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Nonlinear phenomena and chaos in germanium oscillistor

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Abstract

Dynamic chaos evolution scenarios of the development of a Kadomtsev–Nedospasov instability in the electron–hole plasma in germanium at 77 and 300 K have been studied experimentally in external electric and magnetic fields at high control parameters. The development of a spatio-temporal chaotic state in the system has been analysed using probe measurements along a sample. It is shown that several attractors, with their own dimensions and power characteristics, may exist simultaneously in the same sample. Scenarios have been found leading to chaos through period doubling, quasi-periodicity and intermittency, depending on the parametric space; transitions of the order–chaos–order type have also been observed.

1. Introduction

Numerous effects in semiconductors are readily observable and reproducible, being characterized by high spatial-temporal resolution. That is why these materials have become the most suitable model systems for studying complex nonlinear dynamics and synergetic processes. Oscillistor is one of the simplest real physical systems. Ivanov and Ryvkin [1] were the first to report spontaneous oscillations of electric current in germanium crystals placed in parallel electric and magnetic fields. Later, this instability was observed in other semiconductors [2] and theoretically described in terms of the Kadomtsev–Nedospasov instability theory for gas plasma [3]. This theory being sufficiently elaborate and well substantiated experimentally, we do not go deep into the theoretical aspects of this phenomenon. Spiral instability is one of the best-understood instabilities in semiconductors. We make an attempt to take a somewhat different approach to this problem—from the viewpoint of nonlinear dynamics. Previously obtained data on nonlinear dynamics and chaos in semiconductors referred to kinetic effects for a single type of carrier, associated with impact ionization of shallow impurities at very low temperatures or with carrier generation and recombination [4, 5]. Studies dealing with two-component systems (electron–hole plasma) or with measurements at high temperatures are few, so that the potentialities of the theory [6] have hardly been exhausted.

2. Experimental details

Oscillistors were fabricated from n-type germanium with background concentration $N_D - N_A = (10^{12}-10^{14})$ cm^{-3}. Samples were cut in the form of cylinders or parallelepipeds 10 mm long with cross-section of 1 mm^2. The samples were etched in a polishing etchant. Contacts of In with 0.5% Ga and Sn with 7% Sb, injecting, respectively, electrons and holes, were deposited onto the sample edges. To study the spatial-temporal coherence in the system, up to five pairs of Hall probes were deposited along the sample length, with their ohmic behaviour in external electric fields carefully tested. It should be noted that all experiments were carried out in the steady-state mode with rectangular pulses, and the dynamics of evolution scenarios was recorded with triangular pulses of varied duration and amplitude. For comparison with the theory of nonlinear dynamic systems, the experimentally obtained time series were used to construct phase portraits, bifurcation diagrams, two-dimensional Poincare maps, and power spectra. The time series of electric current oscillations from different parts of a sample were digitized using an analogue-digital converter with sampling rate of 200 MHz.

3. Results and discussion

The conventional evolution scenarios leading to a chaotic state in many physical, chemical, biological and other systems have been studied in sufficient detail. The convergence parameters have been calculated for these scenarios as universal constants from one-dimensional maps. For example, for a scenario of transition to a chaotic state via a sequence of period-doubling bifurcations (Feigenbaum scenario) [8], the values of the parameter r_n, at which the number of stable points doubles to become equal to 2^n, satisfy the scale relation, $r_n = r_\infty - \text{const}\,\delta^{-n}$, where $n \gg 1$. The distance d_n from the point $x = 1/2$ in the bifurcation diagram to the nearest point in $2n$th cycle satisfies the equation $d_n/d_{n+1} = -\alpha$, where $n \gg 1$. The Feigenbaum constants determined with rather high precision have the following values: $\delta = 4.6692016091\ldots$ and $\alpha = 2.5029078750\ldots$.

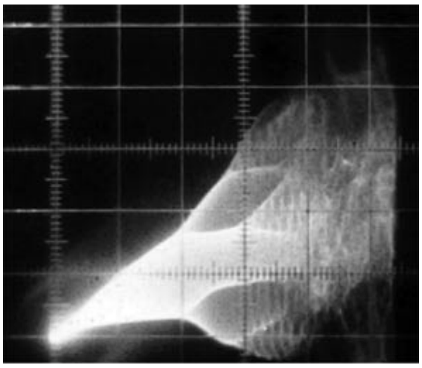

Figure 1. Bifurcation diagram of the evolution scenario for Ge oscillistor at 77 K. Scale: abscissa, 2 V/division; ordinate, 0.2 V/division.

