Semicond. Sci. Technol. 8 (1993) 1298–1302. Printed in the UK

Magnetoresistance of n-GaAs at filamentary current flow

S A Proshin†, V G Golubev†, S Würfl‡, J Spangler‡, A Schilz‡ and W Prettl‡

† A F Ioffe Physico-Technical Institute, St Petersburg, Russia
‡ Institut für Angewandte Physik, Universität Regensburg, D-8400 Regensburg, Federal Republic of Germany

Received 27 January 1993, accepted for publication 23 March 1993

Abstract. A large number of sharp structures are observed in the 4.2 K magnetoresistance of n-GaAs biased above impurity breakdown in a regime where current flow is filamentary. Most of the structures cannot be attributed to spectral properties of the semiconductor such as impact excitation of shallow donors or the magnetoimpurity effect. Experimental results give evidence that these structures are caused by a redistribution of the filamentary current flow when one filament border is swept across an imperfection in the material.

1. Introduction

At low temperatures, impurity breakdown in high-purity semiconductors leads to a non-equilibrium 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]. This highly nonlinear current–voltage characteristic arises from the formation of a current filament due to the autocatalytic process of impact ionization of shallow impurities [3, 4]. A strongly ionized channel in the sample carries nearly all the current, and the growth of the current at constant voltage is caused by a corresponding increase of the channel width. In the course of filament formation and in the regime of filamentary current flow, hysteretic structures in the current–voltage characteristics and self-sustained regular and chaotic oscillations have been observed in various semiconductor materials [5]. Previous investigations on thin epitaxial layers of n-GaAs revealed that an external magnetic field normal to the plane of the semiconductor plays a crucial role in the formation and the stability of a current filament [6]. Without a magnetic field or with a field parallel to the current flow, at the threshold of breakdown a repetitive ignition and extinction of a current filament yields regular relaxation oscillations which proceed with increasing average current into a stable filamentary current flow. Application of a magnetic field in the plane of the epitaxial layer and normal to the current drives the relaxation oscillations into chaos, which may be due to the nonlinear coupling between the external electric field and the Hall field. The current filament is not affected in this magnetic field configuration. A magnetic field normal to both the epitaxial layer and the current flow leaves the relaxation oscillations unchanged but destabilizes the filamentary current flow. Typically a transition to chaos following a Ruelle–Takens–Newhouse scenario is observed. For any magnetic field configuration, however, stable filamentary current flow is found at a sufficiently high average current. Reconstructions of the spatial structure of the current filament using a scanning optical microscope [4] have shown that even small magnetic fields increase and decrease the impact ionization probabilities at the filament boundaries due to the accumulation and depletion, respectively, of mobile charges by the Lorentz force. In the chaotic regime the collapses of the Hall voltage indicate drastic rearrangements of the lateral charge distribution [7].

Here we report on a detailed investigation of the magnetoresistance of n-GaAs epitaxial layers. A large number of structures have been found in the hysteretic region of the current–voltage characteristic where autonomous oscillations occur and at higher currents in the range of stable filamentary current flow. Similar features in the magnetoresistance have previously been observed by Holmes *et al* [8] in a biasing regime very close to but below breakdown characterized by warm or hot electron conditions. The structures were attributed to impact excitation of shallow impurities out of the ground state and by inelastic scattering of hot electrons from excited neutral donors. In the present case, however, most of the structures cannot be associated with spectral properties of the material. The positions of the structures on the current scale depend strongly on the magnetic field. Some structures are found to shift up in current with rising magnetic field strength while others move downwards. More importantly, however, no strong feature could be detected that occurred at the same current if the magnetic field was inverted. This

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result rules out an explanation based on energy level separations, like inelastic scattering of carriers from donors [8, 9] due to impact excitations or the magneto-impurity effect [10]. Instead, the experimental findings support an interpretation in terms of spontaneous filament nucleation and sudden displacements of filament borders due to imperfections in the material. Magnetoresistance measurements complemented by reconstructions of the spatial distribution of current flow [3] may be a new method for investigating the dynamics of current filaments.

