Self-Organized Critical Dynamics and Phase Transition Behavior During Avalanche Breakdown in p-Germanium

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We give experimental evidence that self-organized criticality takes place during the formation of low-temperature semiconductor breakdown. Quantitative evaluation of the characteristic scaling properties together with the appropriate parameter ranges of validity further support the applicability of the model conjectured.

Key words: Semiconductor breakdown, Structure formation, Self-organized criticality.

Certain classes of cellular automata that go under the name of "Self-Organized Criticality" (SOC) [1–3] have attracted enormous attention within the physics community and beyond. The reason is that these models reach a critical state as a result of their own dynamics without the adjustment of any external parameter. Due to the absence of characteristic length and time scales, this intrinsic criticality obeys a distinct power law behavior, providing nontrivial information about the nonequilibrium state of the dynamics investigated. So far, SOC models have been applied to a huge variety of spatially extended, dissipatively coupled systems that usually are guided by an avalanche-type mechanism. Thus far, the overall significance of SOC conjectured originally still seems to persist under controversial discussion.

Motivated by first experimental findings of SOC behavior in an exemplary semiconductor system [4–6], the present work deals with a quantitative verification of the corresponding critical parameters and exponents. Specifically, we have first determined the scale invariance underlying the transition from the temporal to the spatial coexistence of different conducting phases under variation of the temperature. Then, via looking at a particular oscillatory mode of the current flow, we have uncovered the characteristic power law behavior of SOC over a certain range of the parameters voltage and temperature.

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The experimental system investigated consists of a p-doped germanium single crystal, electrically driven into low-temperature impact ionization breakdown [7, 8]. Two samples with the dimensions $8 \times 8 \times 3$ mm^3 (sample 1) and $8 \times 4 \times 0.3$ mm^3 (sample 2) and an indium acceptor concentration of 3×10^{14} cm^{-3} were furnished with ohmic aluminum contacts, evaporated and alloyed onto the facing two largest specimen surfaces. The electric circuitry consisted of a series combination of the sample and a 100 kΩ load resistor, biased by a constant voltage source. The lead wires connected to the sample and the load resistor served to measure the voltage drop along the sample and the current, respectively. During the experiments, the semiconductor sample was always kept at liquid-helium temperatures (in the range between 4.2 and 8 K with an accuracy of better than 10 mK) and carefully protected against external electromagnetic irradiation (visible, far-infrared).

Avalanche breakdown in the present semiconductor system provides a particularly promising candidate for studying self-organized critical phenomena that follow the concept of the SOC model approach mentioned above. As the fundamental mechanism, we have the electric-field-induced transition from a nearly insulating state of the semiconductor material to a high conducting state via impact ionization of the shallow impurities above a distinct threshold electric field of usually some V/cm [7]. The underlying autocatalytic process of mobile carrier multiplication ends up in an avalanche breakdown of the resistivity of the

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sample. Due to the fact that in a certain regime of the applied electric field both the low conducting and the high conducting state can coexist, the global system behavior can be interpreted as first-order nonequilibrium phase transition [9–11].

The corresponding time-averaged current-voltage characteristic displays negative differential resistance behavior pronounced at the onset of avalanche breakdown. One distinguishes different regimes owing to distinct slopes that result from the particular temporal structure of the current signal. At low bias voltage, the current is typically less than 10 nA. If a certain voltage is reached, short current pulses occur with a statistical temporal distribution. The height of these pulses reaches some hundred nA. The pulse duration is about 100 μs. An increase of the bias voltage leads to a larger time-averaged current, since the time intervals between the current spikes become shorter, ending up in a quasi-regular signal. At even higher voltages (i.e., beyond the ensuing region of negative differential resistance), the oscillation mode gets qualitatively different both in amplitude and frequency. A detailed classification of the overall dynamical behavior can be found elsewhere [12, 13]. In the following, we concentrate on the regime where the time periods between single spikes are long and show a broad distribution. Such a peak in the time trace of the current signal derives from a temporary breakdown of the resistance of the sample during the rise time of the spike (of less than 20 μs). Immediately after its occurrence, the breakdown is switched off again because, due to the increased current through the load resistor, the voltage drop across the sample is reduced. The decay time of the spike (in the range from 10 to 100 μs) sensitively depends on the electric circuitry applied (i.e., the input capacitance of the measuring amplifier). Therefore, we call this global oscillatory mode "Circuit-Limited Oscillations" (CLO), in contrast to the circuit-independent "Structure-Limited Oscillations" (SLO), reflecting the local spatio-temporal dynamics in the stable post-breakdown region of the characteristic [13].

A straightforward way to analyze the transition behavior near the critical point where the temporal coexistence of the low and high conducting phase (CLO) vanishes in favor of the spatial coexistence of the two phases (SLO) is to look at the onset current I_0 of both oscillatory modes as a function of temperature (Figure 1). Here, I_0 means the time-averaged lower-limit current value of CLO and SLO existence, respectively.