Figure 1 presents the results of a natural experiment carried out at 77 K. A bifurcation diagram typical of the Feigenbaum scenario was recorded on the oscilloscope screen, from the threshold of the Kadomtsev–Nedospasov instability till the onset of the chaotic state. The amplitude of sawtooth voltage pulses is plotted along the abscissa axis, and the amplitude-frequency signal taken from the potential probes, along the ordinate. The constants δ calculated using experimental data for various control parameters not only differ essentially from the theoretical values, but also do not coincide with one another. By contrast, the constant $\alpha \approx 2.5$ is close to the theoretical value within the experimental error. These discrepancies are presumably due to the essentially inhomogeneous distribution of the plasma concentration and, therefore, of the electric field along the sample. The parameter actually governing the development scenario of the dynamic system is the local electric field, rather than the average field $E_{\mathrm{av}} = V/L$ (where V is the voltage applied to a sample of length L). To verify this assumption, we measured the time series in different regions of the sample and demonstrated that several attractors with appropriate attraction areas may exist simultaneously in the same sample, depending on local electric fields and carrier concentrations.

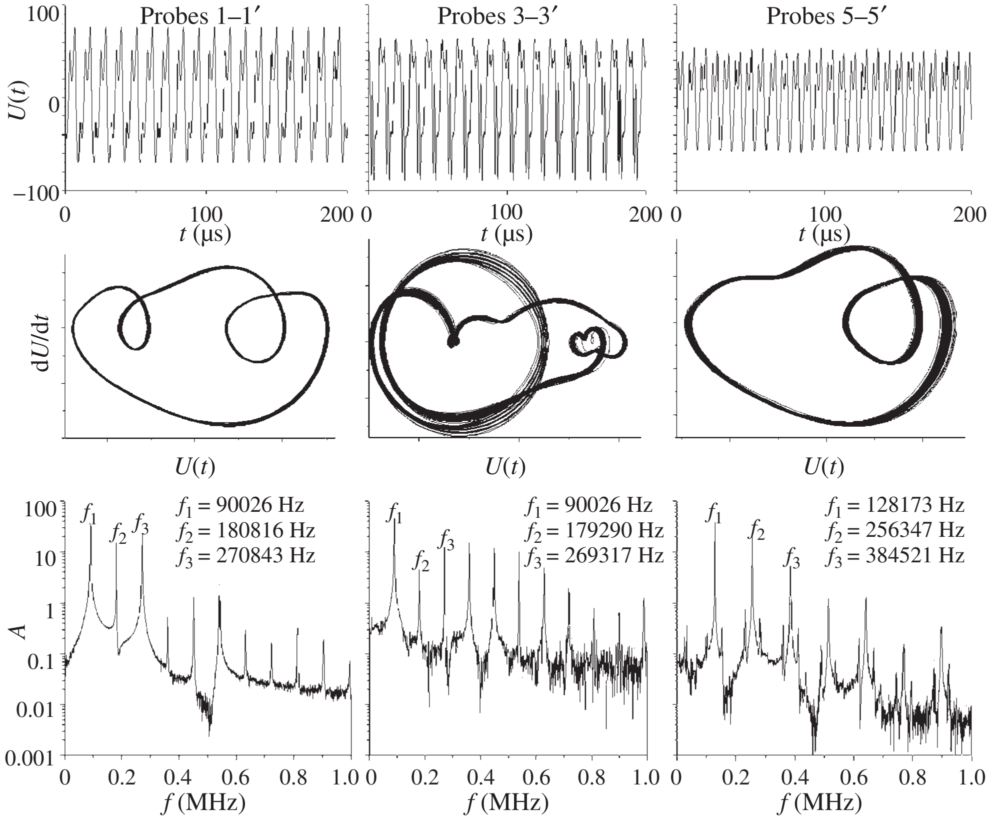

Figure 2. Time series, phase portraits and power spectra in different parts of the sample at $U = 6.4$ V, $H = 4.5$ kOe, $T = 77$ K.

Figure 2 shows time series, phase portraits and power spectra measured simultaneously for the same external voltage and magnetic field. The phase portraits constructed on the basis of different partial voltages across each pair of Hall probes not only describe a two-dimensional projection of the attractor, but can also be interpreted as results of direct measurements of the temporal and spatial coherence between well localized areas of the sample under study. For comparison, figure 3 shows experimental results for a somewhat stronger electric field. A partial voltage may grow, decrease or remain constant, with other partial voltages changing in different ways, demonstrating total mutual independence in the course of time. However, in the chaotic state shown in figure 4 the phase portraits exhibit a certain correlation between different parts of the sample. The loss of the spatial coherence between different parts of the sample may indicate disintegration of an integral multicomponent semiconductor system into more independent subsystems with a greater number of degrees of freedom. With the spatial coherence lost, the system is characterized by phase portraits with diverging trajectories and a band of continuous noise in the power spectra (figure 4).

