Hall Voltage Collapse at Filamentary Current Flow Causing Chaotic Fluctuations in *n*-GaAs

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(Received 24 July 1989)

Experimental investigations of the Hall effect at the occurrence of autonomous current fluctuations in high-purity *n*-GaAs epitaxial layers at low temperatures show that the transition to chaos is accompanied by intermittent collapses in the Hall voltage. This may represent the significant third mechanism for a transition into chaos according to the Ruelle-Takens-Newhouse scenario. Basically, space charges accumulated in the filament boundaries yield different impact ionization probabilities at opposite sides of the filament, destabilizing the current flow and causing multimodal oscillation phenomena originating at the filament borders.

PACS numbers: 72.20.−i, 05.40.+j, 72.70.+m

At low temperatures the autocatalytic process of impact ionization of shallow impurities in high-purity semiconductors leads to a nonequilibrium phase transition, usually called impurity breakdown, which brings the sample from a low-conducting phase to a high-conducting phase.[1] In the course of this transition, which is characterized by filamentary current flow, regular oscillations and different routes to chaos were observed in various materials and have been analyzed in the framework of phenomenological nonlinear dynamics.[2] Current fluctuations and chaotic phenomena may occur self-sustained under steady-state external conditions[3,4] as well as upon subjecting the system to a periodic driving force.[5] Previous investigations of *n*-GaAs epitaxial layers revealed that an external magnetic field plays a crucial role in the occurrence of autonomous multifrequency oscillations and chaos.[6] At zero magnetic field the onset of nonequilibrium current flow is associated with regular relaxation oscillations which develop into a steady-state current carried by one stable filament. Applying a magnetic field strength of no more than 10 mT destabilizes the current filament and induces quasiperiodic and frequency-locking behavior culminating in a Ruelle-Takens-Newhouse (RTN) route to chaos.[4] High-resolution reconstructions of the spatial structure of the current filament using a scanning optical microscope have shown that even the weak magnetic field asymmetrically deforms the filament boundaries[7] indicating a close relation between overall current fluctuations and local nonlinear processes occurring in the transition zone between filament and low-conducting outside regions.[8]

The main problem up to now has been the physical origin of at least three independent oscillatory modes successively undergoing Hopf bifurcations leading to a RTN scenario.[9] Regular oscillations are produced by the fundamental electric-field–dependent impact-ionization generation and recombination cycle. As a magnetic field induces space charges in the filament borders constituting the source and drain of a Hall field, dielectric relaxation of this Hall system occurs.[10] These two mechanisms together may lead to quasiperiodic and frequency-locked oscillations. In the present Letter we report on a novel nonlinear dynamical phenomenon associated with filamentary current flow in the presence of a magnetic field which represents the missing third cyclic process and points to microscopic mechanisms leading to chaos in semiconductors. Measurements of the Hall effect revealed that the Hall voltage across the filament decreases in intermittent bursts and may even collapse to vanishingly small values. It turns out that the onset of chaos is associated with the occurrence of these Hall-voltage bursts.

Experimental results are presented for a 16-μm-thick *n*-GaAs epitaxial layer of $n = 1.3\times10^{14}$ cm^{-3} electron density and $\mu = 8.9\times10^{4}$ cm^2/V s mobility at 77 K corresponding to $N_D = 5.7\times10^{14}$ cm^3 donor concentration at a compensation ratio of 77%. The specimen was mounted at the center of a superconducting magnet and immersed in liquid helium at 4.2 K. The sample geometry and the arrangement of the measuring devices is sketched in Fig. 1. The magnetic field **B** was normal to the current flow and the [100] sample surface. Four Ohmic point contacts were formed in a rectangular arrangement on the surface. The bias voltage was applied in series with a load resistor R_L of 200 kΩ on two opposite point contacts. As a probe of the current through the sample the voltage drop V was recorded across the longitudinal contacts; the voltages V_1 and V_2 at the lateral contacts were determined with respect to one of the longitudinal contacts. By definition the Hall voltage V_H is given by $V_H = V_2 - V_1$. All voltages are measured as a function of time, applying cryogenic field-effect-transistor impedance transformers soldered directly on the sample

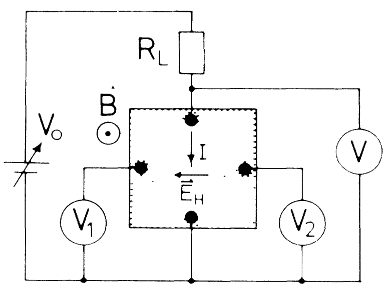

FIG. 1. Schematic drawing of the experimental arrangement and the orientation of magnetic field **B**, current I, and Hall field $\mathbf{E}_H$. The contacts are in a quadratic arrangement on a 3×3-mm^2 sample, opposite contacts being 2 mm apart.

