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1995 J. Phys.: Condens. Matter 7 L41

(http://iopscience.iop.org/0953-8984/7/5/001)

J. Phys.: Condens. Matter 7 (1995) L41–L48. Printed in the UK

LETTER TO THE EDITOR

Temperature-induced transitions between insulator, metal, and quantum Hall states in a two-dimensional electron system

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Received 4 October 1994, in final form 17 November 1994

Abstract. We report temperature-induced transitions between insulating, metallic, and quantum Hall states in a 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 at high temperatures, the extended states at $\nu = 1$ are above the Fermi energy so that the system is insulating; with decreasing temperature they sink below the Fermi energy, so that the quantum Hall effect occurs. As the extended states cross the Fermi energy, the conductivity has a temperature dependence characteristic of a metallic system.

Recently there has been considerable experimental [1, 2, 3, 4, 5, 6] and theoretical [7, 8, 9] interest in transitions between insulating, metallic, and quantum Hall (QH) states of the two-dimensional electron system (2DES). In spite of this intensive activity, the published experimental work [1, 2, 3, 4, 5, 6, 10, 11, 12, 13] is restricted to descriptions of such transitions driven by changes in two-dimensional carrier density (n_s), and/or magnetic field. However, in this letter we report experimental data which conclusively demonstrate that transitions between insulator, metal, and QH-like behaviour can also be observed at fixed field and n_s as the *temperature* is decreased. In particular, we have observed 2DES delocalization (i.e. an insulator to metal transition) with decreasing temperature, whereas increasing localization is the usual consequence of lowering the temperature of a 2DES [1, 2, 3].

This letter is arranged as follows: our experimental observations are described first, and compared with earlier studies. This comparison suggests a theoretical description which accounts qualitatively for our data. A summary is given in the final paragraph.

Two Si MOSFET samples made from different wafers have been studied: Si-14, which has a maximum mobility ($\mu_{\max}$) of 1.9×10^4 cm^2 V s^{-1}, and Si-22, which has $\mu_{\max} = 3.5 \times 10^4$ cm^2 V s^{-1}. 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 involving cold amplifiers with input resistances $> 10^{14}$ Ω installed inside the cryostat. The output of these amplifiers was connected to a standard lock in amplifier. Great care was taken to ensure

0953-8984/95/050041+08$19.50

that all data discussed here were obtained in regions where the I–V characteristics were linear.

In this work we choose to concentrate on the region close to filling factor ν ($= n_s/(eB/h)) = 1$ (here e is the electron charge, and h is Planck's constant). The various phases of the 2DES are distinguished in the following manner:

(1) *Insulating.* The 2DES is defined as insulating if its diagonal (σ_{xx}) and Hall (σ_{xy}) conductivities exhibit temperature dependences characteristic of an insulator, i.e., $\mathrm{d}\sigma_{xx}/\mathrm{d}T$, $\mathrm{d}\sigma_{xy}/\mathrm{d}T > 0$ with $\sigma_{xy} < \sigma_{xx} < e^2/h$.

(2) *Metallic.* The 2DES shows metallic behaviour if $\mathrm{d}\sigma_{xx}/\mathrm{d}T$, $\mathrm{d}\sigma_{xy}/\mathrm{d}T < 0$.

(3) *Quantum Hall.* The quantum Hall state at $\nu = 1$ is characterized by the well known behaviour $\sigma_{xy} \to e^2/h$ and $\sigma_{xx} \to 0$ as the temperature is lowered to zero [14].

