Reconstruction of the spatial structure of current filaments in n-GaAs in a magnetic field

A. Brandl, M. Völcker,[a] and W. Prettl
Institut für Angewandte Physik, Universität Regensburg, D-8400 Regensburg, Federal Republic of Germany

(Received 13 March 1989; accepted for publication 12 May 1989)

The spatial pattern of current filaments generated by impurity breakdown has been investigated in a semiconductor for the first time as a function of the magnetic field. Large asymmetries of shallow impurity excited-state population were observed occurring at opposite edges of a filament normal to the magnetic field. Deformation of filament boundaries evolves at very low field strengths being comparably small to those which destabilize current flow yielding current fluctuation and chaos.

At low temperatures impact ionization of shallow impurities in high-purity semiconductors causes highly nonlinear current-voltage characteristics. At a critical electric field strength, impact ionization rate of impurities exceeds the capture rate of free carriers yielding a rapid increase of the current at a practically constant voltage across the sample. Steady-state properties of the transition from the low-conducting state to the high-conducting state have been described in the framework of nonequilibrium phase transformations.[1,2] In the course of the transition, spontaneous oscillations and chaotic current fluctuations were observed in various materials[3-9] and have been analyzed in terms of nonlinear dynamics.[10,11] Recently detailed investigations of n-GaAs epitaxial layers revealed that an external magnetic field plays a crucial role for the occurrence of chaos.[7,12] Without a magnetic field only regular relaxation oscillations were observed having a single fundamental frequency. Applying a magnetic field of not more than 10 mT changes the temporal structure of the current flow significantly. A second oscillatory mode spontaneously evolves which, with increasing magnetic field strength, generates a sequence of quasiperiodic and mode-locking states. Finally, a third mode drives the system by a Ruelle–Takens–Newhouse transition into chaos.[6,7] This scenario requires at least three independent oscillations being nonlinearly coupled. Thus, a surprisingly small magnetic field substantially affects the nonlinear dynamics of electrons in a state far from thermal equilibrium.

The nonlinearity of the current-voltage characteristic and the pertinent current fluctuations are intimately related to a filamentary structure of the current flow. The increase of the average current at constant voltage is maintained by a lateral growth of current filaments. Several methods have been applied to reconstruct the spatial pattern of the current distribution in semiconductors under nonequilibrium conditions.[13-16] Recently high-resolution filament "images" were achieved by using low-temperature scanning electron microscopy.[17] Electron beam techniques, however, are limited to zero magnetic field strength. In the present contribution we report on a new purely optical method which allows investigations with magnetic fields of any strength. Measurements were carried out on n-GaAs epitaxial layers. The focused beam of a He-Ne laser was scanned line by line across the sample surface and the photocurrent through the sample was monitored as a function of the position of the focal spot. Spatially resolved ridge-like structures of the response were observed. They are attributed to photocurrent multiplication in the boundaries of a current filament, thus indicating the extent of the filament. Our measurements show that the widths and the photosignal of filament boundaries are extremely sensitive to an external magnetic field becoming asymmetric for field strengths being comparably small like those which cause chaotic current fluctuations. Hence, the physical mechanism of multimodal oscillations and chaos in n-GaAs must be searched for in the transition zones between current filaments and low-conducting regions.

Experimental results are presented for an epitaxial layer of 29 μm thickness and of 4.1 mm $\times$ 3.7 mm area. The donor concentration, compensation ratio, and electron mobility at 77 K were $N_D = 12 \times 10^{14}$ cm^{-3}, $N_A/N_D = 0.9$, and $\mu = 4.5 \times 10^4$ cm^2/V s, respectively. Point contacts were formed on opposite edges of the layer being 3.3 mm apart. The sample was mounted at the center of a superconducting magnet in an optical immersion cryostat and cooled to 1.8 K. The magnetic field was applied normal to the layer surface. The sample exhibits a pronounced S-type current-voltage characteristic with negative differential conductivity. With rising average current, three different regimes may be distinguished[7]: the pre-breakdown regime of high resistance, a regime of switching between low- and high-conducting states yielding an oscillating current with large amplitude, and the post-breakdown regime of small current fluctuations approaching stable current flow. The measurements were carried out in this latter regime of the current-voltage characteristic where the formation of current filaments is expected. The sample was biased in series with a load resistor of 1 kΩ and the interband excitation induced voltage change across the sample was recorded. The spatially filtered beam of the He-Ne laser was scanned across the sample surface by a mechanical deflection unit. Line scans were performed reflecting the beam by a rotating drum carrying 16 individually adjustable plane mirrors. Subsequent lines were addressed by tilting the axis of the drum. The beam was focused on the epitaxial layer by a lens of 30 mm focal length giving a spot

