On the Scaling of Type-I Intermittency in a Semiconductor Experiment

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Z. Naturforsch. **46a**, 1012–1014 (1991); received October 4, 1991

Spontaneous oscillations developing during low-temperature impact ionization breakdown in extrinsic germanium are looked at with respect to characteristic features of type-I intermittency.

Key words: Semiconductor breakdown, Intermittency, Scaling behavior.

1. Introduction

More than ten years ago, Pomeau and Manneville [1] have started their pioneering work on intermittent phenomena with the discovery of the now called type-I intermittency in the Lorenz equations. Although this most elementary type of intermittency has been found in a variety of experimental systems, only few quantitative investigations exist so far [2]. Such deficiency mainly results from the low-frequency range accessible in the well-studied (e.g., hydrodynamical) systems.

In recent years, transport instabilities in semiconductors turned out to represent a highly promising candidate for nonlinear dynamics. Due to their shorter time scale (typically in the kHz regime), we have been able to measure directly the scaling behavior of the mean laminar phase length. Taking further into account the distribution of the phase lengths, the return map of the oscillation maxima, and the reinjection probability, we give experimental evidence that type-I intermittency takes place in a self-generated manner (i.e., without external forcing).

2. Experiment

Our semiconductor system consists of a homogeneously doped p-type germanium sample (acceptor concentration of about $10^{14}\ \mathrm{cm}^{-3}$) with ohmic contacts. At liquid-helium temperatures, nearly all charge carriers are frozen out. Electric breakdown due to impact ionization of shallow impurities by hot charge carriers takes place at field values of typically a few V/cm, causing current-voltage characteristics with S-shaped negative differential resistance. In the not fully developed breakdown region, plasma-like current filaments arise together with spontaneous oscillations as dissipative structures. These findings can be explained, in principle, by semiconductor physics treating generation and recombination processes. The detailed structure of the current and voltage oscillations shows a high sensitivity against smallest changes of the experimental control parameters (namely, the temperature, the time-averaged current, or the bias voltage together with the load resistor, and the external magnetic field oriented perpendicular to the direction of the electric field) [3].

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3. Results

For the intermittency investigated, all parameters except the magnetic field were kept constant. With increasing magnetic field, more and more bursts interrupt the self-generated oscillations (Figure 1). This transition to chaos shows four particularities aiming to type-I intermittency.

First, the intermittent time signal of Fig. 1 (b) displays a monotonous increase of the oscillation maxima prior to each burst event. Looking more carefully at their increase, one clearly unveils a turning point (indicated by the arrow). Figure 1 (c) gives the fully developed chaotic dynamics.

Second, the return map of the intermittent state (Fig. 2) manifests the narrow channel that gives rise to the laminar phases. The "bottleneck" of the channel (indicated by the arrow) is the remnant of the formerly

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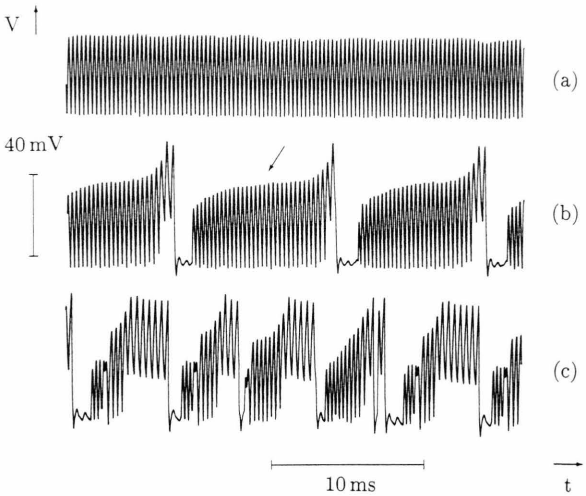

Fig. 1. Temporal structure of the spontaneous voltage oscillations obtained at different magnetic fields $B = 2.64$ mT (a), $B = 2.67$ mT (b), $B = 2.79$ mT (c), and the constant parameters time-averaged current $\bar{I} = 0.826$ mA and temperature $T = 2.12$ K.