Figure 1(a) shows the resistivity components ρ_{xx} and ρ_{xy} (both are in units of h/e^2) versus magnetic field for $n_s = 9.1\times10^{10}$ cm^{-2} at three different temperatures. 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 [15]. The Hall resistivity is almost T independent; at low temperatures, narrow QH plateaux start to develop near $\nu = 1$ and 2 [4, 6, 14]. Note that as the temperature is decreased from 1.82 K to 942 mK, ρ_{xx} at $\nu = 1$ decreases while remaining larger than $\rho_{xy} = h/e^2$; this corresponds to $\mathrm{d}\sigma_{xx}/\mathrm{d}T < 0$ characteristic of a *metallic* state and reflects *delocalization* with decreasing temperature, whereas ρ_{xx} increases at $B = 0$, indicating an insulating ground state. At still lower temperature, ρ_{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 ρ_{xx} near $\nu = 1$ is an intrinsic effect of the whole 2DES and not an artefact of contacts or current paths such as, e.g., edge currents [16]. Furthermore, in principle the current distribution in a 2DES at low temperatures can be inhomogeneous. If this is the case, it is difficult to draw conclusions about the behaviour of σ_{xx} using ρ_{xx} data. To check these points and to obtain information about σ_{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 imbalance signal is proportional to inverse σ_{xx} averaged over the sample area [17]. The magnetic field dependence of the signal, proportional to σ_{xx}^{-1}, is shown in figure 1(b). One can see that it is qualitatively similar to $\rho_{xx}(B)$, as expected in the case of $\rho_{xx} > \rho_{xy}$. (In case of raised eyebrows at this statement, it should be mentioned that in the familiar, high-n_s QH effect, where $\rho_{xx} < \rho_{xy}$, the dependence is qualitatively different, due to the form of the transformation relationships between the conductivity and resistivity tensors [14]; at integer filling factors $\nu = 1$ and 2, σ_{xx}^{-1} has extreme *maxima* instead of minima (see figure 1(b) inset).) Again, as the temperature is lowered, σ_{xx} increases at $\nu = 1$, showing metallic behaviour, and decreases at $B = 0$, showing insulating behaviour. 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 σ_{xx} and σ_{xy} from the data for ρ_{xx} and ρ_{xy}.

Figure 2 shows the temperature dependence of ρ_{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; as the inset shows, this is characteristic activated behaviour. On the other hand, for the highest electron density, ρ_{xx} always lies below h/e^2 and monotonically decreases as the temperature is decreased below $T \approx 3$ K showing the QH state behaviour. However, turning to the two intermediate n_s, the $\rho_{xx}(T)$ curves are non-monotonic, showing apparent activated behaviour at high temperatures (see inset) and

