RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 45, NUMBER 20 15 MAY 1992-II

Regular and chaotic current oscillations in *n*-type GaAs in transverse and longitudinal magnetic fields

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(Received 5 February 1992)

Self-sustained current oscillations due to impurity breakdown in *n*-type GaAs epitaxial layers are reported for various magnetic-field strengths and orientations of the field with respect to the direction of current. In all cases relaxation oscillations at the onset of breakdown and formation of a current filament in the postbreakdown regime are observed. A magnetic field normal to the epitaxial layer destabilizes the filament and causes multifrequency oscillations and chaotic fluctuations. On the other hand, if the magnetic field lies in the plane of the layer the filamentary current flow is stable up to field strengths of 2 T.

At low temperatures impact ionization of shallow impurities in high-purity semiconductors leads to a nonequilibrium phase transition which transforms the sample from a low-conducting phase to a high-conducting phase where the current rapidly increases at an almost constant voltage.[1,2] In many cases this impurity breakdown is associated with the formation of a current filament and the growth of the current at constant voltage is caused by a lateral increase of the filament.[3,4] In the course of the phase transition nonlinear oscillations including different routes to chaos were observed in various semiconductor materials.[5–9] Previous investigations of *n*-type GaAs thin epitaxial layers revealed that an external magnetic field plays a crucial role for the occurrence of autonomous multifrequency oscillations and chaotic fluctuations.[10,11] Without a magnetic field at the threshold of breakdown a repetitive ignition and extinction of a filament yields regular relaxation oscillations which proceed with increasing average current into a stable filamentary current flow. Application of a magnetic field normal both to the direction of the current and to the plane of the epitaxial layer significantly changes the temporal structure of the oscillations and, most important, destabilizes the current filament. At a magnetic-field strength of not more than 10 mT two independent oscillatory modes evolve and, with increasing magnetic field, a third mode drives the system into chaos following the Ruelle-Takens-Newhouse scenario.[4] In the chaotic regime Hall voltage collapses indicate drastic rearrangements of the lateral charge distribution.[12] Reconstructions of the spatial structure of the current filament using an optical scanning microscope[4] have shown that even small magnetic fields increase and decrease the impact ionization probabilities in the filament boundaries due to accumulation and depletion of mobile charges by the Lorentz force, respectively.

The experimental results for the observed dynamical phenomena revealed a concise microscopic basis which has been used to model current-voltage characteristics.[13] This gives rise to different modes of cyclic generation and recombination of free carriers in the filament boundaries and in the filament itself yielding the multifrequency oscillations. Coupling of the modes by carrier drift and diffusions causes the observed nonlinear dynamical behavior in particular chaos.

In the present paper we report on measurements of autonomous oscillations and current-voltage characteristics with the orientation of the magnetic field in the plane of the epitaxial layer both parallel and normal to the current flow. In comparison to the transverse magnetic-field configuration, our results give clear evidence for the fundamental role of the Lorentz force and the Hall field for destabilizing the current filament in thin *n*-type GaAs films. In the case of the magnetic field parallel to the current only large amplitude regular relaxation oscillations and stable filamentary current flow were observed. With the magnetic field normal to the current but in the plane of the semiconductor layer, large amplitude regular and chaotic oscillations were found but no destabilization of the current filament.

The measurements were carried out on a 16-μm-thick *n*-type GaAs epitaxial layer of $n = 1.3\times10^{14}$ cm^{-3} electron concentration 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 density at a compensation ratio of 77%. The layer was grown on a semi-insulating GaAs substrate of 3×3 mm^2 area. At the center of two opposite edges of the sample Ohmic contacts were prepared by alloying Indium spheres of 0.5 mm diameter. The free distance between these two point contacts was 2 mm. The sample was fixed in the center of a superconducting magnet and immersed in liquid helium at 4.2 K. A mount was used which allowed a precise orientation of the sample in the magnetic field. Thermal background radiation was suppressed by a cold metallic shield. The sample was biased in series with a 100 kΩ load resistor by a constant current source. The voltage drop across the sample was measured as function of time applying a cryogenic field-effect transistor impedance transformer fixed very close to one sample contact. The bandwidth and the linear dynamic range of the device was 20 MHz and 120 dB, respectively, being independent of the magnetic field. From the constant current through the linear combination of load resistor and sample and the voltage oscillation across the sample, current-voltage characteristics were numerically reconstructed yielding the extent of oscillations in the current-voltage plane.[11]

The geometrical orientations of the magnetic field with respect to the sample and the direction of the current are plotted in Fig. 1. Three different configurations were investigated: the magnetic field (a) normal to the plane of the sample and normal to the current, (b) parallel to the current, and (c) in the plane of the epitaxial layer and normal to the current. The experimental results for these three configurations are represented in Figs. 2-4. The obtained current-voltage characteristics are shown for different orientations and strengths of the magnetic field. The hatched areas show regions of fluctuations where no definite relation between current and voltage exists. The increase and the decrease of the average current is indicated by right- and left-inclined hatching, respectively, and by arrows. Two examples of the temporal structure of voltage oscillations are plotted in the insets of the figures. The oscillations were measured for different biasing conditions. The corresponding load lines are shown as dash-dotted lines cutting through the current-voltage characteristics. The upper and lower load lines belong to the upper and lower insets, respectively.