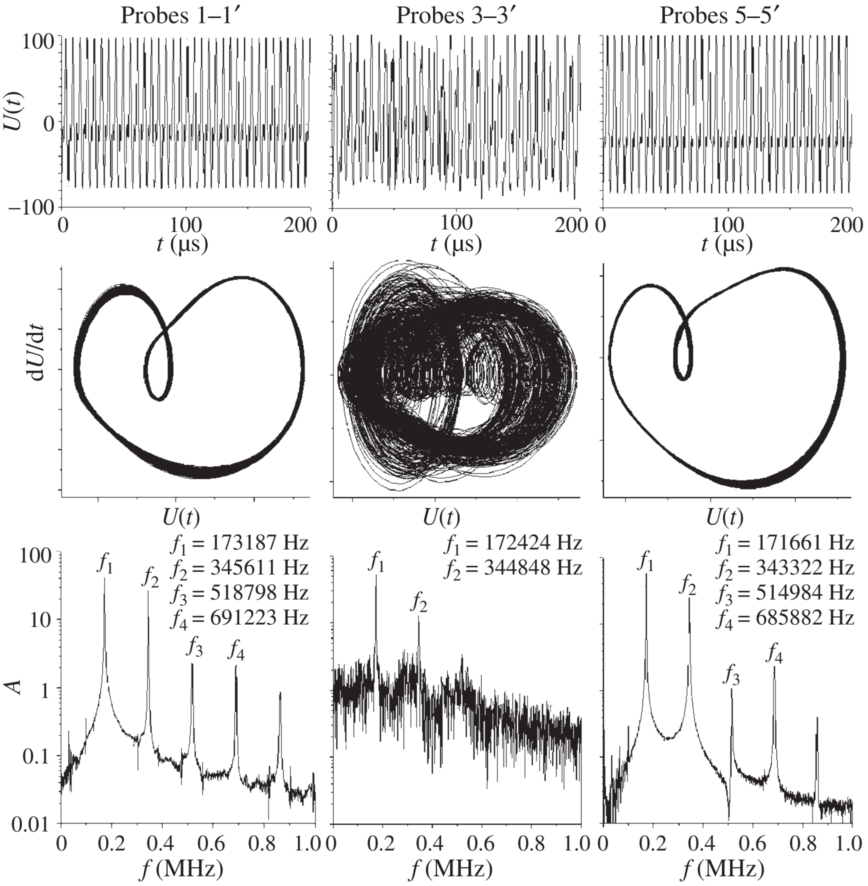

Figure 3. Time series, phase portraits and power spectra in different parts of the sample at $U = 9.6$ V, $H = 4.5$ kOe, $T = 77$ K.

At small control parameters, the same pattern was observed in all parts of the sample (transitions from an unstable focus through the Andronov–Hopf bifurcation to a limit cycle and further period doubling). Not all of the evolution scenarios evolve by the conventional scheme. We observed transitions of the limit cycle–doubled cycle–quadruple cycle–doubled cycle (1–2–4–2) type. Further, with increasing electric field, the system evolves according to the Feigenbaum scenario or shows transitions between cycles with periods 1–2–4–3 etc.

Not only external electric and magnetic fields, injection level and temperature are parameters of the system, but also the angle φ between E and H, i.e. deviation from their strict parallelism. The oscillistor effect is known to exist in the aperture $\varphi = \pm 7^\circ$ about $E \parallel H$ [1]. A screw instability develops by the Feigenbaum scenario at rather strict alignment of a sample with the magnetic field, i.e. at $\varphi \to 0$.

It can be demonstrated experimentally that a pronounced deviation from $\varphi \to 0$ leads to an instability development scenario via quasi-periodicity (Ruelle–Takens–Newhouse scenario) [9]. Transitions to chaos via a sequence of period-doubling bifurcations or through quasi-periodicity can be observed in the same sample at a given magnetic field H, depending