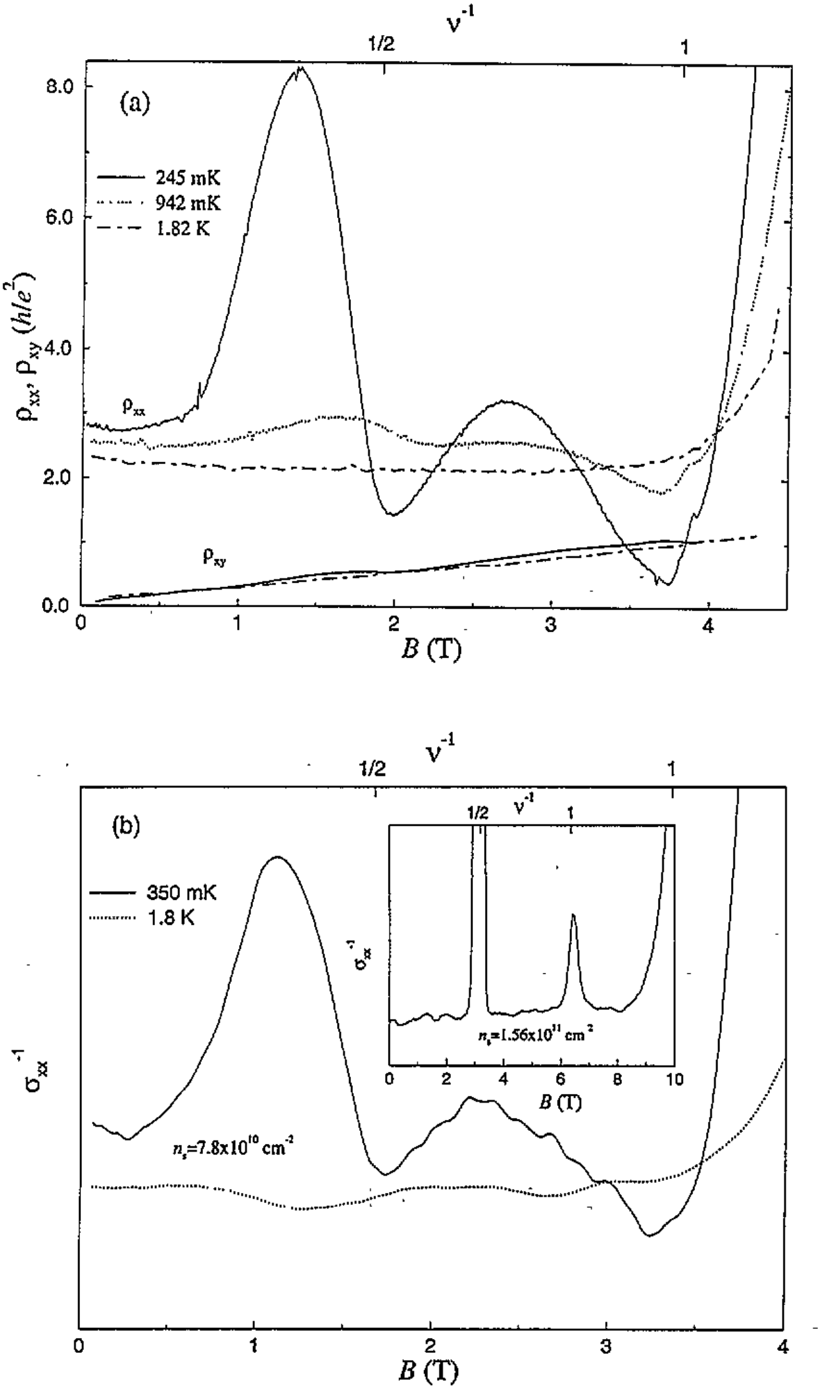

Figure 1. (a) Diagonal and Hall resistivity of sample Si-14 in units of h/e^2 against magnetic field at three temperatures and $n_s = 9.1 \times 10^{10}$ cm^{-2}. (b) Inverse σ_{xx} of sample Si-22 obtained by impedance measurements against magnetic field at two temperatures and $n_s = 7.8 \times 10^{10}$ cm^{-2}. The inset shows 'conventional' $\sigma_{xx}(B)$ for a higher electron density, $n_s = 1.56 \times 10^{11}$ cm^{-2}.