In Fig. 2 the well-known results are reproduced for the usual transverse configuration (a) at zero magnetic field and (b) $B=100$ mT.[11] At $B=0$ [Fig. 2(a)] large voltage amplitude relaxation oscillations occur just above the impact ionization threshold. These oscillations are strictly periodic and rise in frequency up to about 5 MHz with increasing average current. Above a certain current, the current flow stabilizes by formation of a stationary filament. In that range of the current-voltage characteristics, hysteresis and abrupt steps in the curves are observed which were attributed to the formation of multiple filaments.[14] Such patterns are associated with strong structures in the magnetoresistance[15] and nonequilibrium far-infrared photoconductivity[16] and may also be due to impact excitations of shallow donors, impact ionization out of excited states, and a sudden displacement of a current filament.[16] With increasing magnetic field the area of regular oscillations shrinks and the stationary current filament is destabilized yielding complex oscillations with typically smaller voltage amplitudes than those of regular oscillations at $B=0$. These oscillations show quasiperiodic, mode-locked, and chaotic behavior depending on the magnetic field and the average current.[11,17]

In Fig. 3 corresponding measurements in the configuration in Fig. 1(b) are displayed with the magnetic field parallel to the current for $B=150$ mT [Fig. 3(a)] and 1 T [Fig. 3(b)]. In both cases the gross structure of the

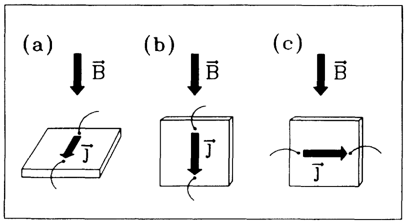

FIG. 1. Geometrical configurations of the epitaxial layer, the current **j**, and the magnetic field **B**.

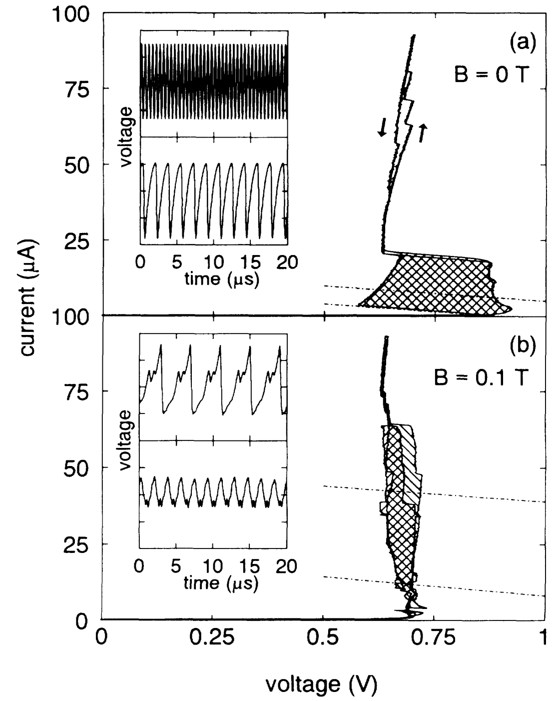

FIG. 2. Current-voltage characteristics for (a) zero magnetic field and (b) $B=100$ mT for the configuration displayed in Fig. 1(a). The insets show oscillations of the voltage across the sample for different biasing conditions indicated by load lines (dash-dotted lines) in the current-voltage characteristic. The upper and lower load lines belong to the upper and lower insets, respectively.

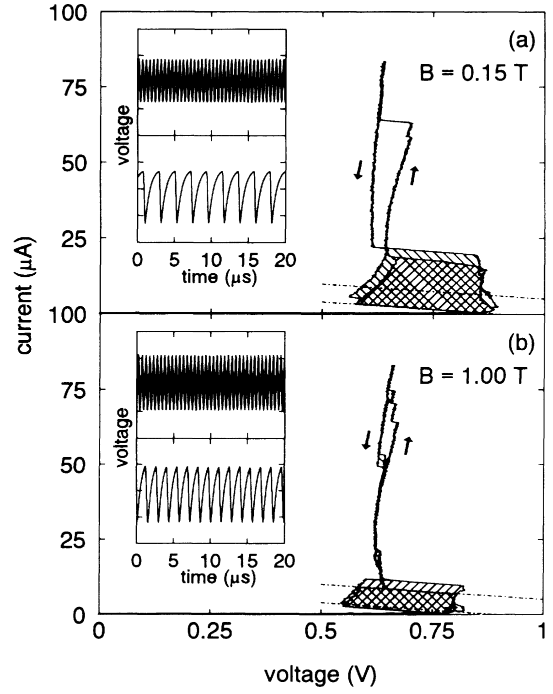

FIG. 3. Current-voltage characteristics for the configuration displayed in Fig. 1(b) for (a) $B=150$ mT and (b) $B=1$ T. The insets have the same meaning as in Fig. 2.

