Transitions between dissipationless and dissipative states at GaAs-Al$_x$Ga$_{1-x}$As heterostructures in the quantum Hall effect

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Breakdown at a GaAs heterojunction has been studied at $T = 0.35$–3.5 K and $H \approx 120$ kOe. The results reveal the existence of metastable states with a lifetime between 10^{-3} s and $\gg 100$ s, the development of breakdown in the form of a chain of subjumps in ρ_{xx}, a hysteresis in each of the individual subjumps in ρ_{xx}, and an effect of the direction of the Hall field on the current-voltage characteristic of the breakdown.

An interesting but little-studied feature of the quantum Hall effect is breakdown, i.e., the abrupt increase in the resistivity ρ_{xx} in a 2D layer which occurs as the transport current J_x increases.[1] The existing experimental data on breakdown are contradictory, and on the theoretical side there is no generally accepted model for this effect. Breakdown is seen most clearly at GaAs-AlGaAs heterojunctions.[2,3] We have accordingly undertaken a study of breakdown at the GaAs-AlGaAs heterojunction. We used samples with the Hall geometry (see the inset in Fig. 1) with $L = 1.5$ mm and $W = 0.2$ mm, an electron density $n = 5.5 \times 10^{11}$ cm^{-2}, and a mobility $\mu = 1.3 \times 10^5$ cm^2/(V s) at $T = 4.2$ K. In the experiments we measured the voltage (V_x) between contacts 1 and 2 (or 3 and 4) as a function of the current J_x through the structure. The range over which the magnetic field was varied, $H \approx 110$–122 kOe, corresponded to a Hall plateau with a Landau-level occupation number $\nu \approx 2$.

Experimental results. Figures 1 and 2 show some typical results on the behavior $V_x(J_x)$. The breakdown current J_c increases with decreasing H, and it does so in an asymmetric way with respect to the middle of the ρ_{xy} plateau ($H_0^{\rm pl} = 115.1$ kOe) the middle of the ρ_{xx} minimum ($H_0^{\rm min} = 112.9$ kOe). The amplitude of the jump in ρ_{xx} simultaneously decreases, vanishing at $H \approx 110$ kOe.

Near $J_x = J_c$, two metastable states appear in the 2D layer: (1) an essentially dissipationless state and (2) a dissipative state, with a resistance several orders of magnitude higher than that of the first. The typical lifetimes of these states of the 2D layer near breakdown range from $\sim 10^{-3}$ s (in weak fields) to times exceeding the duration of the experiments ($\gg 100$ s) (in strong fields). In the weaker fields we observe an intense noise in V_x at $J_x \approx J_c$, and the breakdown occurs in the form of a single jump, or more rarely, two jumps. At a constant J_x, the time dependence of V_x under these conditions is a wide-band noise against the background of transitions from one state to the other (see the inset in Fig. 2). With increasing J_x, the time spent by the system in the dissipative state increases.

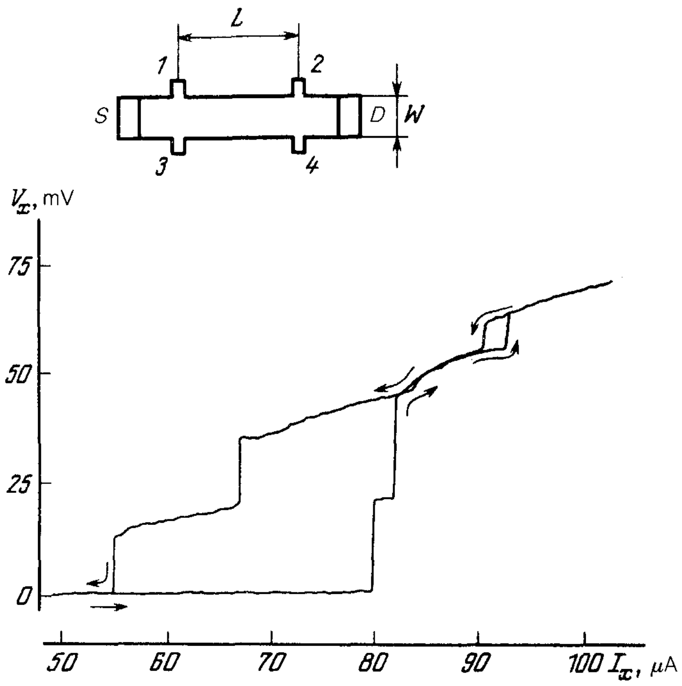

FIG. 1. Fragment of a current-voltage characteristic near breakdown ($H = 115.3$ kOe, $dJ_x/dt = 2.27$ μA/s, $T = 0.9$ K). The inset shows the sample geometry.

With increasing H, the lifetimes of the metastable states increase, the noise weakens, and several (from two to five) subjumps in V_x appear. The front of each of the subjumps steepens; the amplitudes of the jumps increase along with an increase in the overall jump (Fig. 2), and hysteresis effects appear when the current is swept in the opposite direction. Figure 1 shows a typical current-voltage characteristic in the high-field region. It was established that the hysteresis is more probably a function of the current than of the sweep time. It should be noted, however, that the positions of the subjumps along the current scale are not completely reproducible, even when dJ_x/dt remains constant. An external agent, e.g., the connection of a measurement instrument, can stimulate jumps. The value of J_c depends on the history of the sample and may span a range of several days.

