

The Dynamics of Structure Formation in Semiconductor Breakdown
Experiments

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The universe we see is a ceaseless creation, evolution, and annihilation of structures or patterns which are endowed with a degree of stability. They take up some part of space and last for some period of time. It is a central problem of the natural sciences to explain this change of structure and, if possible, to predict it.

Nature surprises us with the fact that the tremendous amount of physical data and results can be condensed into a few simple laws and equations that summarize our knowledge. These laws are essentially qualitative and the question arises how nature generates the enormous variety and novelty of structures by starting from such simple principles. Unaware of the scope of simple equations, man has often concluded that more than mere equations is required to explain the complexities of the world. Today, we are not so sure, for already a simple random walk described by the Laplace equation provides a prototypical situation with behaviors ranging from orderly to chaotic. The formation of spatio-temporal patterns is, first of all, a geometrical problem. Thus, in our quest to understand how structures are generated by nature, the relationship between physical forces and the geometries they can shape is of fundamental importance. This relationship and the ensuing universal character of nonlinear pattern-forming processes are the central themes motivating the work outlined in the following.

The mechanisms that lead to pattern formation are best understood in continuous nonlinear systems, which to external probes appear to be governed by a few essential degrees of freedom. In such systems, structural changes are characterized by the appearance of singularities and bifurcations which occur if a balance existing between competing system-immanent effects breaks down. As a consequence, an initially quiescent system becomes unstable and, in a sequence of bifurcations, restabilizes successively in ever more complex space- and time-dependent configurations. Within particular symmetry constraints, the bifurcations occur in certain definite and classifiable ways if the system is structurally stable.

So far, it appears that the subject of such complex nonlinear behavior is dominated by theoretical investigations and computer simulations, whereas experimental measurements on real-world physical systems represent the minority. Among the various objects which can be studied experimentally, solid-state turbulence in semiconductors looks highly promising (Huebener, Peinke, and Parisi, 1989). Nonlinear current transport behavior during low-tem-

perature avalanche breakdown of extrinsic germanium comprises the self-sustained development of spatio-temporal dissipative structures in the formerly homogeneous semiconductor (Huebener et al., 1987; Peinke et al., 1988; Parisi et al., 1989a). This kind of nonequilibrium phase transition between different conducting states results from the autocatalytic nature of impurity impact ionization generating mobile charge carriers (Schöll, 1987; Schöll et al., 1987; Parisi et al., 1987). The simple and direct experimental accessibility via advanced measurement techniques favors semiconductors as a nearly ideal study object for complex nonlinear dynamics compared to other physical systems. Further representing a convenient reaction-diffusion system that exhibits distinct universal features, the present semiconductor system may acquire general significance for many synergetic systems in nature. Finally, 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.

We have performed experiments with single-crystalline p-doped germanium (typical dimensions of about $0.2 \times 2 \times 5 \text{ mm}^3$), electrically driven into low-temperature avalanche breakdown via impurity impact ionization (Peinke et al., 1989a). Analogous to the corresponding phenomena in gaseous plasma discharges and atmospheric lightning, impact ionization of the shallow impurity acceptors can be achieved in the bulk of the homogeneously doped semiconductor. In the temperature regime of liquid helium (somewhat below 5 K) 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 all impurities are ionized (Parisi et al., 1988). 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 (Schöll, 1987; Peinke et al., 1987a). 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), 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). Under slight variation of distinct control parameters (electric field, magnetic field, and temperature in the range of some 10^{-6} V/cm , 10^{-4} G , and 10^{-3} K , respectively) the resulting electric current flow displays a wide variety of spatio-temporal nonlinear transport behavior, embracing the spontaneous symmetry-breaking emergence of both filamentary spatial and oscillatory temporal dissipative structures. One of the major issues of strong current interest is the question to what extent the break-up of spatial order during current filamentation is correlated with the onset of low-dimensional temporal chaos in the current oscillations.

The complex spatial behavior of our semiconductor system can be globally visualized by means of two-dimensional imaging of the current filament structures via low-temperature scanning electron microscopy (Huebener, 1988). As reported elsewhere (Mayer et al., 1987 a,b) in detail, nucleation and growth of filamentary current patterns in the nonlinear post-breakdown regime are often accompanied by abrupt changes between different stable filament configurations via noisy current instabilities. Moreover, the simultaneous spatial identification of oscillatory current flow dynamics in the vicinity of adjacent different conducting phases (e.g., boundary regions of the current filaments) provides a powerful tool for gaining deeper insight into the mutual interplay between spatial and temporal current structures (Mayer et al., 1988).

Self-generated current oscillations (with a relative amplitude of about 10^{-3} in the frequency range 0.1 - 100 kHz) are found to be superimposed upon the steady d.c. current (of typically a few mA) in the strongly nonlinear post-breakdown regime of the measured current-voltage characteristic. By means of slightly varying the applied electric or magnetic field, the temporal behavior of the current changes dramatically, displaying the typical universal scenarios of chaotic nonlinear systems (Peinke et al., 1985a,b, 1987b, 1989b; Rau et al., 1987). On the ladder towards higher orders of chaos we discovered a chaotic hierarchy of strange attractors (Stoop et al., 1989; Parisi et al., 1989b). The abrupt structural change between different dynamical states associated with gradually decreasing spatial correlation of different sample parts indicates a break-up of the semiconductor system from strongly coupled into more independent subsystems. In this way, new actively participating degrees of freedom are gained reflecting increasing dimensionality of the system. Turbulent dynamics may thus be ascribed to nonlinear coupling between competing localized oscillation centers intrinsic to the present multi-component semiconductor system. So far, we have demonstrated experimentally the existence of spatially separated oscillatory subsystems as well as their long-range interaction (Röhrich et al., 1986, 1987; Schöll et al., 1987; Peinke et al., 1987b; Mayer et al., 1987a,b, 1988). Moreover, the underlying nonlinear physics reveals critical phase transition behavior by varying the temperature at constant electric and magnetic field (Röhrich et al., 1988). Most importantly, we disclosed an upper bound for the onset of structure formation (first-order phase transition) and avalanche breakdown (second-order phase transition) at critical temperatures of about 5.5 K and 7.2 K, respectively.

To conclude, our experiments deal with a challenging example of a macroscopic synergetic system, consisting of spatially separated and diffusively coupled subsystems which by themselves show oscillatory behavior. Depending sensitively upon distinct control parameters, the resulting spatio-temporal current flow undergoes various symmetry-breaking phase transitions typical for nonlinear dynamical systems. So far, the crucial role of the relationship between the breakdown of spatial order and the onset of low-dimensional temporal chaos has been unfolded to some extent. There is hope that these promising advances attained in semiconductor physics via cer-

tain fundamental interdisciplinary concepts, such as symmetry and symmetry breaking, linear and nonlinear stability, frustration and constrained dynamics, may open up the possibility of a fruitful interaction with the diverse fields ranging from mathematics to biology, even the creative and performing arts, and most branches of the sciences.

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