STUDY OF THE RESPONSE OF SEMICONDUCTOR STRUCTURES TO EXTERNAL PERTURBATIONS

IBRAGIMKHAN K. KAMILOV, NAIDA S. ABAKAROVA
ik.kamilov@mail.ru, abakarova_naida@mail.ru
Institute of Physics named after Kh. I. Amirkhanov,
94, Yaragsky str., Makhachkala, Russia

This paper presents some previously obtained results of our experiments on the study of the impact of external perturbations on the behavior of nonlinear semiconductor systems. The presented experimental results confirm the theoretical models. The mechanisms of conductivity of nonlinear circuits consisting of several tunnel diodes have been studied. Suppression of current branches of the current-voltage characteristic under noise influence has been discovered. Keywords: synergetic, nonlinear dynamics, instability, control parameter, universal constant, semiconductors, circuits, tunnel diodes.

DOI:10.70784/azip.3.2024CE37

The impact of external parameters on complex dynamic systems leads to various phenomena of instability, generation of oscillations and waves, the emergence of chaotic states and the spontaneous formation of spatial and temporal structures. The study of nonlinear phenomena, non-equilibrium phase transitions and self-organization processes in a bulk and low-dimensional condensed medium with nonlinear properties and their response to external perturbations attracts scientists' strict attention. Due to the comparative ease of studying many effects, fine reproducibility and high spatiotemporal resolution, semiconductors have been selected as the most suitable model systems for studying complex nonlinear dynamics and synergetic processes.

A series of our works are devoted to experimental verification of the theory of nonlinear dynamic systems.

As a result of the research, new evolutional scenario of the development of chaotic states in the electron-hole plasma of semiconductors, the phenomena of absolute negative resistance have been discovered. This work presents some results of our research in this area.

The experiments were originally aimed at confirming the theoretically predicted main universal transition to chaos, i.e. the double-period cascade (Feigenbaum scenario), the interchanging between different modes of oscillation (Pomeau–Manneville scenario) and the quasiperiodic transition to chaos (Ruel–Tackens–Newhouse).

Nonlinear dynamics associated with the development of Kadomtsev-Nedospasov instability (screw instability or oscillatory effect) has been experimentally studied in injected electron-hole plasma (EHP) of bulk germanium samples in longitudinal electric and magnetic fields at high values of supercritical parameters in the temperature range 77-300 K [1].

The influence of a harmonic signal of different amplitude and frequency on the instability of the current in the Ge EHP that was input into the system as an additional control parameter at the bifurcation points of the evolutionary scenario has been studied in detail. At the same time, such phenomena characteristic of a dynamic system as frequency capture, amplification or attenuation of an external signal, as well as issues of stability and randomization of the system have been investigated. Some universal constant and critical indexes are defined.

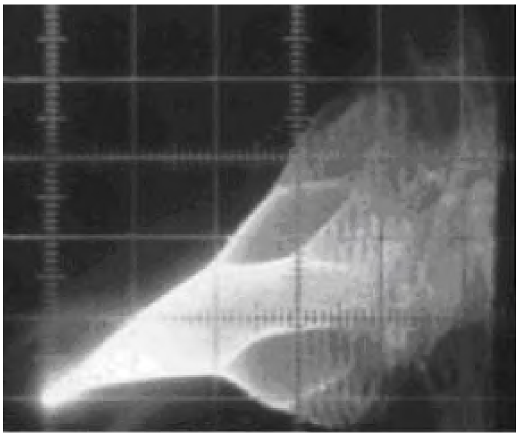

Fig.1. Feigenbaum scenario.

Figure 1 shows the results of a natural experiment carried out at T=77 K. The oscilloscope screen displays the Feigenbaum scenario, starting from the threshold of the Kadomtsev-Nedospasov instability up to the chaotic state. The constants δ calculated from our experiment differ significantly from the theoretically predicted ones. They do not coincide with each other, depending on the temperature and other conditions of the experiment. At the same time, the constant $\alpha \approx 2.5$ is in accordance with the theory within the limits of experimental error.

We have shown that several attractors with relevant basin of attraction can exist simultaneously in the same sample, depending on the local value of the electric field and the concentration of current carriers, i.e. the local electric field, and not the average Ecp =V/L (where V - the voltage applied to the sample with length L) is the true parameter determining the scenario

131, H.Javid ave, AZ-1073, Baku
Institute of Physics
E-mail: jophphysics@gmail.com

for the development of a dynamic system. With the loss of spatial coherence between different parts of the sample, apparently, coupled multicomponent semiconductor system disintegrates into more independent subsystems with a large number of degrees of freedom, leading to chaotic behavior of the system under study.

