troitsk, 142092 Moscow district, Russia

Abstract

We report experimental studies of disorder-induced transitions between quantum-Hall, metallic, and insulating states in a very dilute two-dimensional electron system in silicon at a magnetic field corresponding to Landau level filling factor $\nu = 1$. At low disorder, the lowest extended state at $\nu = 1$ is below the Fermi energy so that the system is in the quantum Hall state. Our data show that with increasing disorder (but at constant electron density and magnetic field), the extended state does not disappear but floats up in energy so that the system becomes insulating. As the extended state crosses the Fermi energy, the conductivity $\sigma_{xx} \sim e^2/2h$ has temperature dependence characteristic of a metallic system.

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It is widely accepted (see, e.g., [1]) that in a low-disordered two-dimensional electron system (2DES), in a quantizing magnetic field, there exist extended states at the center of each Landau level. However, in the “dirty” case, when $\omega_c \tau < 1$ (here $\omega_c$ is the cyclotron frequency and $\tau$ is the electron lifetime), no extended states are expected below the Fermi level. Khmelnitskii [2] and Laughlin [3] theoretically predicted that the extended states “float up” in energy with decreasing $\omega_c \tau$:

$$E_i = (i + \frac{1}{2}) \hbar \omega_c \left[ 1 + (\omega_c \tau)^{-2} \right]. \quad (1)$$

Here $E_i$ is the energy of the $i$-th extended state. This behavior of the extended states is shown schematically in the inset to Fig. 1.

Recent experiments by Shashkin et al [4] made with Si metal-oxide-semiconductor field-effect transistors (MOSFET’s) showed that the extended states indeed float up when magnetic field, $B$, is decreased at a constant electron density, $n_s$ (and therefore approximately constant disorder and $\tau$). Contrary to theoretical predictions, however, $E_i$ did not increase indefinitely; instead, at $B \rightarrow 0$, the extended states corresponding to different Landau levels coalesced into a band of extended states at some finite energy. Experiments further confirming the floating up of the extended states associated with Landau levels were also made by Jiang et al [5] and Wang et al [6] with gated GaAs/AlGaAs heterostructures and by Okamoto, Shinohara, and Kawaji in Si MOSFET’s [7]. In these experiments, both electron density (and hence disorder) and magnetic field were changed simultaneously so that the Landau filling factor, $\nu = n_s/n_B = n_s/(eB/c)$, remained constant (here $n_B$ is the Landau level degeneracy number, $e$ is the electron charge, $B$ is magnetic field, $c$ is the speed of light, and $\hbar$ is Planck’s constant). Therefore, the theoretical prediction that extended states will float up with decreasing magnetic field at constant or increasing disorder has been experimentally confirmed.

However, it is not clear what the effect of disorder on the extended states is when electron density and magnetic field are constant. In this situation the extended states may either become localized or they may float through the Fermi level in agreement with theoretical
predictions [2,3]. In the first case, if the extended states become localized ("die") below the Fermi level, $\sigma_{xx}$ should monotonically decrease to zero as the disorder increases and always have a temperature dependence characterized by $d\sigma_{xx}/dT > 0$. In the second case, if the extended states float up, the diagonal conductivity, $\sigma_{xx}$, should have a maximum corresponding to the conductivity of the extended state ($\text{i.e.}, \sim e^2/h$ [9]) when the extended state passes through the Fermi level. Here the temperature dependence of $\sigma_{xx}$ should be characteristic for a metallic system, $\text{i.e.}, d\sigma_{xx}/dT < 0$. Away from this maximum, $\sigma_{xx}$ should decrease sharply: In the QH regime, when the extended states lie below the Fermi level, and in the insulating regime, when they lie above $E_F$, there are no extended states at the Fermi level; therefore, $d\sigma_{xx}/dT > 0$ and $\sigma_{xx} \rightarrow 0$ as $T \rightarrow 0$.

