# Characteristic Relaxation Times of Low-temperature Semiconductor Breakdown Kinetics

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Z. Naturforsch. **44a**, 629–632 (1989); received April 28, 1989

The nonlinear transport behavior during low-temperature avalanche breakdown of extrinsic germanium is associated with the self-generated formation of spatio-temporal current structures. Very close to the critical phase transition between different conducting states, the underlying physical relaxation processes develop on relatively slow macroscopic time scales in the ms range. We have evaluated the slowing down of the characteristic time constants from independent measurements of the system response behavior to external pulsed excitations.

*Key words:* Semiconductor breakdown, Nonequilibrium phase transition, Structure formation, Nonlinear carrier transport, Relaxation processes.

## 1. Introduction

It is by now well established that, close to instability, the spatio-temporal behavior of systems far from equilibrium can be entirely described by the dynamics of a few order parameters [1]. Systems undergoing such nonequilibrium phase transitions show universal behavior, in so far as the evolution equations for suitably defined order parameters possess a mathematical structure which is to a great extent independent of the concrete system under consideration. As a consequence, these equations apply to quite different systems. Recently, it has been shown that generalized Ginzburg-Landau equations, i.e., evolution equations for the order parameters, can be derived for the oscillatory instability of a spatially homogeneous state in a variety of systems [2]. The instability usually leads to the formation of spatio-temporal structures.

Among the multitude of diverse synergetic systems in nature, electric instabilities in semiconductors represent a convenient study object for such complex nonlinear dynamics [3]. In particular, the simple and direct experimental accessibility via advanced electronic measurement techniques makes semiconductors easy to handle. Moreover, in view of the rapidly growing application of semiconductor technologies, the understanding, control, and possible exploitation of sources of instability in these systems have considerable practical importance.

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This paper focuses on the nonlinear current transport behavior during low-temperature avalanche breakdown of extrinsic germanium. So far, we have demonstrated experimentally the self-generated development of both filamentary spatial and oscillatory temporal current structures in the formerly homogeneous semiconductor [4]. Furthermore, the mutual interplay between the onset of low-dimensional chaotic dynamics and the break-up of spatial order during current filamentation has been unfolded to some extent [5]. The underlying nonlinear physics of impurity impact ionization [6] is shown to reveal critical phase transitions between different conducting states [7]. In the following, we report the experimental observation of characteristic relaxation times dominating the current instabilities in the highly nonlinear breakdown regime of the present semiconductor system. The appearance of these spatio-temporal dissipative structures is generally associated with negative differential conductivity. The relevant physical mechanism sensitively depends upon the nonlinear generation and recombination processes of the charge carriers driven far from the thermodynamical equilibrium [8]. From the above synergetic point of view [1, 2], the interesting system dynamics governed by a few order parameters may develop on "slow" macroscopic time scales enslaving all dynamically irrelevant "fast" modes. Similar to the results obtained from different semiconductor experiments [3, 9, 10], relatively slow time constants of the relaxation processes in the ms range are evaluated throughout the breakdown region investigated.

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## 2. Experimental

Our experimental studies were performed on single-crystalline p-type germanium material, having the typical dimensions of about $0.2 \times 2 \times 5\ mm^3$ and an impurity doping concentration of about $3 \times 10^{14}\ cm^{-3}$ of indium, aluminum, and gallium acceptors (corresponding to shallow acceptor levels in the range of 10 meV above the valence band edge). The compensation ratio was definitely smaller than $5 \times 10^{-2}$. The specific resistivity at room temperature amounted to about $10\ \Omega$ cm. During sample preparation, the extrinsic germanium crystal was successively polished (with diamond paste) and etched (with CP 4), in order to obtain an ideal surface structure. Then properly arranged ohmic aluminum contacts were evaporated upon one of the two largest crystal surfaces. For alloying the contact with the bulk material, the sample was heated above the eutectic point of the system.

To provide the ohmic contacts with an electric field, a d.c. bias voltage ($V_0$) was applied to the series combination of the sample and the load resistor ($R_L$). A d.c. magnetic field ($B$) perpendicular to the broad sample surfaces could also be applied by a superconducting solenoid surrounding the semiconductor sample. The resulting electric current $I$ was found from the voltage drop at the load resistor. The voltage $V$ was measured along the sample. During the experiments, the semiconductor sample was always kept at liquid-helium temperatures ($T = 4.2$ K or below) and carefully protected against external electromagnetic irradiation (visible, far infrared). It is important to note that the germanium sample as well as the surrounding copper shielding were in direct contact with the liquid-helium bath. Small openings in the metal shield covered with baffles served for letting the liquid helium reach the interior of the shielding arrangement. Further details on the experimental techniques can be found elsewhere [11].