During the experimental studies, the control parameters (or supercriticality parameters) for the system under study were not only the external electric and magnetic field, injection level, temperature, but also the angle φ between **E** and **H**, i.e. the deviation from their strict parallelism. It is known, that the oscillistor effect occurs in a solution $\varphi = \pm 7°$ near **E↑↑H**. The development of screw instability according to the Feigenbaum evolutionary scenario occurs with a sufficiently strict positioning of the sample parallel to the magnetic field, i.e. at $\varphi \to 0°$. We have experimentally confirmed that a large deviation from $\varphi \to 0°$ leads to the development of an instability scenario through a quasi-periodicity (Fig. 2, Ruel–Tackens–Newhouse scenario).

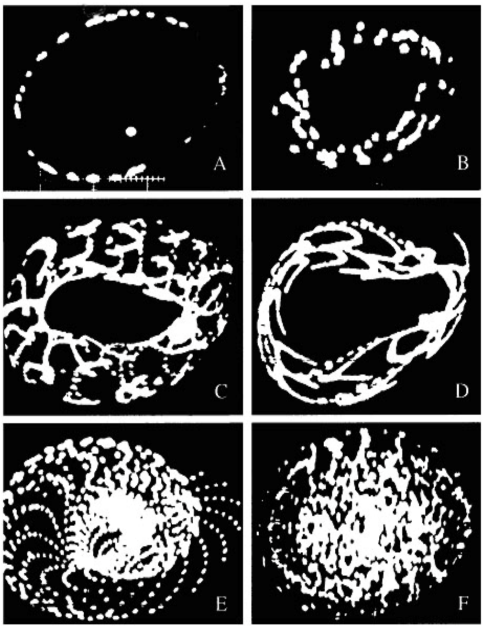

Fig. 2. Poincaré mapping (Ruel–Tackens–Newhouse scenario)

Depending on the angle φ , in the same sample at a given value of the magnetic field **H**, we have observed the transitions to chaos both through the sequence of bifurcations doubling period and through the quasi-periodicity.

Figure 3 shows, without detailed analysis, a picture of dynamic chaos related to the case of transition to a chaotic state through intermittency (Pomeau–Manneville scenario), where bursts of randomness are clearly visible against the background of laminar phases.

All experiments were carried out in a steady-state mode on rectangular pulses, and the dynamics of the development of evolutionary scenarios were recorded using triangular pulses of various durations and amplitudes.

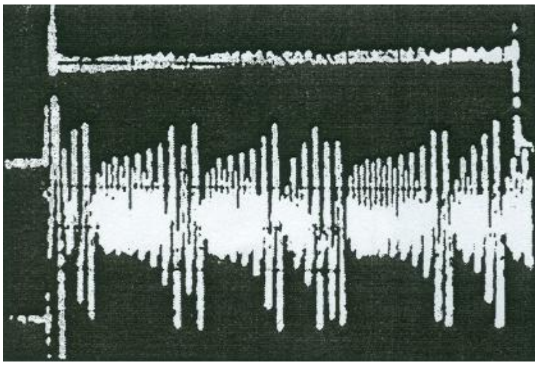

Fig. 3. Transition to a chaotic state through intermittency (Pomeau–Manneville scenario)

For comparison with the theory of nonlinear dynamic systems, phase portraits, bifurcational diagrams, two-dimensional Poincaré maps, power spectral characteristics were drawn based on experimentally obtained time, and fractal dimensions and Lyapunov exponents were calculated.

The recombination instability of the current in p-Ge (Au) during the experimental verification and a detailed study of a one-dimensional theoretical model developed for a gold-compensated electron germanium was discovered for the first time, when recombination instability in strong electric fields leads the system to instability and current oscillations [2]. The model takes into account not only the time, but also the spatial evolution of the high–field domain arising in the system when the applied voltage V and the emission coefficient β change, i.e. in the space of the voltage-emission parameters. Depending on the region of this parametric space, the system demonstrates three different modes of operation (ohmic, extinguished and fly-by-time), subdomains arise and other new properties are observed that are not typical of non-linear systems.

The obtained experimental results fully confirm the theoretical model. Three modes of operation of the system are discovered: (ohmic, extinguished and fly-by-time). The existence of one-, two- and more subdomain states and order-disorder transitions in the system, carried out through intermittency or a non-standard scenario of transition to a chaotic state, have been established.

It is known, that noise in nonlinear systems can play a constructive role, inducing more ordered regimes, leading to the formation of regular structures, an increase in the degree of coherence of the signal-to-noise ratio, etc.

We also experimentally tested the theory of deterministic stochastic resonance 3 in a semiconductor bistable system based on double-injection structure p-Ge<Au> with S-shaped current-voltage characteristic (CVC), which in the switching area exhibits chaotic behavior with interchangeability.