2. Experimental technique

The measurements were carried out on n-GaAs epitaxial layers prepared on semi-insulating substrates by vapour phase deposition. Results are presented for a sample of effective donor concentration $N_D - N_A = 6\times10^{13}\,\mathrm{cm}^{-3}$, compensation ratio $N_A/N_D = 0.8$ and layer thickness $45\,\mu$m. The size of the sample was $7 \times 3\,\mathrm{mm}^2$ and ohmic indium point contacts were alloyed on opposite edges within a distance of 4 mm. The sample was immersed in liquid helium at 4.2 K in the centre of a superconducting magnet and shielded against thermal infrared radiation by a metallic box. For all measurements presented here, the magnetic field was applied normal to the plane of the semiconductor layer. Both orientations of the magnetic field pointing upward and downward with respect to the substrate-to-film direction were investigated and are indicated as positive and negative fields respectively. The sample was biased by a constant-current source. A small alternating current of frequency 1 kHz was superimposed on the biasing current and the AC voltage response across the sample was measured by the lock-in technique. The signal yielded the derivative of the voltage versus current and was measured as function of the current for various magnetic fields. This procedure is different from the usual magnetoresistance measurements where the derivative versus magnetic field is recorded at constant current or constant voltage. The measurement of the differential resistance, however, allows a more obvious comparison with the current–voltage characteristic.

The analysis will be limited to structures in the differential resistance which occur in biasing regimes where a well developed and stable current filament exists. In this case the power spectrum of the voltage response contains only one fundamental frequency, which is equal to the current modulation frequency. In the vicinity of the instability, where self-sustained oscillations occur, the externally applied current modulation mixes nonlinearly with internal oscillations, leading to a whole class of dynamical phenomena [11]. In the present method of lock-in signal recovery such effects are obscured by the averaging procedure. Therefore we will explicitly exclude them from discussion. In order to relate the observed phenomena to the spatial extent of the current flow, the current filament in the sample has been reconstructed using a laser scanning microscope. The focus of a spatially filtered HeNe laser beam of about 15μ m diameter has been scanned across the sample surface by a mechanical deflection unit and the photoconductive signal induced by interband excitation has been recorded as a function of the position of the laser focus. This procedure yields sharp structures in the photoconductive signal at the filament boundaries, which allow the width of the current filament to be measured [4].

3. Experimental results

Figure 1 shows the results of measurements obtained at zero magnetic field. In the insert of this figure the DC current–voltage characteristics measured with a constant-current source is plotted. The current–voltage relation displays the typical nonlinear behaviour of high-purity n-GaAs at low temperatures where the thermal energy is much smaller than the binding energy of shallow donors. Impurity breakdown occurs at about $U_b = 1$ V and the sustaining voltage of current flow far from thermal equilibrium is $U_s = 0.7U_b$ (see inset of figure 1). The high-ohmic regime, $U < U_b$, is followed by a hysteretic portion where regular relaxation oscillations occur due to a repetitive ignition and extinction of a current filament [6, 7, 12]. In the post-breakdown regime above the hysteresis, the current flow is stabilized and the current rises rapidly for a very small increase of the voltage caused by the lateral growth of a current filament. The other curves shown in figure 1 are the voltage (right ordinate scale) and the differential resistance (left ordinate scale), both as functions of the current in the post-breakdown regime. The differential resistance $R = \partial U/\partial I$ has been measured

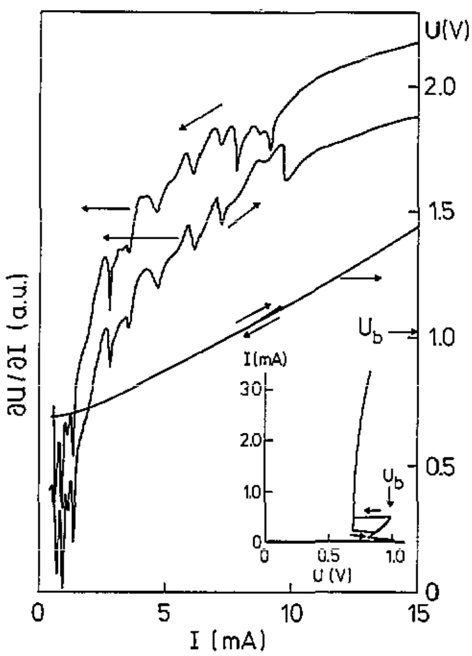

Figure 1. Voltage across the sample as a function of current (right ordinate scale), and differential resistance $\partial U/\partial I$ (left ordinate scale) for increasing and decreasing current symbolized by inclined arrows. The insert shows the DC current–voltage characteristic; the breakdown voltage U_b is also indicated on the right ordinate.