## 3. Results and Discussion

Analogous to the corresponding processes of structure formation in gaseous plasma discharges, impact ionization of the shallow impurity acceptors can be achieved in the bulk of the homogeneously doped semiconductor at low temperatures. In the temperature range of liquid helium most of the charge carriers are frozen out at the impurities. Since the ionization energy is only about 10 meV and electron-phonon scattering is strongly reduced, avalanche breakdown already takes place at electric fields of a few V/cm and persists until nearly all impurities are ionized [12]. The transport mechanism involved in the nondestructive breakdown phenomenon can be attributed to impact ionization of the impurities by mobile charge carriers heated via the applied electric field.

The underlying nonequilibrium phase transition from a low conducting state to a high conducting state is directly reflected in strongly nonlinear regions of negative differential resistivity in the microscopic current-density versus electric-field characteristic [8]. Accordingly, the autocatalytic process of impurity impact ionization also leads to a strongly nonlinear curvature of the macroscopic (measured) current-voltage characteristic (sometimes with S-shaped negative differential resistance [13]), the nonlinearity occurring just beyond the voltage corresponding to the critical electric field where the current increases by many orders of magnitude (typically, from a few nA in the pre-breakdown up to a few mA in the post-breakdown region [6]).

Under slight variation of distinct control parameters (electric field, magnetic field, and temperature in the range of some $10^{-6}$ V/cm, $10^{-1}$ G, and $10^{-3}$ K, respectively) the resulting electric current flow displays a wide variety of spatial and temporal dissipative structures [4]. As described previously, low-temperature avalanche breakdown develops the self-sustained formation of filamentary current flow patterns [14] associated with the appearance of spontaneous current and voltage oscillations [15]. Note that these state variables show – superimposed upon the d.c. current and voltage signals of typically a few mA and some hundred mV, respectively – temporal oscillations with a relative amplitude of about $10^{-3}$ in the frequency range 0.1 – 10 kHz.

In order to attain an independent approach to the system dynamics of these breakdown instabilities, we have evaluated the typical relaxation times as follows. Instead of measuring the conventional d.c. current-voltage characteristic, we looked at the time dependence of the corresponding a.c. plot, obtained by applying triangular bias voltage pulses with varying repetition rate and recording the resulting temporal response of the current as a function of the sample voltage. With the pulses applied, the bias voltage $V_0$ periodically increases from 0 to about 2 V (pulse height) during the time interval of 2 ms (pulse width)

and then abruptly decreases to the initial voltage level within some μs. Figure 1 displays an example of two different a.c. current-voltage curves, measured through the application of distinct sequences of voltage pulses having time distances of more and less than 10 ms (solid and dotted curve, respectively). We emphasize that these findings can be reproduced utilizing a time series of double pulses, the distance of which is varied accordingly. Then the current response to the first voltage pulse always gives the solid curve, while the second pulse can produce the dotted I–V curve, if only the distance between the two pulses is smaller than 10 ms. The graphs of Fig. 1 have been averaged over 100 pulse cycles, but simply recorded during the rising branch of the bias voltage, i.e., for increasing current. The experimental parameters were: load resistor $R_L = 1.1$ kΩ, magnetic field $B = 14.9$ G, and temperature $T = 2.1$ K.

Obviously, the structure of the time-dependent current-voltage characteristic appreciably changes in the highly nonlinear breakdown regime of negative differential resistance, just where the current instabilities develop. The system response behavior is thus governed by a certain "memory" capability, still remembering the preceding excitation if the temporal distance between the voltage pulses applied is not too long. The extracted time constant of about 10 ms clearly supports the relatively slow frequency scale observed experimentally for the relevant relaxation-type system dynamics [4, 5, 14, 15]. Moreover, we have also performed combined d.c. and a.c. current-voltage measurements under variation of experimental parameters in the following ranges: load resistor $R_L = 1\,\Omega - 100$ kΩ, magnetic field $B = 0 - 500$ G, and temperature $T = 1.5 - 4.2$ K. Here the bias voltage $V_0$ consisted of sinusoidal or rectangular pulses superimposed upon the nonzero constant d.c. level. Depending on the parameter region investigated, characteristic relaxation times have been evaluated from the temporal profiles of the current response ranging from 0.1 ms up to 10 ms and, thus, covering the whole frequency span observed experimentally. Most importantly, an overall tendency of slowing down the time constant could be recognized when approaching the critical phase transition point located in the strongly nonlinear breakdown region (see also Figure 1).

