Nonlinear effects in the nonlocal resistance of a 2D electron gas under conditions of the quantum Hall effect

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The nonlocal resistance of a 2D electron gas has been studied under conditions of the quantum Hall effect in the nonlinear regime. A breakdown of the quantum Hall effect has been observed in a nonlocal geometry. Nonlinear features have been observed in the behavior of the nonlocal resistance in the dissipative regime. The results found are interpreted on the basis of a model of edge current states for which the length scale for mixing with bulk states is determined by the magnitude and direction of the current through the sample.

The model of edge current states proposed by Büttiker[1] in 1988 has been used successfully to describe the mechanisms for current flow in 2D systems under the conditions of the quantum Hall effect. The role of edge current states is seen particularly clearly in an analysis of nonlocal effects (Ref. 2, for example). Recent studies have shown that this model is also valid in the case in which the Landau level in the interior of the sample is at the Fermi level, i.e., when the current is transported not only by edge states but also by the interior of the sample (this is the dissipative regime).[3] Unambiguous evidence for this conclusion comes from experimental observations of nonlocal effects in the dissipative regime.[3–5] Several experimental studies of nonlinear effects associated with breakdown of the quantum-Hall-effect regime by the current which is flowing have attempted to extend the applicability of the Büttiker model to this case.[6–8] However, those studies were restricted to the local resistance; nonlinear effects in the nonlocal resistance have gone unstudied, as has the role played by edge current states in the regime of breakdown of the nonlocal resistance.

In this letter we are reporting an experimental study of nonlinear effects in both the local and nonlocal resistance in the quantum-Hall-effect regime. We discuss both the dissipative and nondissipative cases. The results are interpreted in a model of edge current states.

The test samples were fabricated on the basis of an 2D electron gas in a GaAs/AlGaAs heterostructure [$N_s=4.8\times 10^{11}$ cm^{-2}, $\mu=400\,000$ cm^2/(V·s)]. The topology of the test samples is shown in the inset in Fig. 1. In the experiments we studied the resistance of the samples as a function of the direct current in various magnetic fields up to 7 T at $T=1.3$ K. We measured the differential resistance $R_{ijkl}=dV_{kl}/dI_{ij}$ of the test sample in various circuits by passing a direct current $\bar{I}_{ij}$ modulated by an alternating component $\tilde{I}_{ij}$ ($I_{ij}=\bar{I}_{ij}+\tilde{I}_{ij}$) through contacts i and j. A lock-in detector measured the voltage (V_{kl}) between contacts k and l at the frequency of the alternating current

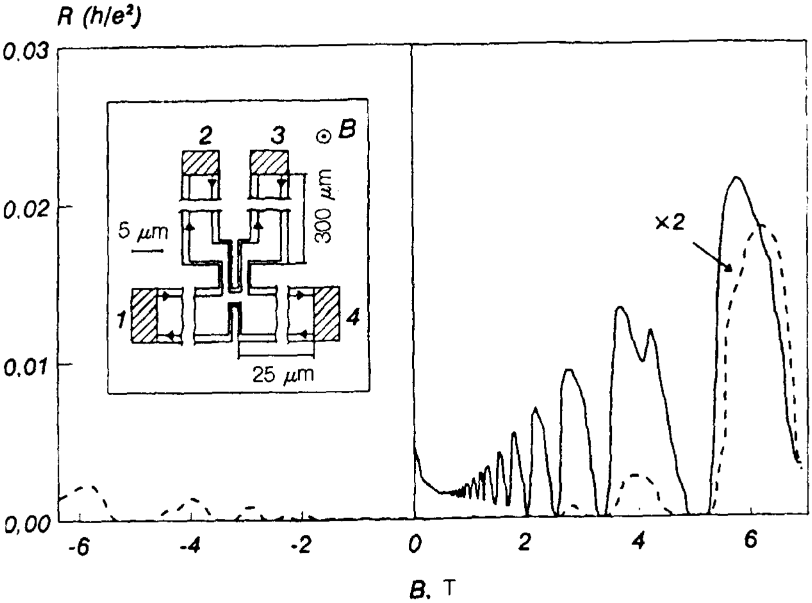

FIG. 1. The local resistance R_{1423} (solid curve) and the nonlocal resistance R_{1243} (the dashed curve) versus the magnetic field. The local resistance R_{1423} did not change when the magnetic field was reversed. The inset shows a schematic diagram of the test sample and of the edge currents corresponding to the positive direction of the magnetic field, as indicated here.

($f=70$ Hz) as a function of the direct component of the current, $\bar{I}_{ij}$. The amplitude of the alternating current $\tilde{I}_{ij}$ was 0.02 μA. The features observed in the differential resistance corresponded to direct currents in the interval 2–60 μA in different cases, so the condition $\Delta\tilde{I}_{ij} \ll \bar{I}_{ij}$ was satisfied.