[a] Permanent address: Max-Planck-Institut für Quantenoptik, D-8046 Garching, FRG.

 0003-6951/89/290238-03$01.00

diameter of 15 μm which determines the spatial resolution of the device. The transient photosignal was recorded using a waveform digitizer and the photocurrent pattern was numerically determined.

Above a threshold intensity, sharp structures were observed superimposed on an almost structureless signal background. Spatially resolved line scans of the photocurrent signal above background are displayed in Fig. 1 for different magnetic field strengths. The signal heights in Fig. 1 represent the photocurrent detected as a function of focus position of the exciting laser on the sample surface. The irradiation intensity was 70 μW and the response of each line was calculated by averaging 100 scans. The orientations of the bias current and the magnetic field with respect to the sample are indicated in Fig. 1(a). The photoconductivity pattern at $B = 0$ shows two ridge-like structures very similar to those observed in p-Ge applying electron microscope techniques.[17] The ridges are parallel to the current flow and located almost symmetrical to a line connecting both electrical contacts. In Figs. 1(c)–1(h), measurements at 10 mT, 100 mT, and 1 T are plotted. For each magnetic field strength two recordings are shown differing in the orientation of the magnetic field. For the right column the field points upward in the sense of Fig. 1(a), and in the left column the field is downward. The measurements demonstrate that the presence of a magnetic field has a drastic effect on the spatial distribution of the photoresponse. The symmetry of both ridge-like structures is broken which can be observed clearly at field strengths as small as 10 mT. With increasing magnetic field the response of one ridge rapidly grows whereas the signal in the other ridge decays. Inverting the orientation of the magnetic field reflects the spatial pattern on the plane of symmetry of the $B = 0$ structure as expected from inversion of the Lorentz force. Not shown in Fig. 1, inverting both current and field reproduces the original pattern. Finally, we note that the distance between the ridges is independent of the magnetic field strength. Measurements with various bias currents in the high-conducting regime revealed that the distance of the ridges grows almost linearly with rising current. The form of the response pattern is independent of scanning conditions like speed or scanning direction.

In Fig. 2 we show the response over one single line as function of intensity at $B = 0.5$ T. The sharp structures show a threshold-like onset at about 2 μW. Below this intensity the signal along the line is a smooth structureless curve due to interband photoconductivity. Above the threshold the peak response of the large ridge remains practically constant whereas the small ridge increases slightly with rising intensity. At large intensities the widths of the ridges grow asymmetrically outside the valley enclosed by them.

All experimental observations demonstrate that the spatially resolved signal ridges are caused by photocarrier multiplication in the boundaries of a single current filament being located in the valley between the ridges. In the current filament, the free-electron concentration approaches saturation. Crossing the filament boundary to the high resistive region outside, the free-electron density gradually decays to very low values. In this transition zone a high population of excited donor states is expected. Well outside the filament almost all electrons are bound to donor ground states. Excess free carriers generated by interband transitions increase the impact ionization probability of shallow donors. Above an intensity threshold the free-carrier concentration may be just sufficient to trigger an avalanche breakdown in regions of excited-state population, but not in those of predominant ground-state population. This is due to the fact that the binding energy of the ground state of hydrogen-like impurities is at least three times larger than that of the first excited state. Inside the filament photocarrier, multiplication cannot occur because the donors are depopulated. Thus, further raising the irradiation intensity may only widen the photosignal