We have also experimentally verified the theory of deterministic stochastic resonance [3] in a semiconductor bistable system based on a double-injection p-Ge<Au> structure with an S-shaped current-voltage characteristic (CVC), which shows chaotic behavior with interchangeability in the switching region. The obtained results experimentally confirm most of the theoretical assumptions about the possibility of deterministic stochastic resonance in a real semiconductor bistable system with intermittency. In particular, the resonance amplification of external signal, the stochastic synchronization effect of the mean switching frequency of the bistable system and the forced frequency capture effect at large amplitudes of external signal, which is usually called «synchronization by extinguishing».

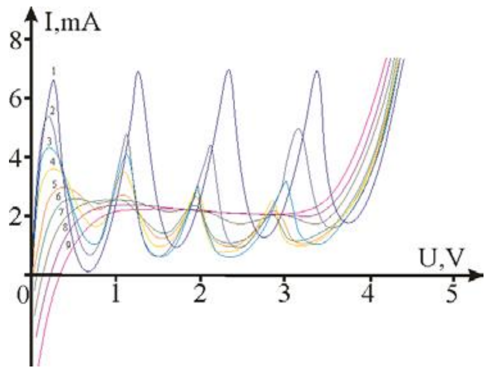

Fig. 4. CVC of a diode circuit exposed to a noise siqnal with a spectral density of 6 MHz with an intensity U, B: 1 – 0; 2 – 0.25; 3 – 0.5; 4 – 0.64; 5 – 0.88; 6 – 1.60; 7 – 2.40; 8 – 3.85; 9 – 4.20.

The study of the influence of external perturbations on the behavior of nonlinear circuits consisting of n series-connected semiconductor structures with negative differential resistances (NDR) is also quite promising.

Such circuits, when an electric voltage is applied, exhibit the properties inherent in superlattices and demonstrate bifurcation scenarios corresponding to them, leading to synchronization phenomena or current branches in this circuit. These studies have important applied aspects related to a wide range of problems: from the dynamics of neural systems to multi-connections of solar panels, random-order memory devices, digital logic systems, etc.

We have experimentally studied [4] mechanisms of conductance of nonlinear circuits, consisting of tunnel diodes of serial production and general application, and their response to external harmonic (up to 100 MHz) and noise (with spectral density up to 7 MHz) high amplitude disturbance. On the CVC (Fig. 4) for the four-diode circuit, when a harmonic signal with a frequency of 50 MHz is superimposed and its amplitude increases to 2.1 V, the following characteristic features of the CVC have been discovered: a significant amplitude attenuation of the current branches; the occurrence of ambiguities on the CVC, i.e. an increase in the number of incident N-sections; the greatest influence of perturbations on the first branch of the CVC; the appearance of a section with absolute negative conductivity on the first branch of the CVC.

When a noise disturbance with a spectral density of up to 7 MHz is superimposed and the intensity of the CVC of the studied circuits increases, completely unexpected results are demonstrated (Fig.4): the amplitude of the current branches is completely suppressed; instead of the first branch, a section with absolute negative conductivity appears on the CVC; the rest of the circuit exhibits only a constant component approximately parallel to the voltage axis in the entire range of applied offsets.

It is possible that the suppression of current branches discovered during noise exposure will find a very interesting and important application for neural systems. It is known, that similar current branches are formed in neurons when they are excited by injection currents. Moreover, with intermediate injection currents, a so-called "firing" mode occurs, which plays a decisive critical role in such systems. If it becomes possible to extinguish such a critical "firing" mode in neural networks with the help of noise of a certain spectral composition and intensity, then the importance of the analogy of the result obtained in nonlinear circuits will become obvious.

[1] *I.K. Kamilov, N.S. Abakarova, Kh. O. Ibragimov, K.M. Aliev.* Nonlinear phenomena and chaos in germanium oscillistor. J. Phys.: Condens. Matter. - 2001. - V. 13. - pp. 4519 - 4524

[2] *И.К. Камилов, Н.С. Абакарова, Х.О. Ибрагимов, К.М. Алиев.* Рекомбинационная неустойчивость тока в германии с золотом в нелинейном режиме. Письма в ЖТФ. - 2001.- т. 27, № 5. - с. 24 - 31

[3] *И.К. Камилов, К.М. Алиев, Х.О. Ибрагимов, Н.С. Абакарова.* Детерминированный стохастический резонанс в полупроводниковой бистабильной системе. Письма в ЖТФ. -2004. -т.30, № 4.-с. 25 – 32

[4] *К.М. Алиев, И.К. Камилов, Х.О. Ибрагимов, Н.С. Абакарова*. Отклик полупроводниковых нелинейных цепей на внешние возмущения. ФТП, 2015, т. 49, № 3, с.413-417