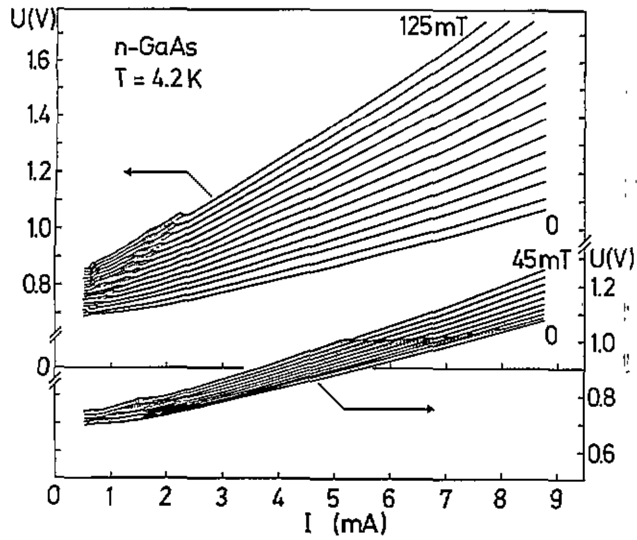

Figure 2. Voltage as a function of current for various positive ($B = 0$ to 125 mT) and negative ($B = 0$ to -45 mT) magnetic field strengths B. Adjacent curves differ by 9 mT and 5 mT for $B > 0$ and $B < 0$ respectively. The hysteretic portion of the characteristics is indicated by dotted curves for decreasing current.

for both increasing and decreasing current I, as indicated by inclined arrows. An offset along the R axis has been introduced in figure 1 to separate the two curves. The differential resistance R, as a function of the current I, shows a series of sharp structures which begin just above the oscillatory regime of the current–voltage characteristic where the current flow is stabilized and constant in time. A lot of weak, well reproducible structures are also observed. All these structures occur only for voltages between the sustaining voltage U_s and the breakdown voltage U_b, and have been observed in all investigated samples with S-type current–voltage characteristics. Above the breakdown voltage, which corresponds to $I = 1.0$ mA for the present sample at zero magnetic field, no sharp peaks in R have been found. In some cases the structure in R may be related to abrupt jumps and hysteretic portions in the current–voltage characteristic. One example can be seen in figure 1 between about 0.8 and 1.0 mA. In the case of hysteresis different structures occur for increasing and decreasing current. If the voltage across the sample is a smooth curve within the accuracy of the measurement, the structures are practically the same for the two cases.

In figure 2 the voltage as a function of current is shown for various positive and negative magnetic field strengths. Hysteresis in the characteristics is indicated by full curves for increasing current and by dotted curves for decreasing current. Several hysteretic regions are observed, being different for the magnetic field pointing upward or downward. Their extent and location in the current–voltage plane change as a function of the magnetic field. Some hystereses shift up and others shift down as the magnetic field strength increases.

The corresponding differential resistances are plotted in figure 3. Measurements for decreasing current are shown for various positive and negative magnetic field strengths. A large number of resonance-like sharp struc-

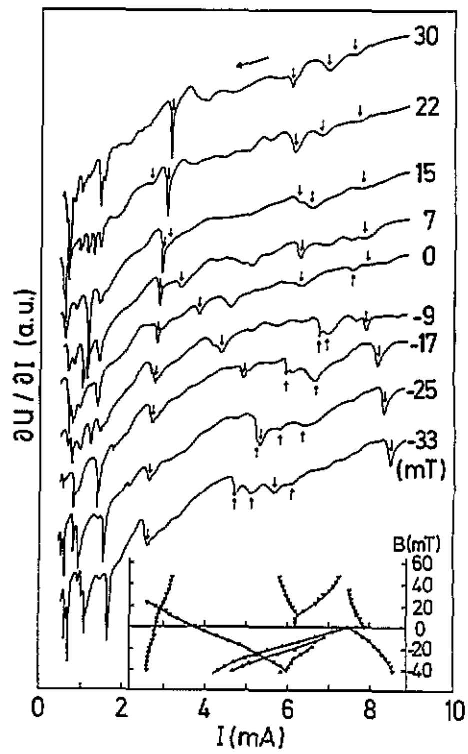

Figure 3. Differential resistance as a function of current I for various positive and negative magnetic field strengths B. Recordings are shown for decreasing current. The insert displays the location of strong structures in the B–I plane.

tures occur in the bistable regime of the current–voltage characteristic as well as above the threshold of instability in the range of stable filamentary current flow. Strong structures in the latter part of the current–voltage characteristics are indicated by arrows. The measurements demonstrate that the resonance current of all structures shifts with varying magnetic field. In the inset of figure 3 the locations of these strong lines are plotted in a magnetic field–current (B–I) plane. The structures in the differential resistance cut the zero magnetic field line continuously or are present only for either positive or negative magnetic field. The resonances between about 4 mA and 8 mA at negative magnetic fields are related to the hysteresis which occurs in the same current range in the current–voltage characteristics (figure 2). These hystereses are also present only for negative magnetic field. No strong structure could be found whose resonance current is an even function of the magnetic field.