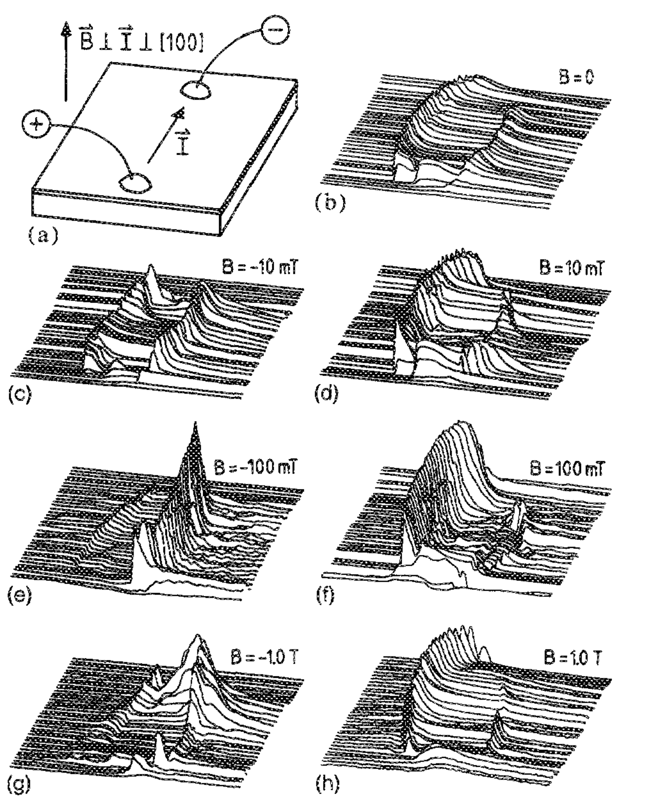

FIG. 1. Reconstruction of a current filament in an n-GaAs epitaxial layer at a bias current of 0.82 mA. (a) Sample geometry. (b)–(h) Spatially resolved line scans of the photocurrent for various magnetic field strengths. The signal heights are the photocurrent detected as function of the position of interband excitation on the sample surface. $B > 0$ and $B < 0$ indicate the magnetic field pointing upward and downward, respectively.

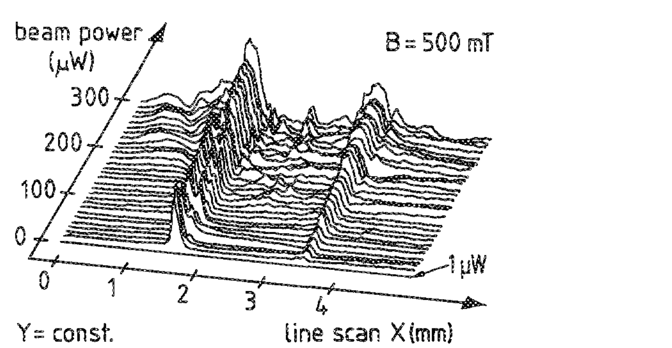

FIG. 2. Intensity dependence of the photocurrent signal along a single line scan at $B = 0.5$ T for various laser beam intensities. The foremost line (1 μW) is a recording below threshold of photocarrier multiplication.

ridges outside the filament into the high resistive zones due to enhanced impact ionization probability of donors in the ground state. Just this behavior is shown in Fig. 2.

The most striking feature is the formation of differently shaped filament boundaries by a relatively weak magnetic field. This phenomenon may be understood from filament formation and free-carrier drifting and diffusion in crossed electric and magnetic fields. Charge neutrality is lifted in the filament boundaries giving rise to an electric Hall field across the current filament. In the geometry of the measurements of Fig. 1 with the magnetic field pointing upward, electrons are accumulated in the right filament boundary and the left transition zone is depleted getting positively charged. The diffusion length in the negatively charged layer generated by mobile electrons decreases with rising magnetic field like $1/B^{\alpha}$ with α between 1 and 2.[18] Thus, the width of the right boundary shrinks. The filament as a whole tends to shift to the right side leaving behind a widening left transition zone which is positively charged by immobile ionized donors.

In conclusion, we have reconstructed the spatial pattern of nonequilibrium current flow by a new optical method and studied the evolution of a current filament as a function of a transverse magnetic field. It seems to be conceivable that the asymmetry of the electron distribution across the filament is the physical reason of nonlinear generation-recombination processes of different cycle periods and, hence, yielding the observed multifrequency oscillations and chaotic current fluctuation.

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

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