First Evidence of Self-Organized Criticality in the Impact Ionization Breakdown of Semiconductors

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Z. Naturforsch. **45a**, 835–836 (1990); received March 4, 1990

We have investigated the dynamical behavior of p-Ge at the very onset of impact ionization breakdown. The statistical temporal distribution of the recurrent breakdown events exhibits a power law behavior supporting the model of self-organized criticality introduced by Bak, Tang, and Wiesenfeld.

Key words: Semiconductor breakdown, Self-organized criticality.

Recently, Bak, Tang, and Wiesenfeld (BTW) [1] introduced the concept of "self-organized criticality" for the modelling of spatially extended, dissipatively coupled systems. Self-organized criticality means that there exists a broad parameter interval where the system behaves critically in the sense that its dynamical nonequilibrium state can be characterized by a power law behavior.

Semiconductor systems driven into parameter regimes where their current-voltage characteristic becomes highly nonlinear often show very complex spatio-temporal behavior [2–4]. The impact ionization breakdown of p-Ge which has been investigated in this paper belongs to this class of systems. It appears that for the first time our experimental results demonstrate the validity of the model developed by BTW.

Slightly doped semiconductors cooled to low temperatures are almost ideal insulators because most of the extrinsic carriers are frozen out at the impurity atoms. But, if an applied electrical field exceeds a critical value, the few remaining carriers can gain enough energy to release bound carriers by impact ionization. This autocatalytic process ends up in an avalanche breakdown of the resistivity of the sample.

We report measurements on p-Ge with an acceptor concentration of $N_A = 10^{14}$ cm^{-3} performed in a bath cryostat at 4.2 K. The series combination of the sample and the load resistor R_L (100 kΩ) was biased with a constant voltage V_0, while the current was measured via the voltage drop across R_L. 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. For a detailed classification of the dynamical behavior of p-Ge, see [5]. 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 can be understood as a temporary breakdown of the resistance of the sample during the rise time of the spike (of less than 20 µs) [5]. 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.

For investigating the dynamics at the onset of impact ionization breakdown, we took power spectra of the current signal. Two spectra are shown in Fig. 1 for the values of the bias voltage V_0, 349 mV and 370 mV, both in the range where the current exhibits randomly distributed spikes separated by time delays between 0.2 and 10 ms. In the frequency range between 0.2 and 3 kHz, which is the important one with respect to the mean time intervals between the spikes, the spectra can be approximated by a straight line of slope -0.4. Furthermore, we have analyzed the distribution of the time intervals between the individual avalanche events. In Fig. 2, we show a log-log plot of this distribution recorded at the same bias voltages as in Figure 1. These plots clearly exhibit a power law behavior in the range of 0.6–6 ms. The appropriate exponent can be extracted from the fit with a straight line of slope -1.33. Our experimental results indicate critical behavior over a considerable regime of bias voltages, apparently connected with complex spatio-temporal behavior. The importance of the system's spatial degrees of freedom becomes evident in a more detailed treatment of our experiments [6].

Next, we turn to the connections between our experiment and the BTW model [1]. The basic idea of self-organized criticality is illustrated by an idealized

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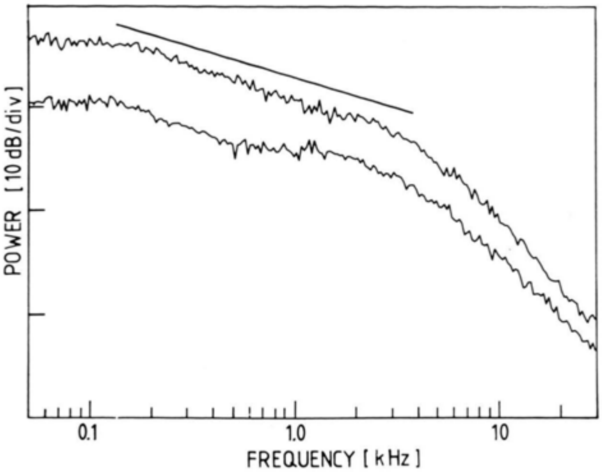

Fig. 1. Double-logarithmic plot of the power spectra (in units V^2/Hz) of the current obtained at the bias voltages $V_0 = 349$ mV (lower curve) and $V_0 = 370$ mV (upper curve). For clarity, the curves are shifted along the y-axis by arbitrary units. The solid straight line corresponds to a power of -0.4.

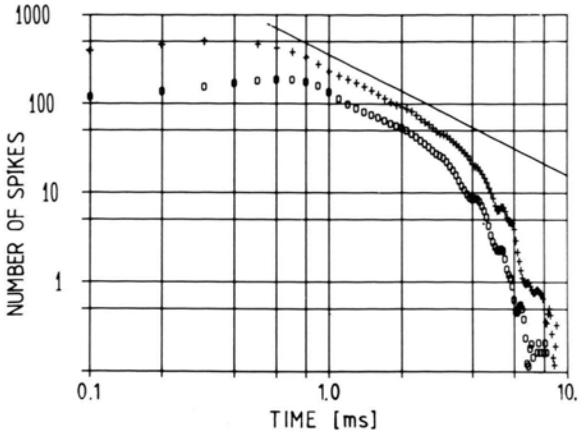

Fig. 2. Distribution of time intervals between current spikes obtained at the bias voltages $V_0 = 349$ mV (circles) and $V_0 = 370$ mV (crosses). In the range 0.6–6 ms the curves can be approximated by a solid straight line of slope -1.33.

"pile of sand", built up between an open and a closed boundary by randomly adding sand grains to individual sites. Transport from site to site is ruled by the local slope, i.e., the height difference between neighboring sites. This local slope is determined by the global height difference between the boundaries and by local deviations from this global slope, caused by adding grains to single sites. In the semiconductor system, we identify the global slope with the average electrical field inside the sample caused by the application of the external voltage. Local deviations can be due to space charges existing within the sample as a result of spontaneous generation-recombination and transport processes. Because this thermally activated process happens statistically, it corresponds to the spreading of grains onto the surface of the model sandpile. An important difference lies in the nonlocal character of electrodynamics. However, it appears that during the time intervals between the current spikes the local field strength and the free carrier density are permanently rearranged according to the model of self-organized criticality. With a certain probability, the critical values of the electrical field and of the carrier density are exceeded along a continuous channel leading to an avalanche breakdown event, showing up as a current spike in the electrical circuit. This breakdown marks the endpoint of the critical process. In contrast to the BTW model, the critical state in our experimental system can not persist stationarily, but is involved in a global relaxation process.

We thank R. P. Huebener and H. M. Jaeger for stimulating discussions. Part of the work was supported by the Deutsche Forschungsgemeinschaft.

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