Current-voltage discontinuities in high-quality two-dimensional electron systems at low Landau-level filling factors

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(Received 12 May 1989)

We report the observation of discontinuities in the dV/dI characteristics of high-mobility two-dimensional (2D) electron systems in GaAs/$Al_xGa_{1-x}As$ heterostructures at very low Landau-level filling factors. We discuss a model of inhomogeneous current transport that is able to account for many of the observations independent of the 2D electron state.

Recent low-temperature experiments on high-quality, two-dimensional (2D) electron systems in GaAs/$Al_xGa_{1-x}As$ heterostructures indicate anomalous transport behavior in the extreme magnetic quantum limit.[1] A rapid increase of the magnetoresistivity ρ_{xx} is observed for Landau-level filling factors smaller than $\nu \approx 0.3$ with a strikingly activated temperature dependence for any given ν. This is in stark contrast with the transport characteristics at higher Landau-level filling factors where the fractional quantum Hall effect[2] (FQHE) dominates. It is argued that these anomalous transport properties may arise from various disorder dependent electronic states, ranging from magnetic-field-induced single-particle localization (magnetic freeze-out), to the formation of an electron Wigner solid pinned to residual disorder.[1,3]

In order to investigate further the small-filling-factor regime, examination of other transport properties of this phase appears warranted. Towards this end we have studied the current-voltage properties of high-quality 2D systems at millikelvin temperatures and over a range of filling factors. At low filling factors we find strongly nonlinear current-voltage characteristics in several samples manifested as discontinuities in the differential resistance and reminiscent of transport in charge-density-wave compounds. This Brief Report describes the characteristics of these discontinuities and discusses a possible model for their origin.

The experiments were performed in a dilution refrigerator compatible with both Bitter and superconducting magnet systems. Standard lock-in modulation techniques were employed to determine the differential resistance (dV/dI) versus current (I) in a four-probe geometry. The amplitude of the 5-Hz modulation current never exceeded 1 nA (peak to peak) and was always smaller than 1% of the maximum dc current ramp.

We studied a total of eight samples from four different wafers. Three samples showed the characteristic discontinuities whereas in five other specimens these features were not discernible. In two of these samples an abnormally large noise level in ρ_{xx} prevented the observation of any structure on the scale of the discontinuities. In the remaining specimens we found a correlation between sample quality and the existence of discontinuities in the dV/dI characteristics. The three specimens (A_1, A_2, B_1) which clearly exhibit steps come from our two highest-quality wafers, A and B. The densities n and mobilities μ of these wafers are $n_A = 4.5\times10^{10}$ cm^{-2}, $\mu_A = 1.2\times10^6$ cm^2/sec and $n_B = 6.0\times10^{10}$ cm^{-2}, $\mu_B = 1.2\times10^6$ cm^2/V sec. The discontinuities were absent in a sample from a third wafer of much lower mobility ($\mu < 5\times10^5$ cm/V sec) with poorly developed FQHE features. In spite of the high mobility of wafer A, a third sample A_3 also exhibited poorly developed FQHE features in the low-filling-factor regime and, in turn, no steps were observed in the dV/dI characteristics. The remaining negative observation was made on a second specimen, B_2 of wafer B, whose ρ_{xx} data resembled closely those of sample B_1. The origin of the discrepancy between samples B_1 and B_2 remains unclear. The high quality of wafer B is confirmed by its demonstration[4] of the FQHE at $\nu = \frac{1}{7}$.

Figure 1(a) shows the magnetoresistance ρ_{xx} versus magnetic field B for sample A_1. The arrows $a-e$ refer to

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the field positions at which the dV/dI characteristics of Fig. 1(b) were determined. At filling factor $\nu=\frac{1}{2}$ (trace a) strictly Ohmic behavior is observed. This characteristic persists throughout the filling-factor regime down to $\nu=\frac{1}{3}$ (trace b). At filling factors less than $\nu=\frac{1}{3}$, in the range at which anomalous transport has been reported in this sample, discontinuities in the differential resistance appear, as seen in Fig. 1. The discontinuities take the form of an Ohmic dependence, i.e., constant dV/dI, persisting up to a threshold current value, I_c, at which point an abrupt drop in dV/dI of about 5% occurs. No further structure is observed at higher currents. Trace d at larger magnetic field shows a small increase in the magnitude of I_c. As larger magnetic fields are applied (traces d and e), the differential resistance no longer displays Ohmic behavior as the background to the discontinuities. Instead, as the excitation current increases the differential resistance drops. At sufficiently large currents (not shown in this figure), a constant dV/dI results. This finding is consistent with heating of the 2D electron system, since in previous work[1] it was shown that the magnetoresistance at small ν is particularly sensitive to temperature.