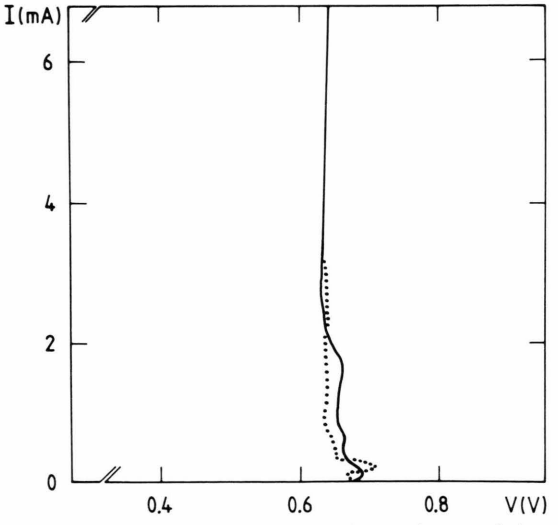


Fig. 1. Time-dependent current-voltage characteristics obtained through the application of triangular bias voltage pulses with different repetition rate: 70 Hz (solid curve) and 340 Hz (dotted curve). Further details see text.

We further point out that the above time scale is also found in the pre-breakdown regime at sufficiently high magnetic fields (typically, a few hundred Gauss), where relaxation-type current instabilities could be attributed to the stochastical firing of individual avalanche breakdown bursts [16]. Corresponding to the initial rising part of the time-averaged d.c. current-voltage characteristic just below the critical electric breakdown field, the time-resolved current profiles revealed increasing firing density and magnitude of the breakdown bursts with increasing applied bias voltage (see Fig. 2 of [16]). Both the parameter dependence and the characteristic shape of such relaxation instabilities suggest an oscillatory generation-recombination mechanism where the autocatalytic process of impurity impact ionization is dominated by the competing recombination of the mobile charge carriers. As a consequence of stability arguments, avalanche breakdown occurs sporadically on current pulses before reaching the stationary state of stable filamentary conduction in the post-breakdown regime.

The physical origin of the complex nonlinear dynamics observed in the present semiconductor system is not yet fully understood. First model attempts involve the autocatalytic process of impact ionization of one or more impurity levels coupled either with dielectric relaxation of the electric field [17] or with energy relaxation of the hot charge carriers [18]. The underlying multilevel transport model is based on the assumption that the charge carriers can occupy the conducting band or can be bound to the ground and excited states of impurity centers [19]. Therefrom, analytical conditions for negative differential current-

voltage characteristics as well as for both filamentary and oscillatory instabilities can be derived explicitly. The central idea of "breathing" current filaments together with long-range coupling of spatially separated (localized) oscillation centers via energy exchange may roughly explain some filamentary and oscillatory behavior of our samples. But, on the other hand, a detailed description of the rich variety of nonlinear effects, especially the complex spatio-temporal dyamics, can not be expected on the ground of such physical models. Like in turbulence, it seems to be impossible to describe the global system behavior starting from first principles. Furthermore, it is well known that complex nonlinear behavior can be modelled with an astonishingly high precision by universal ad-hoc models.

The still open question arises to what extent the physical mechanism discussed can contribute to the understanding of the relatively slow macroscopic time scale observed experimentally for the present semiconductor system. Certainly, the possible increase of the carrier life time in the lowest excited bound state of the hydrogen-like multilevel energy spectrum of p-germanium [20] may affect the dynamics of the breakdown instabilities. The spatial identification of spontaneous oscillations in the boundary region of the current filaments [4, 5] gives a further hint for critical slowing down behavior. Note that these privileged sites of the experimental oscillators are just very close to the sample locations where phase transitions between different conducting states occur (see definition of "current filaments" [8]). Nevertheless, we feel – in the sense of Haken [1, 2] – that all traditional disciplines in physics, which are concerned with the macroscopic behavior of multicomponent systems, require new ideas and concepts based on the synergetic approach, in order to cope with self-organizing systems. In a first step, we have derived a phenomenological reaction-diffusion model from the generic Rashevsky-Turing theory of morphogenesis [21], which so far looks highly promising.

*Acknowledgements*

We thank R. P. Huebener and E. Schöll for clarifying discussions. J. Pe. was supported financially by the Stiftung Volkswagenwerk, U. R. by the Deutsche Forschungsgemeinschaft.

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