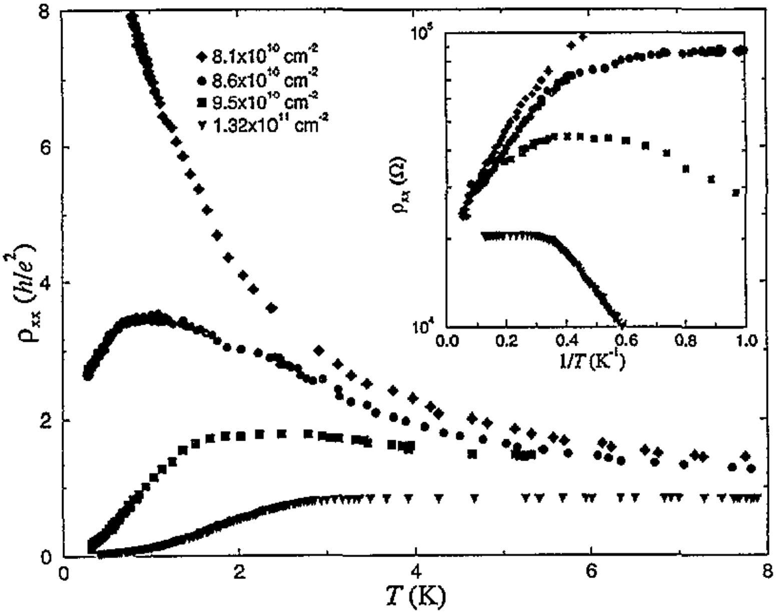

Figure 2. Temperature dependence of diagonal resistivity of Si-14 at $\nu = 1$ for four electron densities. The inset shows activated temperature dependence of ρ_{xx} at higher temperatures for the same sample.

decreasing as $T \to 0$. This non-monotonic behaviour implies, as will be shown below, temperature induced transitions from insulator-like to metallic and QH states of the 2DES.

The temperature dependences of σ_{xx} and σ_{xy} at $\nu = 1$, calculated from the ρ_{xx} and ρ_{xy} data, are shown in figure 3. Figure 3(a) shows σ_{xx} and σ_{xy} for the case of the familiar 'high-n_s' QH effect; σ_{xx}, which is always less than $e^2/2h$, monotonically decreases to the expected very small value as $T \to 0$, and σ_{xy}, which is always higher than $e^2/2h$, monotonically increases to the familiar quantized value as $T \to 0$. Neither metallic nor insulator-like behaviour is observed at $n_s \gtrsim 1.3 \times 10^{11}$ cm^{-2} for any temperature. However, at a slightly lower electron density (figure 3(b)), both components of conductivity are no longer monotonic functions of T.

(1) 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 decreasing T; this is characteristic of an insulating state. Furthermore, according to Khmelnitskii [7], σ_{xy} in units of e^2/h is a 'counter' of the number of extended states below E_F; as $\sigma_{xy} \ll e^2/h$ at $T \gtrsim 2.5$ K, this indicates that there are no extended states below E_F, confirming the existence of an insulating state in this temperature region.

(2) At $1 \lesssim T \lesssim 2.5$ K (between the two vertical dotted lines), both σ_{xx} and σ_{xy} increase with decreasing T, indicating 'metallic' behaviour. Both also reach $e^2/2h$, the value expected for an extended (as opposed to a localized) state ($\sigma^0_{xx} \sim \sigma^0_{xy} = e^2/2h$ at $\nu = \frac{1}{2}$ and $T = 0$ [18]).

(3) Below $T \approx 1$ K (to the right of the second dotted line), σ_{xx} again tends to zero as $T \to 0$ while σ_{xy} approaches e^2/h. The value of σ_{xy} now corresponds to one band of extended states below E_F; this is a QH state [14].

At even lower n_s (figure 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 σ_{xy} always remains $< e^2/2h$ and the