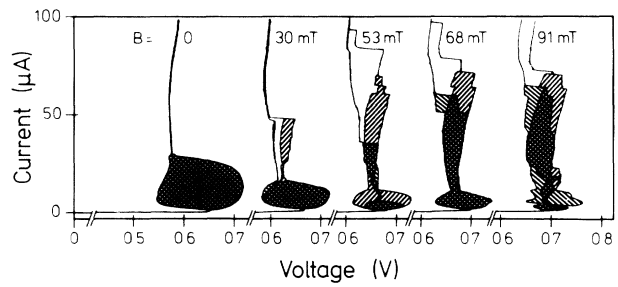

FIG. 2. Current-voltage characteristics for various applied magnetic fields B (load resistor $R_L = 1$ MΩ and bath temperature $T = 4.2$ K) recorded by a method marking the extent of the oscillatory regime (hatching inclined from bottom left to top right denotes recording direction to increasing current; top-left to bottom-right-inclined hatching denotes decreasing current).

contacts. The bandwidth and the linear dynamic range of each device was 20 MHz and 120 dB, respectively, being independent of the magnetic field. As in the case of the spatial structure of the current filament,[7] all observed dynamic effects did not change upon reversing the current and the magnetic field.

Current-voltage characteristics measured by using the longitudinal contacts are plotted in Fig. 2 for various magnetic field strengths. A dynamical method was applied to record the extension of fluctuations[6] which are shown in Fig. 2 by the hatched areas. Two types of oscillations having distinctly different amplitudes for low magnetic fields may clearly be recognized. Just above the threshold of impact-ionization breakdown large-amplitude relaxation oscillations occur, which are strictly periodic and rise in frequency up to 5 MHz with increasing average current. At $B = 0$ and upon raising the average current, the relaxation oscillations vanish again by formation of a stable high-current filament,[7] whereas at $B \neq 0$ a sharp transition to small-amplitude fluctuations of complex temporal behavior is observed. Quasiperiodic, frequency-locking, chaotic, and intermittent switching current behavior, based on multifrequency oscillations, all occur in this latter regime.

In Fig. 3 the lateral voltages V_1 and V_2, the Hall voltage $V_H = V_2 - V_1$, and the longitudinal voltage V obtained at $B = 0.5$ T are plotted as a function of the external voltage V_0. Hatched areas indicate fluctuations in these voltages again. In the stable prebreakdown regime the voltages V_1 and V_2 are also stable and increase symmetrically with rising bias voltage V_0 for $B = 0$. Applying a magnetic field, a Hall voltage V_H is generated following the rules of the conventional Hall effect. Above the threshold of breakdown in the regime of regular relaxation oscillations, a synchronous crosstalk of the current is observed in both lateral voltages V_1 and V_2 and with smaller amplitudes in V_H. This behavior again agrees with the standard Hall effect. According to the geometrical orientation of the magnetic field and the current flow shown in Fig. 1, the voltages V_1 and V_2 correspond to the potentials at the negatively and positively charged sides of the filament, respectively. The temporal behavior of the lateral voltages changes drastically in the regime of complex multifrequency oscillations. In spite of the fact that with increasing V_0 a sequence of quasiperiodic, mode-locking, and chaotic behavior of the longitudinal current is observed, the potential at the positively charged side of the filament remains constant in time. The potential V_1 measured at the negative side is also constant up to a critical value V_{0c} depending on the magnetic field strength. Above V_{0c}, the voltage V_1 exhibits positive pulses in an intermittent manner. V_1 may even rise up to V_2, yielding a total collapse of the Hall voltage V_H. In Fig. 4 typical Hall-voltage bursts are shown simultaneously with the fluctuating longitudinal voltage V. Bursts in V_H appear to be triggered by a de-

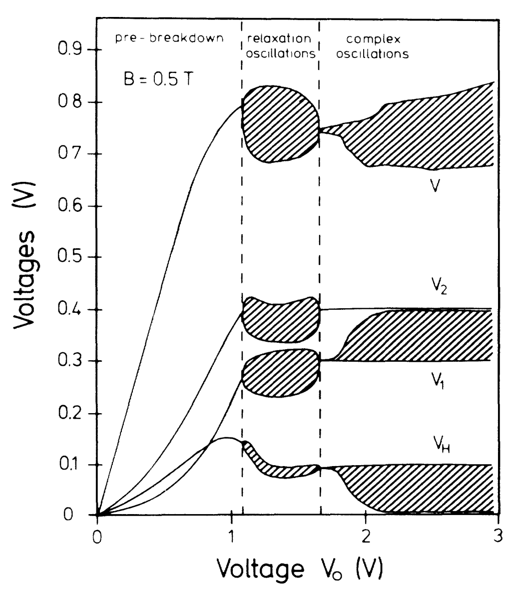

FIG. 3. Potentials V, V_1, V_2, and Hall voltage V_H as a function of the external voltage V_0 for an applied magnetic field $B = 0.5$ T. The extent of fluctuations is marked by hatched areas.