Here we report experimental data consistent with the second type of behavior. We have studied the integer QH effect at the border of its existence, at very low $n_s$. For consistency with the proposed global phase diagram for the integer QHE [3] shown in Fig. 1, we have confined ourselves to Landau level filling factor $\nu = 1$. For this phase diagram, Fig. 1, there is a maximum amount of disorder above which the QHE no longer exists at a given magnetic field and electron density. Studying a number of samples with different amounts of disorder, we were able to observe the QHE-to-insulator transition as a function of disorder at constant $n_s$ and $B$, as illustrated by the arrow in Fig. 1. We have found that $\sigma_{xx} \rightarrow 0$ on both sides of the transition, while between the QHE and insulating regimes, $\sigma_{xx}$ has a maximum of $e^2/2h$ corresponding to the extended states at the Fermi level, and its temperature dependence is characteristic of a metallic system. Hall conductivity, $\sigma_{xy}$, was found to be close to 0 on the insulating side of the transition and to approach $e^2/h$ on the QHE side. According to Khmelnitskii [2], $\sigma_{xy}$ in units of $e^2/h$ is a “counter” of the number of extended states below the Fermi level; further evidence that there are no extended states below $E_F$ on the insulating side of the transition and there is one extended state below $E_F$ on the QHE side.

Samples studied were silicon MOSFET’s from wafers with different mobilities. All of them were rectangular. One set of samples had a source to drain length of 5 mm, a width of
0.8 mm, and an intercontact distance of 1.25 mm; another set had corresponding dimensions 2.5 mm, 0.25 mm, and 0.625 mm. Resistances were measured using a four-terminal DC technique including cold amplifiers with input resistances $> 10^{14}$ Ω. Great care was taken to ensure that all data discussed here were obtained where the $I-V$ characteristics are linear.

To characterize the disorder strength, we measured the diagonal and Hall resistivities, $\rho_{xx}$ and $\rho_{xy}$, at $\nu = 1$ and at relatively high temperature $T = 4$ K where the quantum Hall effect does not exist at the electron densities studied in these experiments, and where $\rho_{xx}$ is independent of $B$ for $B \leq B_{\nu=1}$. Then $\omega_c \tau^*$ was calculated as $\rho_{xy}/\rho_{xx} = \mu B$ (here $\mu$ is mobility). Of course this procedure only gives an approximate value for $\tau$ because there is still a weak residual temperature dependence. Thus, we label it $\tau^*$. However, we feel this is a reasonable and consistent way to characterize the disorder quantitatively because $\tau^*$ is a monotonic function of the strength of the disorder and because the value of $\tau^*$ determined in this way is free of quantum corrections.

Figure 2 shows typical temperature dependencies of the diagonal resistivity for constant Landau filling factor $\nu = 1$. One set of data (open symbols) was obtained at $B = 3.95$ T using 3 different samples with different strengths of disorder; another set of data (closed symbols) corresponds to $B = 3.6$ T. The two highest curves have temperature dependencies characteristic of insulators; the two lowest curves correspond to the QH state. The middle curve has almost no temperature dependence. This figure is very similar to Fig. 4 in Ref. [5] which shows $R_{xx}(T)$ for $\nu = 2$ in a GaAs/AlGaAs sample at very low electron densities. The essential difference here is that each set of data was obtained at both constant $B$ and constant $n_s$; only disorder was changed.