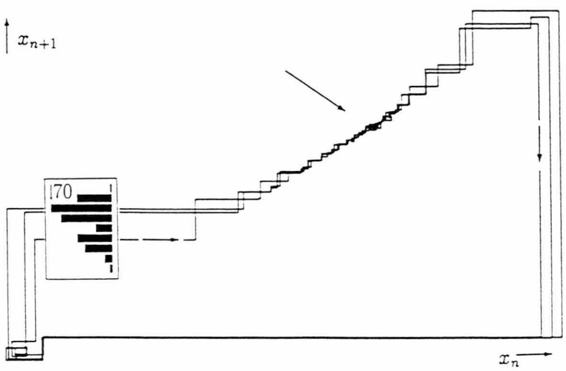

Fig. 2. Return map constructed from few successive maxima out of the time signal in Figure 1 (b). The inset displays the histogram of the reinjection probability.

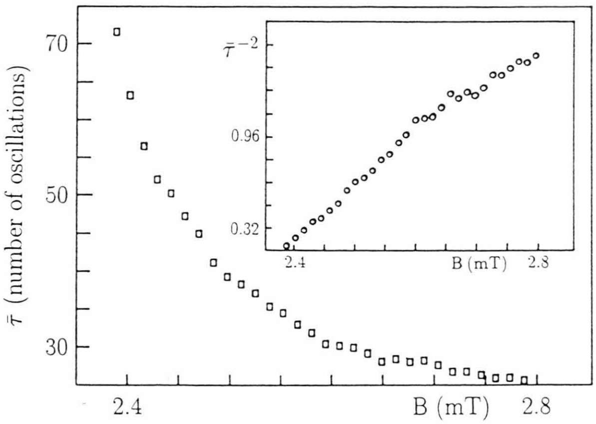

Fig. 3. Mean laminar phase length versus magnetic field. The inset shows the proper scaling. The constant parameters are slightly shifted compared to Figure 1.

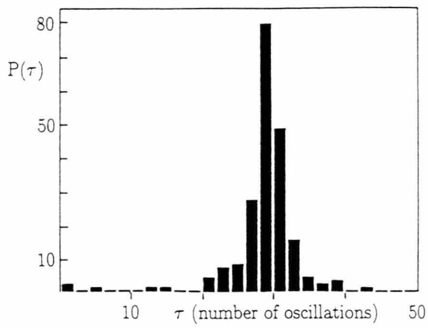

Fig. 4. Histogram of the laminar phase lengths in the time signal of Figure 1 (b).

stable fixed point. Note the relation to the turning point in the time signal. We emphasize that a finite reinjection probability is located only near the channel inlet, far below the bottleneck (see inset).

Third, we discuss the scaling of the mean laminar length $\bar{\tau}$ with the experimental control parameter (Figure 3). For type-I intermittency, it is expected from theory that $\bar{\tau}$ scales proportional to $(\mu - \mu_c)^{-1/2}$, where $\mu - \mu_c$ stands for the distance of the control parameter μ from the bifurcation point μ_c, the latter being defined by the first occurrence of an intermittent burst. To verify the scaling, experimental data of about 500 phase lengths were detected for 30 different values of the magnetic field control parameter. Just as expected, we found a clear linear scaling of the inverse square of $\bar{\tau}$ (see inset).

Fourth, in Fig. 4 the distribution of the laminar phase lengths τ shows a steep decay for large τ. It derives from the finite channel width for a given control parameter, providing pronounced contrast against intermittency of type II and type III [4]. Further, because of the exposed reinjection probability, the histogram has only one maximum. All trajectories will have to pass the bottleneck of the channel. There are no trajectories left to enter the upper part of the channel that would give rise to the second maximum at very short phase lengths known from a uniform reinjection probability.

To summarize, we demonstrate that experimental data obtained from semiconductor breakdown clearly obey four characteristic features of type-I intermittency. It turns out that intermittency can be taken as a possible mechanism for $1/f$ noise in low-dimensional systems.

Acknowledgements

The authors gratefully acknowledge financial support by the Volkswagen-Stiftung.

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