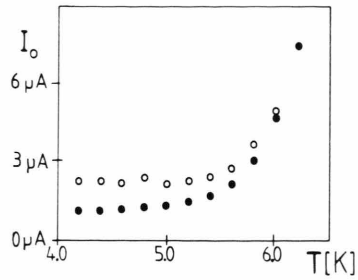

Fig. 1. Onset current of Circuit-Limited Oscillations (CLO, full circles) and Structure-Limited Oscillations (SLO, open circles) versus temperature obtained for both samples investigated. The phase portrait illustrates the existence range of CLO in between the two curves.

For the case of CLO, the phase portrait yields the scaling $I_0^{-1} \propto (T_c - T)^\beta$ with the critical temperature $T_c = 6.428 \pm 0.128$ K and the critical exponent $\beta = 0.902 \pm 0.020$ (cf. previous experimental findings [10, 11]).

In order to gain deeper insight into the first-order phase transition behavior characterizing the temporal coexistence of different conducting states in the subcritical pre-breakdown region, we focus on the stochastical features of CLO dynamics and calculate the distribution of time intervals between two subsequent breakdown events, $D(\tau)$, upon variation of the bias voltage and the temperature. Throughout the parameter range analyzed, we generally found a power law $D(\tau) \propto \tau^{-\alpha}$ with α amounting from 0.8 to 1.8. The appropriate values were extracted from the characteristic slope of the straight line fitted onto the corresponding histogram. Specifically, at $T = 5.6$ K an almost voltage-independent scaling with an exponent $\alpha = 1.24 \pm 0.05$ could be detected over more than two decades (Figure 2). It is emphasized, however, that only in the vicinity of the critical temperature T_c a unique scale invariance was found over the total voltage region of CLO existence. At temperatures below 5 K, parameter-independent power law behavior turned out to be more and more restricted to the lower-limit regime of CLO.

Obviously, our experimental results (together with earlier findings [4–6]) indicate critical spatio-temporal dynamics over an extended range of bias voltages and, thus, a close analogy to the SOC model introduced above. Self-organization in the semiconductor system may originate from deviations in the average electric field due to space charges. For example, thermally

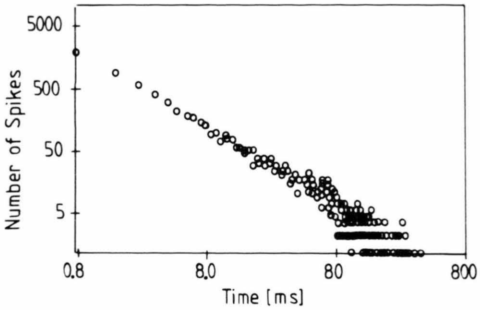

Fig. 2. Histogram of time intervals between subsequent current spikes obtained for sample 1 throughout the voltage range of CLO dynamics at the temperature $T = 5.6$ K.

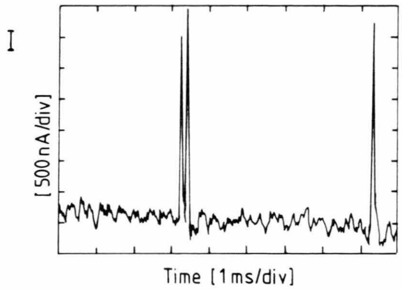

Fig. 3. Temporal current structure of CLO obtained for sample and parameters of Figure 2. The noisy signal parts between the current spikes indicate the temporal existence range of SOC.

activated carriers can be forced away from their site at an impurity atom by the electric field and can be trapped somewhere else. But every change of the space charge density ϱ yields a modification of the local electric field ε according to div $\varepsilon = 4\pi\varrho$. Since the semiconductor is in a state of extremely high resistivity, every creation of space charges (i.e., every rearrangement of charge carriers) causes a current flow in the outer circuit, in order to keep the voltage drop constant across the sample. This thermally activated process takes place in a statistical way. As a consequence, a certain noise level in the current signal should be expected. Figure 3 gives a typical time series, characterized by a pronounced noisy signal in between the CLO spikes. Note that the noise level is only present during limited parameter regimes of CLO existence. These findings deliver evidence that our semiconductor system displays SOC behavior during the time intervals between the CLO spikes. There, the local electric field strength and the mobile carrier density are permanently rearranged according to the model of self-organized criticality. With a certain probability, the critical values of the electric field and the carrier density are exceeded along a continuous channel leading to an avalanche breakdown event, showing up as a current spike in the electric circuitry. We conclude that the stochastically appearing breakdown of the sample voltage must definitely not be regarded as part of the critical state, but as the endpoint of a self-organizing process, taking place in the intermediate time between the breakdown events.

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