All samples investigated show analogous structures in the differential resistance. However, no identical resonances have been observed in different samples. The locations of the structures in the B–I plane are even different for different contacts on the same n-GaAs layer. In a particular sample, however, and under the same experimental conditions, the structures are reproducible with high accuracy, representing a characteristic fingerprint of the sample.

In figure 4 the reconstruction of the current filament in the centre of a sample is shown as a function of the current for zero magnetic field. The sample used for filament reconstruction is very similar to that used for the

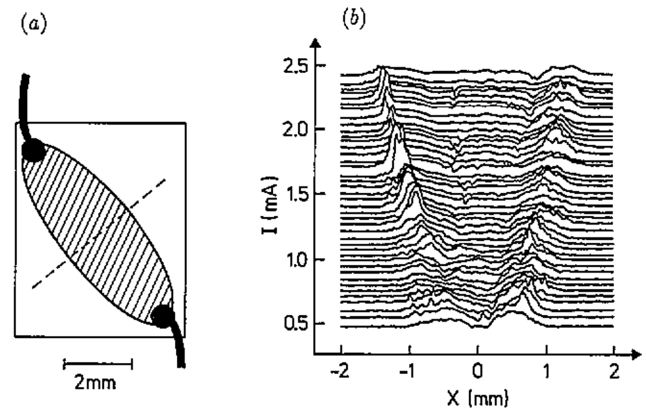

Figure 4. Reconstruction of the current filament. (a) Sketch of the sample: the shaded region indicates the current filament between point contacts shown by black spots. The spatially resolved interband photocoductivity has been measured along the broken line. (*b*) Spatially resolved photoconductive signal for various bias currents.

other measurements but is larger. Figure 4(a) sketches the sample and the current filament (shaded region) between the two point contacts [4]. The laser focus has been scanned along the broken line in the middle between the contacts. Figure 4(b) shows the photoconductive signal for various biasing currents along a coordinate normal to the current flow. Above a structureless background signal due to interband excitations, two signal ridges occur and move apart with increasing current. These two ridges indicate the borders of the current filament. The reason for this structure of the spatially resolved photocurrent is the marginal stability of a current filament at its borders. Irradiation of the filament boundaries cause current avalanches [13], which are recorded as a photoconductive signal. This measurement shows that the width of a current filament increases linearly with rising current as long as the current does not exhaust the total volume of the sample.

4. Discussion

The experimental results clearly show that strong features which show up in the current–voltage characteristics itself or in the first derivative of the voltage versus current cannot be attributed to spectral properties of the material. For an isotropic band, which is a good approximation of the conduction band of GaAs close to the band edge, Landau levels and shallow impurity levels are independent of the orientation of the magnetic field. Even in the case of anisotropy and including spin, the energy levels are symmetric with respect to inversion of the magnetic field due to time reversal symmetry. Thus structures in the magnetoresistance determined by energy level separations should be symmetric about the $B = 0$ axis in the B–I plane. However, no strong structure could be found that satisfied this condition.

In previous discussions [8–10] of magnetoresistance due to hot electrons generated by impact ionization the fact that the current flow under these conditions is inhomogeneous has not been taken into consideration. Current filaments are dissipative structures which are formed in a state far from thermal equilibrium by a critical balance of outward and inward directed forces on the electrons. Structure-forming forces on the current flow in a semiconductor are the internal pressure of the hot electron gas, lateral diffusion, drift by local electric fields and the self-attraction of a current [12]. The spatial distribution of the current flow is very sensitive to perturbations at the filament borders [3, 4, 13, 14]. Slight variations of the local electron population due to changes in the electron generation or recombination rate in the filament borders caused by impurities or imperfections in the material may lead to large changes in the overall current flow. This may occur by sudden jumps in the width of a filament if one border flows around an imperfection or by the nucleation of an additional new filament [15]. The filament borders move in opposite directions as the current is varied whereas the magnetic field displaces both borders in the same direction due to the Lorentz force. Thus, the positions of the structures in current may be a monotonically increasing or decreasing function of the magnetic field strength, depending on which filament border hits an imperfection with respect to the orientation of the magnetic field. This interpretation also explains why some structures continuously cross the $B = 0$ line in the B–I plane because the magnetic field continuously shifts the filament borders.