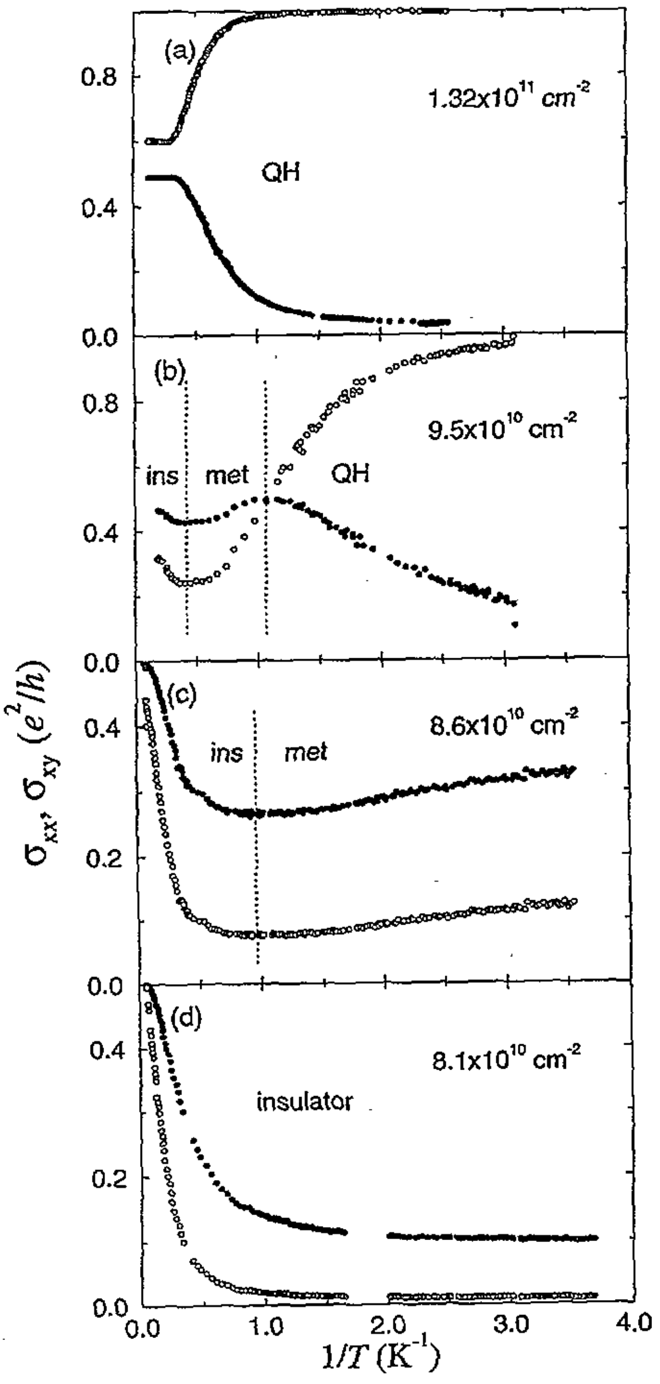

Figure 3. Temperature dependences of diagonal and Hall conductivities for sample Si-14 at $\nu = 1$ for four different n_s. Open symbols correspond to σ_{xy}, closed, to σ_{xx}. Vertical dotted lines approximately separate different kinds of temperature dependence.

QH conditions are never obtained for this n_s.

Finally, for the lowest n_s (figure 3(d)), both $\sigma(T)$ components decrease monotonically down to the lowest temperatures while $\sigma_{xy} < \sigma_{xx} < e^2/h$; therefore 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 behaviour 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 an insulating to a metallic state without a further transition to QH behaviour. For even lower $n_s = 8.1 \times 10^{10}$ cm^{-2}, the system remains insulating.

In both high-mobility silicon inversion layers [1] and low-mobility GaAs/(Al,Ga)As heterostructures [2, 3] it has recently been demonstrated that a 2DES, strongly localized in zero magnetic field ($B = 0$), can nevertheless manifest the integer QH effect. References [4, 5, 6] discuss this magnetic-field-induced transition from the point of view of many-body effects, whereas [2, 3] 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 and co-workers [9] as the basis for the insulator–QH transition. According to Khmelnitski [7] and Laughlin [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 and may sink below E_F [19]; at high magnetic fields, the extended states approximately follow the centres of the Landau levels (see figure 4). At zero temperature, the diagonal conductivity (σ_{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 (σ_{xy}) is also zero and the system is *insulating. For each band of extended states below* E_F, σ_{xy} *increases by* e^2/h, *providing the* next integer QH state. If the temperature is not zero and there are no extended states at E_F, σ_{xx} displays activated behaviour with the activation energy equal to the energy difference between E_F and the nearest extended state [14].