Figure 1 shows the resistance of the sample as a function of the magnetic field in a local circuit (R_{1423}) and in a nonlocal circuit (R_{1243}) (the positive sign of the magnetic field corresponds to the direction shown in the inset in Fig. 1). The local resistance in high magnetic fields represents Shubnikov–de Haas oscillations. The vanishing of this resistance at $B \approx 5$ T corresponds to a filling factor $\nu=4$. The local resistance does not change when the magnetic field is reversed. It can be seen from Fig. 1 that the nonlocal resistance of the sample is zero in weak magnetic fields, up to 2 T, and also at integer values of the filling factor. Maxima of the nonlocal resistance correspond to half-integer values of the filling factor, i.e., to the dissipative regime of the quantum Hall effect. It can also be seen from this figure that the nonlocal resistance is very asymmetric with respect to the $B=0$ axis. The reason is that the geometry of the sample is not symmetric. Below we discuss separately the results found in our study of the nonlinear effects in the nondissipative and dissipative cases.

NONDISSIPATIVE REGIME ($\nu=4$)

The behavior of the local and nonlocal resistances as a function of the direct current is of the nature of a breakdown in the nondissipative regime (Fig. 2). This breakdown in

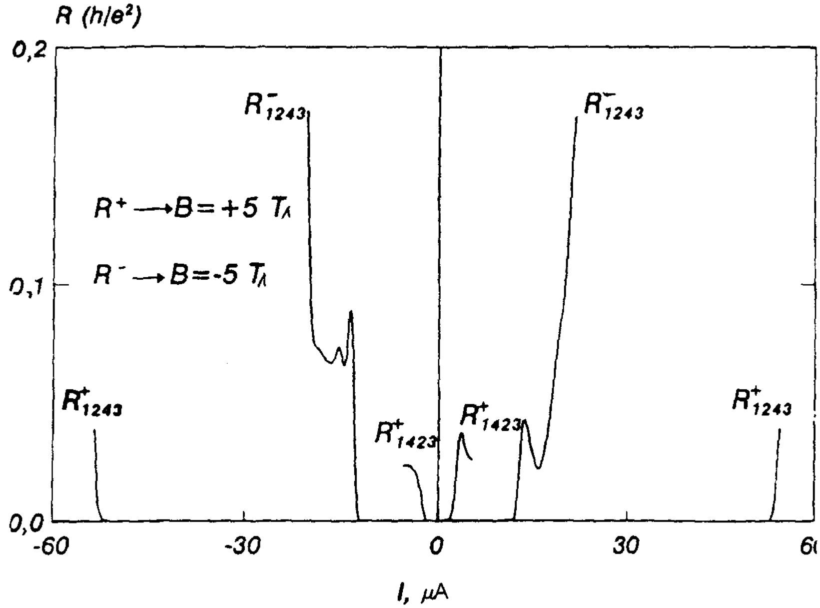

FIG. 2. Breakdown characteristics of the local resistance R^+_{1423} and of the nonlocal resistance R^+_{1243} and R^-_{1243} for positive and negative directions, respectively, of the magnetic field.

seen as a sharp increase in the resistance, from zero to 1–4 kΩ upon the attainment of the critical current I_c. The current of the local-resistance breakdown is 1.8 μA and is independent of the direction of the magnetic field and that of the current. A similar behavior is seen at $B = 3.3$ T, which corresponds to $\nu = 6$. It can be seen from Fig. 2 that the current of the nonlocal-resistance breakdown is also independent of the direction of the current, but it changes dramatically when the magnetic field is reversed, from 11 μA for the positive direction of the magnetic field to 54 μA for the negative direction. These values are considerably higher than the current of the local-resistance breakdown.

We believe that the behavior described here can be explained by the model of edge current states. According to that model, the breakdown of the quantum Hall effect results from a backscattering of edge states stimulated by the current.[6,7] As the current is raised, the region of the local arm (between contacts 1 and 2) breaks down first. Breakdown of the nonlocal resistance R_{1243} occurs at much higher currents (Fig. 2). A necessary condition for this breakdown to occur is that the edge current connecting contacts 3 and 4 exchange electrons with the interior of the sample. The latter process can occur if, with increasing current, the breakdown region propagates across the bridge and comes sufficiently close to this edge state. We believe that this process actually occurs and that the reason it does is that the edge current state which enters the bridge has an electrochemical potential μ_e which is not equal to the bulk value μ_b. Although the difference $|\mu_e - \mu_b|$ is small, it increases upon a large increase in the current, and it leads to a propagation of the dissipative breakdown region across the bridge into the nonlocal arm.