The almost linear dependence of the magnetic field on the current where a sharp structure in the differential resistance occurs may be understood from the observation that the width of a current filament depends linearly on the current. The location of a boundary measured from the centre of the filament may be written as $x_b = x_0 + \alpha I \pm \beta B$ where $2x_0$ is the minimum width of the filament, I is the current and α and β are two coefficients describing the growth of the filament with increasing current and the displacement of the filament due to the Lorentz force, respectively. The sign in front of βB is given by the orientation of the magnetic field B with respect to the direction of the current. The minimum width follows from the process of nucleation [16] and is determined by the balance of the power dissipated in the filament and the power flow from the filament surface to the surroundings. Assuming that an imperfection is placed at $x = a$, an abrupt change in the current may occur if $x_b = a$. From this the linear relation $B = \pm(1/\beta)(a - x_0 - \alpha I)$ between B and I is obtained where the slope $\partial B/\partial I = \pm\alpha/\beta$ can be positive or negative. The coefficients α and β must depend strongly on the location of the imperfection along the direction of the current because a filament is more stable in the large electric field gradient close to the contact than midway between the contacts. Thus, curves of different slopes in the B–I plane are expected, as has been observed.

Structures that are present only for one orientation of the magnetic field reflect the asymmetric distribution of imperfection in the epitaxial layer. Nucleation of filaments depends critically on the contact geometry and carrier injection there. Thus different structures in the magnetoresistance may occur for different contacts on the same epitaxial layer.

The structures in the differential resistance seem to be related to recently observed far-infrared photoconductive signals in n-GaAs which could not be attributed to spectral properties of the material like transitions between shallow donor levels [17]. Strong lines were found in the magneto-photoconductivity if the sample was biased in the post-breakdown regime where the current flow is filamentary. Similar to the present case, the structures in photoconductivity shift in magnetic field if the bias voltage is varied. This effect was attributed to the inherent feedback in the system that is necessary to sustain a current filament. Small variations of the electron population by infrared irradiation may cause substantial rearrangements of the spatial current distribution, yielding large changes in the resistance which in turn are recorded as photoconductive signals. However, the increase in free carrier concentration by infrared irradiation may facilitate a filament border flowing around imperfections. Hence the mechanism discussed in the present paper may also contribute to the non-equilibrium photoconductivity.

Finally we would like to point out that it may be tempting to attribute the structures in the differential resistance to mesoscopic current fluctuations [18]. The spatial resolution of the present optical scanning device is limited to several μm. Even methods with higher resolution based on electron microscopes [15] do not resolve the spatial structure of the current flow on a mesoscopic scale. Thus a mesoscopic structure such as a flash-like branching, which may even be fractal, could be hidden behind all reconstructions. However, mesoscopic fluctuations require very low temperatures whereas the electrons in a current filament are hot. The electron temperature far exceeds the lattice temperature [12, 17] and therefore mesoscopic effects may be disregarded.

5. Summary

In summary, our results demonstrate that a full understanding of the magnetoresistance of high-purity semiconductors must take into account the spatial inhomogeneity of current flow under hot electron conditions. Inhomogeneous current distibutions are caused by nucleation of current filaments due to the autocatalytic nature of impact ionization. The stability of filaments is a critical balance of counteracting forces. Thus, local pertubations, in particular at the filament borders, may lead to large changes in the overall current due to the inherent feedback of the system. Such changes are recorded as structures in the resistance. Besides the well established magnetoimpurity lines, magnetoresistance measurements typically show a wealth of very detailed structure. In many cases these structures are not reproducible in the sense that they are different for different samples or depend on not always well controlled experimental conditions like thermal background radiation. It is conceivable that most of these structures are caused by lateral shifts and nucleations of filaments.

Acknowledgment

The financial support of the Deutsche Forschungsgemeinschaft is gratefully acknowledged.

Note added in proof. A paper dealing with several aspects of this contribution has been published recently [19]. We thank the referee for directing our attention to this work.

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