Dissipation and Dynamic Nonlinear Behavior in the Quantum Hall Regime

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Dynamic nonlinear behavior is reported at high currents in the quantum Hall regime of GaAs heterostructures, resulting from breakdown of the dissipationless current flow. It is demonstrated that this breakdown is spatially localized and transient switching is observed on microsecond time scales among a set of distinct dissipative states. A simple macroscopic picture is proposed to account for these novel phenomena.

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The quantum Hall effect[1,2] is of great import for both many-body physics and fundamental metrology. The extreme accuracy with which the Hall resistance is quantized, despite the presence of disorder in the inversion-layer devices, is now fairly well understood as being due to the nearly complete freedom from dissipation in the quantized Hall regime. However, the nature of the localized states in a high magnetic field, the role of finite electric fields, and the nature of various dissipative effects remain poorly understood. Ebert *et al.*[3] have recently discovered that there is a critical current density above which the dissipation suddenly rises by several orders of magnitude. We report in this Letter unexpected new phenomena associated with this breakdown. We show that the breakdown is spatially localized and exhibits a rich time-dependent structure. In addition to a strong background of broadband noise we observe transient switching on a microsecond time scale among a discrete set of distinct dissipative states. Our observations demonstrate the significance of this breakdown phenomenon and provide a deeper understanding of the novel transport properties associated with the quantum Hall effect.

Two high-quality GaAs-$Ga_{1-x}Al_xAs$ ($x = 0.29$) heterojunction devices [hereafter referred to as GaAs(7) and GaAs(8)] were used in this study. Both devices have zero-magnetic-field mobilities in excess of 10^5 $cm^2/(V\ s)$ at 4.2 K, and at 1.1 K yield excellent 6453.2-Ω ($i = 4$) Hall steps that are flat and reproducible to at least 0.02 ppm.

Figure 1 gives the sample geometry and displays the current dependence of the Hall resistance $R_H \equiv (V_3 - V_4)/I_{SD}$ and the dissipative voltage $V_x \equiv V_2 - V_4$ (at its minimum) for GaAs(7). Table I shows that V_x changes by 7 orders of magnitude between $I_{SD} = 25$ and 370 μA and becomes as large as one-tenth of the Hall voltage V_H while (as shown in Fig. 1) the value of R_H decreases by only 0.1 ppm! Similarly the other Hall-probe resistance $R_H' \equiv (V_1 - V_2)/I_{SD}$ decreases by only 0.6 ppm. These changes in R_H are ~0.01% of what is expected from the mixing of V_x into V_H due to the known misalignment of the Hall probes (3 rel-

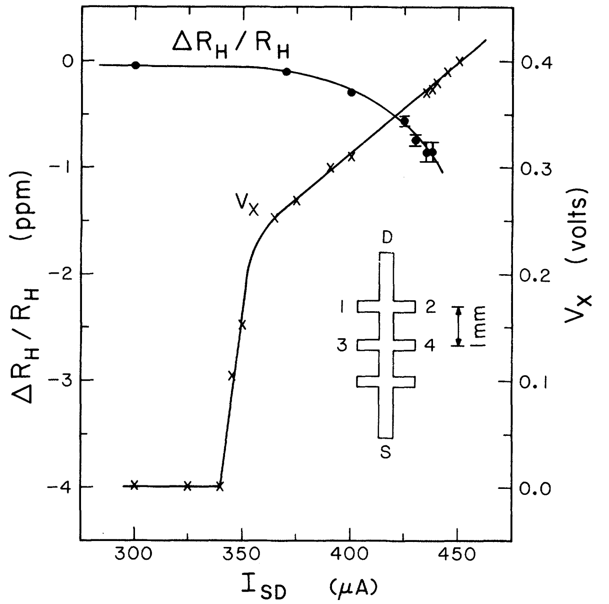

FIG. 1. Current dependence of $\Delta R_H/R_H \equiv R_H(I_{SD})/R_H(25\ \mu A) - 1$ and V_x for the $i = 4$ step of GaAs(7) at 1.1 K. The solid lines are meant to guide the eye. Also shown are the source, drain, and four potential probes. Each device is 4.6 mm long and 0.38 mm wide.

ative to 4 and 1 relative to 2). This strongly suggests that the breakdown is highly inhomogeneous, with essentially all of the voltage drop V_x in GaAs(7) occurring in the region *between* but *not including* the two Hall probe sets. Furthermore, *the dissipative region must extend across the full width of the channel* (otherwise there would exist a dissipationless path connecting the two probes and $V_x = \int \vec{E} \cdot d\vec{l}$ would necessarily vanish). In GaAs(8) the change in R_H was also relatively small (~ 1% of that expected from the probe misalignment) but the change in R_H' was much larger (~ 100% of the expected amount). This indicates that for GaAs(8) the dissipative region happens to extend into the space between probes 1 and 2.