The shape of the I–V characteristics changes significantly when the direction of J_x is changed, but when J_x and H are simultaneously reversed, i.e., if the direction of the Hall field is kept the same, the shapes of the characteristics do not change.

In an effort to determine whether the breakdown was associated with contact effects, we carried out a separate experiment in which we passed a current initially through contacts *S-D* and then through 1-*D* or 3-*D* (see the inset in Fig. 1). In these experiments we measured V_x at the free contacts. The resulting I-V characteristics

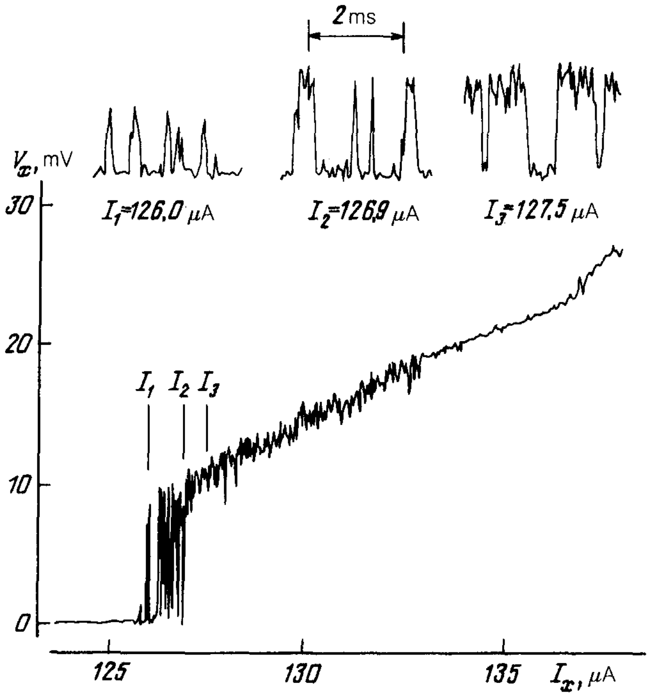

FIG. 2. Fragment of a current-voltage characteristic near breakdown (weaker fields) ($dJ_x/dt = 11.7$ μA/s). The J_x resolution is 0.023 μA/channel ($H = 112$ kOe, $T = 0.35$ K). The inset shows the time evolution of V_x for three fixed values of the current J_x.

were identical, indicating that the breakdown resulted from conditions in the interior of the sample, rather than near the contacts.

Discussion of results. If we assume a uniform current distribution over the channel width W, we find the electron drift velocity at $J_x = 100$ μA to be $v_d = 6 \times 10^4$ cm/s, while the electric field is $E_y^{\exp} = 60$ V/cm. Before breakdown we have $\rho_{xx} \sim 5 \times 10^{-2}$ $\Omega/\square$ ($T = 0.95$ K, $H = 112.9$ kOe), while after breakdown we have $\rho_{xx} \sim 10$ $\Omega/\square$ under the same conditions.

In the phonon-mechanism model,[1,4] breakdown sets in when the drift velocity reaches the sound velocity (in GaAs, the minimum value is $v_s = 2.5 \times 10^5$ cm/s). We see that in order to reconcile this model with the experimental results, we would be forced to assume that the effective channel width W_{eff} is ~0.25 of the geometric channel width W.

In the model of Zener tunneling in a transverse electric field,[2] breakdown occurs when the Hall field reaches a value $E_y^{\text{mod}} = \Delta/a_H e$, where Δ is the energy gap, and a_H is the magnetic length. At $H = 120$ kOe we have $E_y^{\text{mod}} = 10^4$ V/cm. In this model it is thus necessary to assume that the effective width of the current-carrying part of the channel is smaller than W by a factor $E_y^{\text{mod}}/E_y^{\exp} \sim 150$. There is the possibility, however, that the tunneling occurs not across the gap Δ but between localized states in the gap between Landau levels (the density of these states is known to be nonzero[3]).

Let us examine the experimental results in the light of a phenomenological model of the thermal instability of a 2D electron gas.[3,5] Numerical estimates of the breakdown current based on Ref. 5 agree with our data. The independence of the hysteresis from the sweep rate is further evidence in favor of this model. The jump in V_x corresponds to a power dissipation $\sim 1\ \mu\text{W}$ in the 2D layer, and the value of ρ_{xx} observed after the jump $(J_x > J_c)$ may be interpreted as a consequence of a heating of the electrons of the 2D layer to temperatures $\sim 10^2$ K, again without contradiction of Ref. 5. The final state after the jump $(J_x > J_c)$ corresponds to a filling of the dissipative region of the entire gap between the potential contacts, while each of the subjumps corresponds to the appearance in this gap of a dissipative domain which spans the entire width of the channel. From the maximum observed number of subjumps (i.e., domains) we find $L/5 = 0.3$ mm as an estimate of the length of a domain. This estimate agrees with the expected value $\sim W$. An important argument in favor of a local nature of the breakdown and the presence of individual domains is the manifestation of separate hysteresis effects for each of the subjumps (Fig. 1).

In summary, this study has established the following results: (1) There are substantial hysteresis effects upon the appearance and disappearance of a dissipative state, in an individual way for each subjump in ρ_{xx}. (2) The lifetime of "superheated" or "supercooled" states can range from 10^{-3} s to $\gg 100$ s. (3) The breakdown effect is sensitive to the direction of the Hall vector. (4) The effects which occur at contacts are not involved in the onset of breakdown.

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