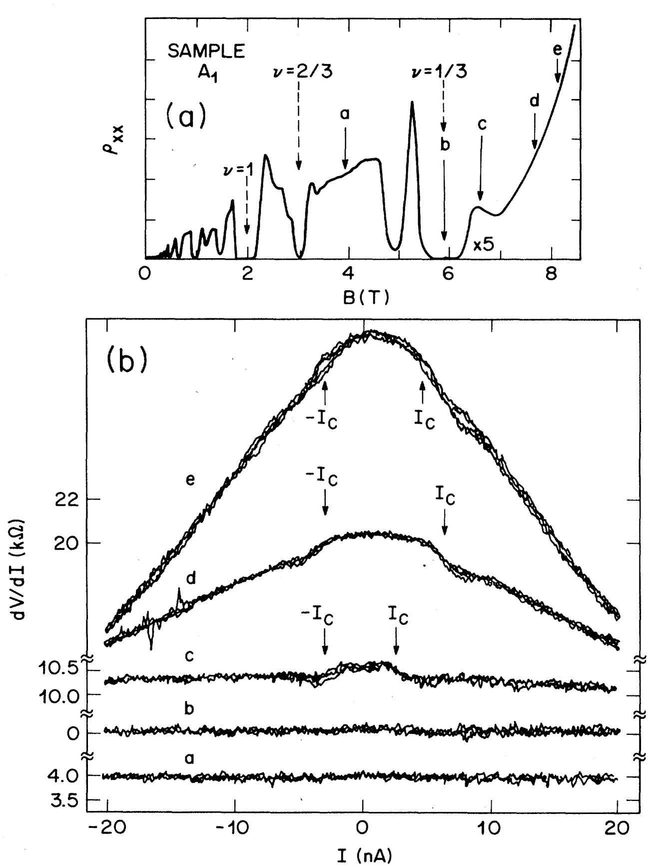

FIG. 1. Longitudinal resistivity vs magnetic field (a) and differential resistance vs excitation current (b) in sample A_1. Field values at which differential resistance is measured in (b) are marked a through e in (a). The temperature is 80 mK.

The temperature dependence of the discontinuities was tested by observing the differential resistance at several magnetic field values while the temperature was stepped up. The non-Ohmic background of traces e and d disappears with increasing temperature approaching a constant dV/dI, whereas the flat background to traces a, b, and c remains practically unchanged. This is consistent with the general T dependence of ρ_{xx} and the existence of electron heating in traces e and d at higher currents. In all cases the superimposed discontinuities gradually vanish and become undetectable at a temperature of ~ 500 mK.

Striking current-voltage discontinuities are also observed in sample B_1. In the low-filling-factor regime $\nu \lesssim \frac{1}{3}$, the discontinuities take on the form of multiple abrupt jumps. Three steps in dV/dI are observed in Fig. 2 at currents $I_{c1} \simeq 7$ nA, $I_{c2} \simeq 21$ nA, and $I_{c3} \simeq 30$ nA. At larger magnetic fields these prominent discontinuities persist but as in Fig. 1 a background due to carrier heating develops. Under appropriate conditions of temperature and magnetoresistivity, the discontinuities can be observed up to the strongest fields of 23 T, equivalent to $\nu \approx \frac{1}{9}$, but their identification becomes more difficult. An important characteristic of the data in Fig. 2 is that the multiple discontinuities appear at longitudinal resistivity values comparable to those reached at $\frac{2}{5} > \nu > \frac{1}{3}$ where no discontinuities are observed. The dependence of the threshold currents, I_{c1} and I_{c2}, on magnetic field was more closely examined in sample B_1 at base temperature $T \sim 80$ mK in the filling-factor range $0.23 < \nu < 0.29$, where the discontinuities were readily discernible. In spite of a variation of the longitudinal resistivity ρ_{xx} by about 1.5 orders of magnitude over this interval, the threshold currents remained practically constant, fluctuating by less than $\pm 20\%$.

Before we discuss the possible origins for the discontinuities in the dV/dI traces, we summarize here their characteristics. Since the details of the features are not exactly reproducible when thermally cycled to room temperature, we only state their general properties.

(1) We have observed the discontinuities only at very low Landau-level filling factors $\nu < \frac{1}{3}$.

(2) Not all specimens show these features but there is a

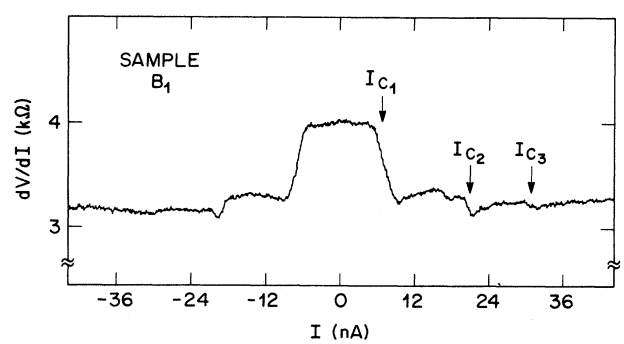

FIG. 2. Differential resistance vs excitation current in sample B_1 at $B=8$ teslas (filling factor $\nu=0.31$) and $T=80$ mK.

tendency for them to appear in the highest-quality samples investigated with $\mu \gtrsim 10^6$ cm^2/V sec.

(3) The discontinuities appear at roughly constant-threshold currents independent of large variations in ρ_{xx}.