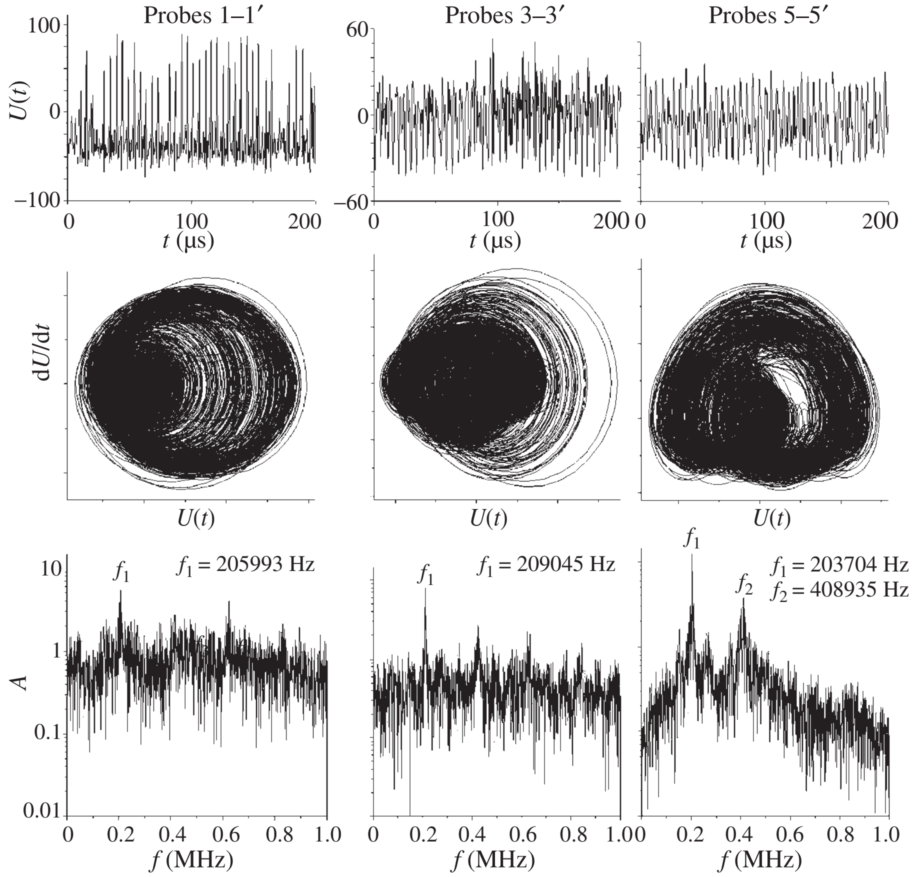

Figure 4. Time series, phase portraits and power spectra in different parts of the sample at $U = 13$ V, $H = 4.5$ kOe, $T = 77$ K.

on the angle φ. Figure 5 shows Poincare maps in the form of oscillograms for (A) two incommensurable frequencies corresponding to a two-dimensional torus with everywhere close packing, (B) collapse of the torus prior to the onset of chaotization and (C, D, E, and F) formation of layered structures with elliptic and saddle trajectories.

A dynamic chaos corresponding to intermittency has also been observed experimentally [10], with bursts of chaotization well noticeable against the background of laminar phases. The intermittency appears simultaneously with the period doubling; the amplitude of subharmonics grows and that of the fundamental harmonic decreases. When the subharmonic amplitude becomes high, the signal loses regularity and turbulent bursts appear, characteristic of the type 3 intermittency [7].

Acknowledgments

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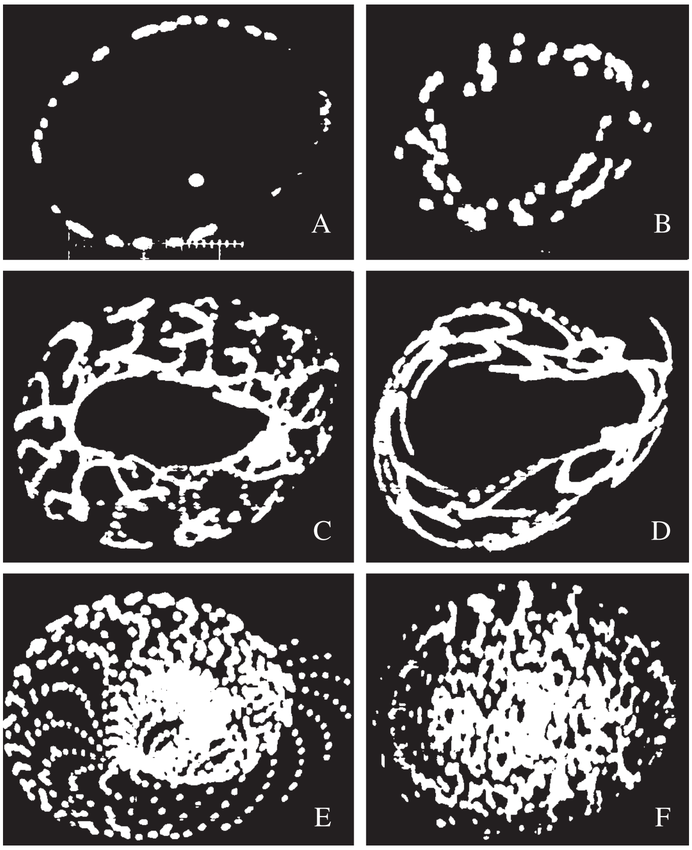

Figure 5. Poincare maps in the quasi-periodicity case with increasing electric field: (A) two-dimensional torus with everywhere close packing, (B) collapse of the torus before the onset of chaotization and (C, D, E, and F) formation of structures with elliptic and saddle trajectories.

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