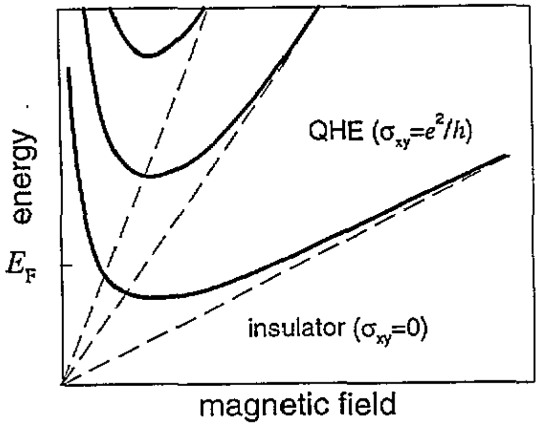

Figure 4. Schematic of the expected behaviour of extended states in a magnetic field (after [7, 8]).

Magnetic-field-induced transitions between insulating and QH ground states have also been investigated in very dilute high-mobility GaAs/(Al,Ga)As heterostructures in the extreme quantum limit (see, e.g., [10] and references therein) and in Si inversion layers around $\nu = 1$, 2, and 6 [5, 6]). In some papers [4, 5, 6, 11, 12, 13] the fact that the insulating state can be disrupted by integer or fractional QH resistivity minima has been discussed in a speculative fashion in terms of the formation of a pinned electron solid melting at integer or fractional ν. However, the global phase diagram [9] can also explain magnetic-field-induced transitions between QH (at $\nu = 1, \frac{1}{3}$, or $\frac{1}{5}$) and insulating ground states without invoking collective effects, although it must be said that recently observed direct transitions from $\nu = \frac{2}{7}$ and $\frac{2}{5}$ [13, 20] and $\nu = 6$ [6] to insulating states do contradict the global phase diagram.

Returning to the Si samples in this work, we have considered the region around $\nu = 1$ at low n_s; under these conditions it is known that there is no electron solid [4, 5, 6, 11, 12, 13]. In view of this, we shall discount the explanations involving an electron solid outlined in the previous paragraph, and instead interpret our experimental data phenomenologically in terms of 'levitation of extended states' [7, 8]. According to [7, 8], the energy of the lowest state at $T = 0$ is

$$E_c = \tfrac{1}{2}\hbar\Omega_c\left[1 + (\Omega_c\tau)^{-2}\right] \tag{1}$$

where Ω_c is the cyclotron frequency and τ is the relaxation time. Therefore, at constant B (Ω_c = constant), E_c increases with decreasing τ, 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 dependences for both diagonal and Hall conductivities. At still lower temperatures, the band of extended states sinks below the Fermi energy, σ_{xy} approaches e^2/h, and the system enters the QH regime.

The mechanism behind this variation of E_c is unclear. It can hardly be a single-particle effect because in a non-interacting system, the electron states are determined by the Hamiltonian and the temperature only defines the distribution of the electrons between the states; in an interacting system, however, the electron states may in principle be temperature dependent. The electron–electron interactions in our samples appear to be much stronger than the disorder potential [17]; evidence for this is seen in the giant enhancement of the valley splitting at $\nu = 1$ [21] and the negative density of states at high magnetic fields [17, 21, 22]. The observed variation in E_c might therefore be connected to the large drop in the resistivity at zero magnetic field at $T \lesssim 1$ K observed very recently in similar Si MOSFET samples [23], and thought to be a manifestation of electron–electron interactions. This drop in resistance appears to be due to the suppression of the dominant scattering mechanism at low temperatures [23], leading to an increase in τ; this in turn will result in a decrease in E_c according to equation (1).

We have studied the temperature dependent behaviour of a very dilute 2D electron system in silicon around 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-like to QH-like temperature dependences of the transport coefficients. The first of these transitions reflects *delocalization* with decreasing temperature; this is in sharp contrast to the familiar situation in which lowering the temperature makes a 2DES more localized.

We acknowledge useful discussions with E I Rashba, L Zhang, B A Mason, X C Xie, and D Shahar. This work was supported by grants from the National Science Foundation, DMR 89-22222 and Oklahoma EPSCoR via the LEPM, and EPSRC (UK).

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