(4) Critical currents are on the order of 10 nA.

(5) The discontinuities disappear at $T \gtrsim 500$ mK.

(6) In at least one specimen we found reproducible multiple threshold currents.

Discontinuities in the dV/dI characteristics reminiscent of the features in our data have been reported earlier in various inorganic linear-chain charge-density compounds.[5,6] There the discontinuities result from a sudden depinning of the charge-density wave when a critical electric field has been reached. It is an attractive possibility to associate the discontinuities in our samples at small Landau-level filling factors with the formation of a Wigner solid[7] pinned to residual imperfections. Upon application of a sufficiently large electric field this electron solid should depin, leading to a sudden drop in the dV/dI trace. While the general features of pinning in traditional charge-density-wave compounds are understood, quantitative comparisons between theory and experiments have proven very difficult.[8] The possibility of a quantitative interpretation is even less encouraging in our 2D systems, where already the existence of a Wigner solid remains questionable,[9,10] not to mention the transport features such a phase may exhibit.

On the other hand, if potential fluctuations are strong in our 2D system, a Wigner solid may not be realized. Instead the electrons may assume a state of much more random character in which electrons are localized around potential minima although maintaining considerable correlation with their respective neighbors. Such a state may be described as an electron glass. In such a system weakly localized electrons may become delocalized when a sufficiently large electric field is applied and subsequent impact ionization produces a discontinuity in the dV/dI trace. However, independent of the specific electronic state, the observation of multiple steps in the dV/dI characteristics is difficult to incorporate into each of the models.

The finding of a constant current threshold represents another puzzling aspect of our data. Generally one would expect steps in dV/dI to originate from a breakdown of transport when a critical electric field is surpassed and depinning of a coherent state or ionization of individual carriers ensues. If we assume that in our system the breakdown is finally also caused by a critical electric field, then a constant critical current can only be accounted for if the relationship between current and field is magnetic field independent. In our 2D system the total local electric field $|E| = (E_x^2 + E_y^2)^{1/2} = (\rho_{xx}^2 + \rho_{xy}^2)^{1/2} j_x$, where j_x indicates the local current density in a suitable coordinate system so that $j_y = 0$. Using the transport data on sample B_1 in the filling-factor range $0.23 < \nu < 0.29$ over which the magnetic field dependence of the critical current can be studied, we find $(\rho_{xx}^2 + \rho_{xy}^2)^{1/2}$ varies by as much as a factor of 3. Almost all of this variation is due to ρ_{xx} whereas $\rho_{xy} = h/(\nu e^2)$ varies relatively little ($\sim 20\%$). However, ρ_{xx} was determined by the standard four-terminal measurement at the perimeter of the specimen. Such a determination of ρ_{xx} assumes a uniform current distribution which may not apply in this low-filling-factor regime. Particularly, if conduction is supported by filaments the standard four-terminal measurement will always overestimate ρ_{xx} which then may be considerably smaller than ρ_{xy}. The fluctuations in carrier density across the specimen, on the other hand, are expected to be small so that the value of ρ_{xy} remains rather uniform. Under such conditions $(\rho_{xx}^2 + \rho_{xy}^2)^{1/2} \approx \rho_{xy} \approx$ const and the constance of the critical current can be understood in terms of an electric Hall field which increases only slightly over the small filling-factor range accessible in our experiments. Such reasoning would imply that only a fraction of the sample width is carrying current at such small filling factors.

In this model the breakdown is caused mostly by the electric Hall field normal to the current direction. At breakdown the total Hall voltage drop across the current carrying parts of the sample is $V_c = \rho_{xy} I_c = h/(\nu e^2) I_c \approx 1$ mV ≈ 10 K. The discontinuities in the dV/dI characteristics, on the other hand, disappear as temperature increases on an energy scale of about 1 K, which may reflect the characteristic depth of a smooth potential confining the current to several channels within the sample. A Hall voltage reaching the equivalent of 1 K across such a potential well would cause breakdown resulting in a sudden change in differential resistance. Since the total V_c is the sum of the voltages across all channels, the existence of several such channels is required. Furthermore, in this model, the multiple discontinuities are a natural consequence of channel-to-channel inhomogeneities.

Our model of inhomogeneous transport can account for many of the observations. It implies that a large fraction of the sample surface does not participate in electrical transport at low-filling factors. However, such a model for the occurrence of discontinuities in the dV/dI characteristics cannot make any statements as to the electronic state in the conducting and nonconducting region of the specimen. It remains undetermined whether a Wigner solid forms at these small filling factors. Within the framework of our inhomogeneous current-transport model, filamentary current paths could well exist within an electron solid multiply pinned by impurities. Likewise, the 2D system may be in an electron glass state with conduction occurring in filaments. The discontinuities in the dV/dI characteristics, therefore, do not provide a definitive indication of the predominant electronic state in the extreme quantum limit.

We would like to thank K. W. Baldwin and the staff of the National Magnet Laboratory for technical support. Partial support of this work by National Science Foundation Grant Nos. ECS-8553110 and DMR-8705002 is acknowledged.

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