Figure 2 shows V_H, V_x, and the source-drain voltage V_{SD} for GaAs(7) at 325 μA and 1.1 K as a function of magnetic field in the region of the

TABLE I. V_x, V_H, and V_{SD} at several currents for the $i = 4$ Hall step of GaAs(7) at 1.1 K.

I_{SD} (μA)	V_x (V)	V_H (V)	V_{SD} (V)
25	2.8×10^{-8}	0.16	0.16
325	1.4×10^{-5}	2.10	2.89
370	2.7×10^{-1}	2.39	3.85

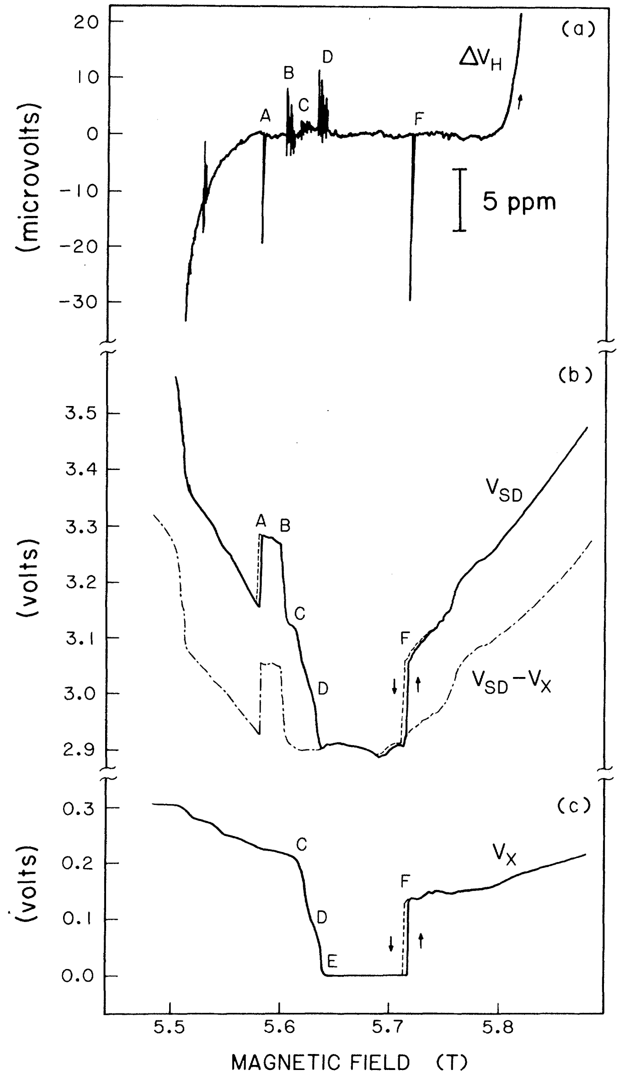

FIG. 2. Hall-voltage deviation ΔV_H, V_{SD}, $V_{SD} - V_x$, and V_x for the $i = 4$ step of GaAs(7) at 1.1 K and 325 μA. Arrows indicate the magnetic-field-sweep direction.

$i = 4$ Hall plateau. There are sharp steplike transitions in both V_{SD} and V_x, indicating that breakdown can occur for currents less than the critical value as one moves away from the center of the Hall plateau. From the plots in Fig. 2 one can deduce the spatial locations of the breakdowns which produce the various features seen in these curves. A feature appearing in V_{SD} but not V_x (such as the one at the points labeled *A* and *B*) must be due to a breakdown occuring in the region outside of the two Hall probe sets. Similarly a feature appearing in V_x but not in the difference $V_{SD} - V_x$ (such as that at the points labeled *C* and *F*) must be due to a breakdown occurring within the channel between the two Hall probe sets. This again demonstrates that the breakdown is inhomogeneous.

We did not observe the "prebreakdown" found in some samples by Ebert *et al.*[3] and characterized by a steplike sequence of increases in V_x as a function of current. Since we have determined that the breakdown is inhomogeneous, a natural interpretation of this "prebreakdown" is that it is a sequence of breakdowns, each occurring in a different region of the sample.

Ebert *et al.*[3] also found that the breakdown showed hysteresis as a function of current. As indicated by the dashed lines in Fig. 2, we find that the system also exhibits hysteresis in both V_{SD} and V_x when the direction of sweep of the magnetic field is reversed. When the device was warmed to 2.1 K (at the same 325-μA current) the hysteresis at point F became so large that the plots of both V_{SD} and V_x separated into two distinct, nonoverlapping but sharp wells corresponding to the two magnetic-field sweep directions.