Diagonal and Hall conductivities, $\sigma_{xx}$ and $\sigma_{xy}$, recalculated from these and analogous data, are shown in Fig. 3 as functions of $\omega_c \tau^*$. The Hall resistivity, necessary for these recalculations, at $\nu = 1$ was always equal to $h/e^2$ independent of temperature and disorder as was reported in many papers [10–14]. We do not repeat the results for $\rho_{xy}$ here. Each symbol corresponds to the same $B$ and $n_s$ (for example, there are four diamonds which means that four samples with different strengths of disorder were studied at magnetic field
$B = 3.6 \text{T at constant } n_s \text{ corresponding to } \nu = 1)$. One can see that $\sigma_{xx}$ as a function of $\omega_c \tau^*$ reaches a maximum of $e^2/2h$ at $\omega_c \tau^* \approx 0.45$ and approaches zero both for higher and lower values of $\omega_c \tau^*$. We have too few samples to determine completely $\sigma_{xx}(\omega_c \tau^*)$ and $\sigma_{xy}(\omega_c \tau^*)$ using data at only one value of $B$ and $n_s$. Therefore, we use data from six different values of $B$ and $n_s$ to produce the complete dependencies. We note that the qualitative trends are clear for each set of data. Temperature dependence of $\sigma_{xx}$ for one point on this maximum (corresponding to $\omega_c \tau^* = 0.46$) is characteristic of a metallic system ($d\sigma_{xx}/dT < 0$) as shown by open circles in the inset in Fig. 2. In contrast, temperature dependencies of $\sigma_{xx}$ for higher or lower $\omega_c \tau^*$ are characteristic of insulating or QHE states with $d\sigma_{xx}/dT > 0$ (closed symbols on the same inset). Hall conductivity, shown in Fig. 3 (b), is close to zero at $\omega_c \tau^* \lesssim 0.35$, then it sharply grows and approaches $e^2/h$ at $\omega_c \tau^* \gtrsim 0.5$. According to Khmelnitskii [2], this behavior corresponds to one extended state below the Fermi level at $\omega_c \tau^* \gtrsim 0.5$ (QH state) and no extended states below the Fermi level at $\omega_c \tau^* \lesssim 0.35$ (insulating state).

We must note that these dependencies of $\sigma_{xx}$ and $\sigma_{xy}$ on $\omega_c \tau$ are very similar to those reported by Okamoto, Shinohara, and Kawaji [7] though in our case, the transition from insulating to QH regime is sharper. Again we emphasize that in our case, only disorder was changed within every set of data while in Ref. [7], both disorder and magnetic field were changed.

The observed behavior of $\sigma_{xx}$ and $\sigma_{xy}$ is consistent with floating up of the lowest extended state with increasing disorder at constant magnetic field and electron density. The fact that $\sigma_{xx}$ reaches its maximum not at $\omega_c \tau = 1$ (when, according to Eq. (1), the lowest extended state crosses the Fermi level), but at lower $\omega_c \tau^* \approx 0.45$ can be due to inaccuracy of the above described method for determining $\omega_c \tau^*$. (Incidentally, in Ref. [7] the maximum of $\sigma_{xx}(\omega_c \tau)$ function was observed at $\omega_c \tau \approx 0.3$). The observed “metallic” temperature dependence of $\sigma_{xx}$ shows that there is an extended state at the Fermi level at $\omega_c \tau^* \sim 0.45$, and the value of $\sigma_{xx}$ at $T \to 0$ is consistent with that expected for the lowest extended state [9]. At higher or lower values of the disorder, the lowest extended state lies either above or below the Fermi
level thus providing for insulating, with $\sigma_{xy} = 0$, or quantum Hall, with $\sigma_{xy} = e^2/h$, states; in both cases $\sigma_{xx}$ approaches zero as $T \to 0$.

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* Permanent address: Department of Physics and Astronomy, Bowdoin College, Brunswick, ME 04011.

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FIGURES

FIG. 1. The global phase diagram for the integer QHE from Ref. 8. The arrow illustrates the QHE-to-insulator transition realized in the current experiments. The inset schematically shows the expected [2,3] floating up of the extended states (thick lines) as $\omega_c \tau$ decreases.

FIG. 2. Temperature dependencies of $\rho_{xx}$ for different values of $\omega_c \tau^*$ at $\nu = 1$. Open symbols correspond to $B = 3.95$ T, closed — to $B = 3.6$ T. Inset shows characteristic temperature dependencies of $\sigma_{xx}$ for three values of $\omega_c \tau^*$.

FIG. 3. Diagonal (a) and Hall (b) conductivities vs $\omega_c \tau^*$. Both magnetic field and electron density are constant for each set of data designated by a particular symbol. Horizontal lines are guide for eye and represent an estimated uncertainty in the determination $\omega_c \tau^*$. 