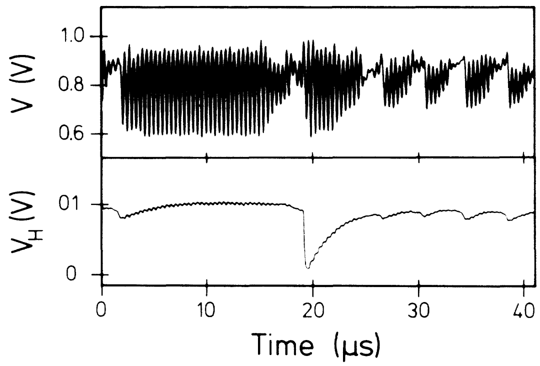

FIG. 4. The temporal characteristics in the longitudinal voltage V and the Hall voltage V_H for an applied magnetic field $B=0.28$ T and $V_0=3.6$ V.

crease of the amplitude and an increase of the average oscillating voltage V.

The essential microscopic mechanism causing all observed dynamic effects is the electric field dependence of the impact-ionization probability. Regular relaxation oscillations are simply due to oscillations of the electric field and thus the impact-ionization probability around their critical values of breakdown, which repetitively causes ignition and extinction of the current flow yielding a flushing filament. At a sufficiently large average current a stable filament is formed at $B=0$. The electric field is strong enough to sustain the current flow in the filament ionization of donors from the ground state and, in particular, from the much more weakly bound excited states.[11] In the high-Ohmic outside regions, where practically all electrons are in donor ground states, the electric field is too low to trigger an impact-ionization avalanche. Applying a magnetic field generates an asymmetry of the electron distribution leading to a Hall field across the filament. As shown previously, the free-carrier multiplication rate due to impact ionization of shallow donors is much larger in the positively charged border of the filament than in the negatively charged edge.[7] Thus, the conditions of impact-ionization instability at the negative side are met at a lower longitudinal voltage than at the negative side. The observed dynamical processes may be understood in the following way: Above a critical voltage in the presence of a current filament additional free carriers are generated at the positive boundary by impact ionization mainly from populated excited donor states,[7,8] leading to a lateral excursion of the filament. This causes an oscillatory process in this filament boundary by the same mechanism as for the ignition-extinction cycle of the total filament. Coupling to dielectric relaxation[11] generates the quasiperiodic and frequency-locked current behavior. Obviously, free electrons penetrate only partly into the positive region leaving the external voltage V_2 practically constant. Continuous relaxation of electrons into donor ground states in the fluctuating filament border reduces the amplitude of oscillations. Thus the average longitudinal voltage V increases (see Fig. 4) and eventually reaches the point where in the opposite negatively charged filament side an impact-ionization–induced avalanche may also be initiated, driving the system into chaos. A pulse of large current density on the negative side of the filament occurs. Assuming that pinching contracts the width of the current flow towards the center of the filament, positive charged donors are left behind. This might cause the observed rapid rise in the potential V_1 and the collapse of the Hall voltage (see Fig. 4). Again the increased average current lowers the longitudinal voltage V, terminating this process and restabilizing the current flow. The decay times of the voltage bursts are determined by the sample resistivity and internal and external capacities. Theoretical calculations show that the local variations of the impact-ionization probability are due to the shielding of charged impurities by free electrons.[12] In the depleted, positively charged filament boundary the local electric field is higher than that one of the negatively charged region, lowering and raising the threshold of impact-ionization breakdown inside these regions, respectively.

In summary, by measurements of the temporal structure of the lateral potentials in the case of filamentary current flow, a concise microscopic physical basis of a Ruelle-Takens-Newhouse scenario could be deduced for the first time. Different impact-ionization rates generated at the filament boundaries by an external magnetic field give rise to different modes of cyclic generation and recombination of free carriers in the thin semiconductor layer at the two sides of the current filament. Together with dielectric relaxation, quasiperiodic and, at increased coupling strength for higher magnetic fields, frequency-locked current behavior occurs. Intermittent Hall-voltage bursts finally drive the system into chaos.

We thank E. Bauser, Max-Planck-Institut für Festkörperforschung, Stuttgart, for provision of the sample and E. Schöll for helpful discussions. Financial support by the Deutsche Forschungsgemeinschaft is gratefully acknowledged.

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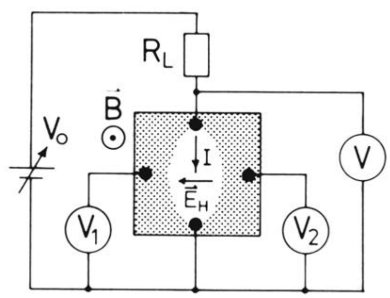

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