Figure 2 also shows a high-resolution plot of V_H for GaAs(7) obtained by means of the measurement system indicated in Fig. 1 of Tsui *et al.*[4] The Hall step remains flat well outside of points E and F because, as argued previously, the V_x breakdown is localized. The spikes seen in V_H in Fig. 2 are due to the presence of a large (~0.01 μF) capacitance in parallel with the sample which electrically differentiates changes in V_{SD}. Taking advantage of this highly sensitive diagnostic tool for studying the steplike transitions in V_{SD} and V_x, we observed the following: (1) The pattern of spikes was reproducible to within our resolution of ± 1 mT (± 10 G) during any given run; (2) the pattern was independent of field sweep rate; (3) the hysteresis increased with current, and at low current increasing the temperature did not produce the dramatic hysteresis described earlier; (4) structure was observed in V_H down to currents as low as 50 μA (less than one-sixth of the critical current) even though associated structure was no longer observed in V_{SD} or V_x. Qualitatively similar results were obtained for GaAs(8) except that the hysteresis was much smaller.

Associated with the nonlinear behavior discussed above we have observed some very strong temporal fluctuation phenomena. There was a significant level (up to ~5 $\mu V/Hz^{1/2}$ at 800 kHz) of nonthermal broadband noise in V_x that spanned the entire spectrum from near dc to more than 5 MHz (the limit of our spectrum analyzer). The frequency distribution changed with magnetic field, particularly when scanning across distinct features in either V_{SD} or V_x. The amplitude was largest at magnetic fields where V_x was increasing from its central minimum and was several orders of magnitude lower at the center of the Hall plateau and in regions off the Hall plateau. This broadband noise was not limited to high currents but was observed at currents as low as 50 μA.

In addition to this general background of broadband noise in V_x, there were regions of magnetic field in which V_x was unstable, jumping rapidly among a discrete set of fixed values. Figure 3 is an oscilloscope trace of V_x that illustrates several features of this activity, but it should not be thought of as typical because the behavior varied widely across the step. In the vicinity of point E of Fig. 2, V_x was very unstable with at least three states among which it jumped with switching times of 5 to 10 μs. As the system moved up the slope in V_x to the left of E, many more states were observed. The baseline in Fig. 3 is representative of the broadband noise in V_x that is found (with varying intensity) all across the Hall plateau. The regions of magnetic field yielding the structure in V_{SD} and V_x shown in Fig. 2 were also those in which the greatest temporal activity was observed. We conclude that these regions are characterized by many distinct, but unstable, states of current flow through the device.

At present there does not exist a theory of the quantum mechanical origin of the breakdown, although a general picture involving electron heating is discussed in Ref. 3. Some theories[5] of the quantized Hall resistance assume that the current is carried by a relatively small number of extended states which percolate through the random impurity potential. Within this picture, a theory of the breakdown would have to assess how

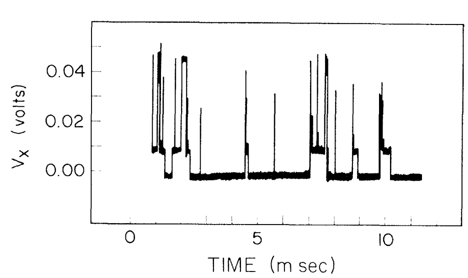

FIG. 3. Oscilloscope trace of V_x taken at 325 μA and fixed magnetic field (point E of Fig. 2).

much current these states could sustain. Tsui, Dolan, and Gossard[6] have recently proposed another picture in which breakdown occurs via Zener tunneling to empty Landau levels, but their estimate of the required current density is 2 orders of magnitude larger than the value we observed (0.9 A/m). However, this estimate did not take into account the macroscopic inhomogeneity of the breakdown or the microscopic features of the impurity scattering.

We believe that our observations can be accounted for by the following macroscopic picture. If we assume that there exists some microscopic mechanism which initiates breakdown in a localized region of the device, it follows from classical electrodynamics that the current will redistribute itself so as to avoid the dissipative region. This will increase the local current density outside the breakdown region and so tends to trigger further spread of the breakdown. On the other hand, the associated large decrease in current within the breakdown region tends to remove the driving force for the dissipation. Which of these opposing tendencies prevails will determine whether the resistive region continues to grow or collapses. If the breakdown succeeds in spreading across the entire width of the channel it will be stabilized by the fact that the current is now forced to pass through the dissipative region. This stabilization mechanism could account for the observed discrete dissipative states, the sharpness of the transitions between these states, and the hysteresis. The temporary formation of dissipative regions which fail to reach across the channel and thus collapse could account for the strong broadband noise. These ideas can be tested experimentally by studying the correlations among the voltage fluctuations on different probes

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