current-voltage characteristics is identical to that of $B=0$ [Fig. 2(a)] and very different from the transverse configuration in Fig. 1(a) shown in Fig. 2(b). Up to $B=2$ T, the largest magnetic field in the present study, only regular oscillations and stable current flow were observed as in the case of $B=0$. Increasing the magnetic field reduces the current where the transition from relaxation oscillations to a stationary current filament takes place. As a result a longitudinal magnetic field stabilizes the filamentary current flow. This observation disagrees with measurements reported by Aoki *et al.*[18] who reported above $B=28$ mT oscillations including chaos for the longitudinal configuration in similar *n*-type GaAs layers. We would like to emphasize, however, that to get the characteristics of Fig. 3 the sample must be very carefully adjusted in the magnetic field. A slight misalignment yields a transverse component of field being sufficient to induce complex oscillations. Additionally, not all samples showed a stationary current in the range above the regular oscillations. A reasonably homogeneous semiconductor is obviously necessary to have a smooth filament which may be oriented parallel to the magnetic field without too large transverse components. These conditions are certainly better fulfilled in samples with point contacts used as in here, where the filament is better fixed within the semiconductor layer than for stripe contacts applied in the above work.[18]

Measurements with the magnetic field in the plane of the epitaxial layer but perpendicular to the current [the configuration in Fig. 1(c)] are shown in Fig. 4 for (a) $B=100$ mT and (b) 750 mT. Now the Lorentz force and the Hall field are normal to the plane of the semiconductor. As the current filament fills the thickness of the layer there are no lateral degrees of freedom in form of filament boundaries, which may be affected by the Hall field as in the case of the transverse configuration of Fig. 2. Consequently, at low magnetic fields [100 mT, Fig. 4(a)] complex oscillations do not appear for average currents above the area of relaxation oscillations in the current voltage plane. The threshold voltage of breakdown is higher at $B=750$ mT than at 100 mT due to the transverse magnetoresistance. The rough pattern of the current-voltage characteristic, nevertheless, is the same as in the case of $B=0$ [Fig. 2(a)] and does not change much with increasing magnetic field strength. At high fields, however [750 mT, Fig. 3(b)], in the range of large voltage amplitude oscillations where a well-developed current filament does not yet exist, chaotic fluctuations may also be observed. Regular relaxation oscillations due to repetitive ignition and extinction of a filament develop into chaos with rising bias current. We point out that due to the confinement of the carriers normal to the magnetic field which itself is perpendicular to the current flow, the experimental configuration corresponds to the geometry of the local theory of Hüpper and Schöll.[19] These authors showed that dielectric relaxation of both the applied electric field and the Hall field coupled with impact ionization may yield self-generated oscillations and period-doubling routes to chaos without spatial degrees of freedom.

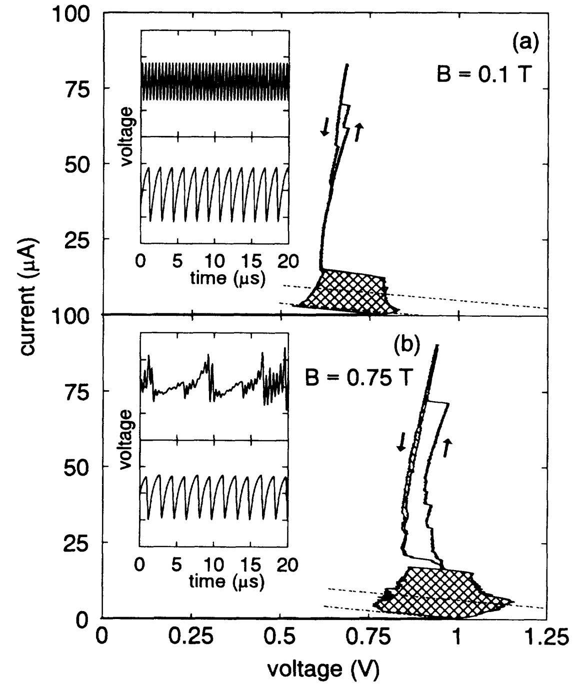

FIG. 4. Current-voltage characteristics for the configuration displayed in Fig. 1(c) for (a) $B=100$ mT and (b) $B=750$ mT. The width of the line for the decreasing current in the range of filamentary current flow is due to noise. The insets have the same meaning as in Fig. 2.

In conclusion, our results demonstrate the importance of the Lorentz force and the spatial degrees of freedom of the filament boundaries for the occurrence of multifrequency oscillations and chaos in the filamentary current flow regime of thin *n*-type GaAs layers. If space charges are accumulated at the boundaries of the current filament by the Hall effect, different modes of cyclic generation-recombination processes occur in the filament and at opposite edges of the filament yielding quasiperiodic, mode-locked oscillations, and chaotic fluctuations. If the Hall field is normal to the plane of the sample the filament boundary oscillations are suppressed due to the confinement of the free carriers and increased free-carrier recombination at the interfaces of the thin semiconductor layer. If the magnetic field is parallel to the current filament no Lorentz force arises and the current flow stays stationary, consequently.

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

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