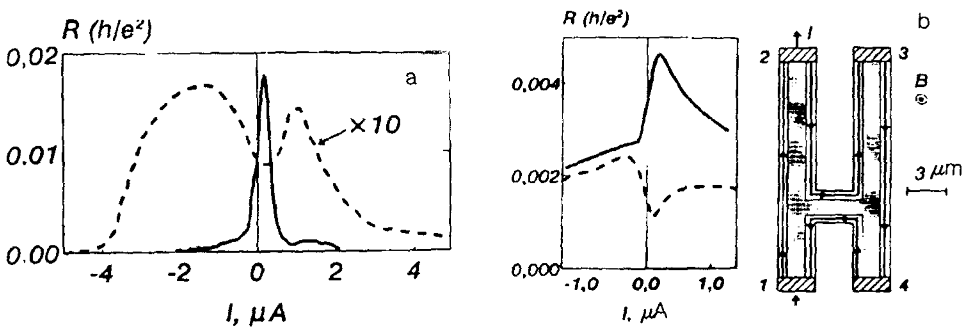

FIG. 3. a: Experimental results on the nonlocal resistance versus the current for the cases of a positive direction of the magnetic field, R^+_{1243} (solid curve), and a negative direction, R^-_{1243} (dashed curve). b: Results of a numerical calculation of R^+_{1243} and R^-_{1243} as a function of the current. Also shown here is the geometry of an H-shaped sample which is topologically equivalent to the experimental samples, with a schematic diagram of the edge currents.

The reason for the difference between breakdown currents for the nonlocal resistance for the different directions of the magnetic field is the asymmetry of the sample. In the case of a positive magnetic field, an edge current state coming from contact 2 reaches the bridge; in the case of a negative field, the state comes from contact 1. For the edge state from contact 2, the exchange of electrons with the interior is more intense than that for the edge state from contact 1, since it occurs through a narrower region with a stronger Hall field. Consequently, the difference between the electrochemical potential of the edge current state which reaches the bridge and that of the interior near the bridge is significantly smaller for a positive magnetic field than for a negative one. Since the nonlocal resistance is determined by this difference in electrochemical potentials, the critical breakdown current is much higher for the positive direction of the magnetic field than for the negative direction.

DISSIPATIVE REGIME ($\nu \approx 4.5$)

At magnetic fields $B = 5.95$ and -5.95 T, which correspond to maxima of the nonlocal resistance, we measured the nonlocal resistance as a function of the direct current. The curves are asymmetric (Fig. 3a) for both positive and negative fields. For the positive direction of the magnetic field, the resistance has a single maximum, $R^+_{1243} = 471\ \Omega$ at $I = 0.2\ \mu$A. For the negative direction of the magnetic field, the resistance has two maxima, at $I = -1.25$ and $1.1\ \mu$A. These figures correspond to $R^-_{1243} = 45$ and $41\ \Omega$, respectively. At high currents, the resistance decreases sharply.

To analyze the results on the basis of the model of edge current states, we carried out numerical calculations of the nonlocal resistance of an H-shaped sample topologically equivalent to the experimental sample (Fig. 3b). By analogy with Ref. 9 we assumed that the conductivity of the interior of the sample is described by a tensor (σ_{xx}, σ_{xy}; the value of σ_{xy} has little effect on the results, and for simplicity we set it equal to zero) and that the exchange of electrons between the edge current states and the interior is determined by the distance L. We assumed that L depends on the difference between the electrochemical potentials of the edge current states, μ_e, and of the interior, μ_b: $L = L_0 \exp(-|\mu_e - \mu_b + \Delta\mu|/t)$, where $L_0 = 100$ μm, $t = 1$ meV, and $\Delta\mu = 0.6$ meV are adjustable parameters. The parameter $\Delta\mu$ leads to an asymmetric dependence of the length L on the difference $(\mu_e - \mu_b)$, associated with the asymmetric configuration of the confining potential and also the effect of the Coulomb repulsion of electrons on the edge current states.[8] These effects are important at small values of the difference $(\mu_e - \mu_b)$. They cause L to become asymmetric with respect to the sign of the current, i.e., to become different at different edges of the sample. In this formulation, we were able to solve the problem numerically at small values of the current. The results of these calculations are shown in Fig. 3b. Comparison of the calculations with experimental data (Fig. 3a) shows that all the basic features of the experimental behavior (the asymmetry in terms of the current direction, the presence of one maximum in R^+_{1243}, and the presence of two maxima in R^-_{1243}) are described well by the model used here.

In summary, the basic features of the nonlinear behavior of the nonlocal resistance can be explained on the basis of a model of edge current states, under the assumption that the length scale of the mixing of the edge and bulk states, L, decreases with increasing current through the sample and furthermore depends on the sign of this current.

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