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L.V.Chirkova[1], E.V.Skubnevsky[2], K.T.Ermagambetov[1], E.T.Arinova[3]

[1]Ye.A.Buketov Karaganda State University;
[2]Institut of Physics of Semiconductors of Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russia;
[3]Gymnasium № 1, Karaganda
(E-mail: ket3853@mail.ru)

Nonlinear phenomena and instability in semiconductors

The nonlinear phenomena and instability in semiconductor structures are considered. Mechanisms of emergence of negative differential conductivity of N and S — types are described. As an example of education and use of drift not stability in semiconductors Gunn effect is considered. Operation of the generator of Gunn from the point of view of development of processes of self-organization in semiconductor structures is analysed. It is shown that the principle of its work is based on features of a power range of AsGa.

Key words: electric instability, domains, semiconductors, power range, Gunn effect.

The physical mechanisms resulting in instability are various, but the observed phenomena — spontaneous formation of spatial and temporary structures — are often similar.

Cooperative processes of self-organization are observed in the systems far from thermodynamic balance, at the expense of a constant exchange of energy and substance. These instability have close analogy to nonequilibrium phase transitions in the systems which are in thermal balance, for example, in ferromagnetic [1].

The open macroscopic systems brought out of thermodynamic balance under the influence of forces and owing to not linearity's inherent in similar systems can spontaneously pass into states with the high-ordered spatial or temporary structures. Such states can be supported at continuous inflow or dissipation of energy.

The isolated and closed systems after indignation always come back to the condition of thermal balance characterized by the maximum entropy. In the open macroscopic system brought out of a condition of thermodynamic balance after indignation there can be self-organization processes during which entropy locally decreases [2]. These processes are connected with the high-quality changes in a condition of system similar to phase transitions in equilibrium systems.

Many semiconductor devices work in the mode of the operated instability. In the semiconductor discomposed by strong external influence (big electric and magnetic fields; high level of injection; big level of light excitement, etc.), there are significantly strong nonlinear phenomena. Namely: considerable deviations from linear dependence between current and tension are observed; arise various type of instability (current breakdown, fluctuations and jumps of current or tension, a hysteresis in volt — the ampere characteristic). These can have instability negative impact on operation of solid-state devices, but in some semiconductor devices can make a basis of their functioning. Microwave ovens treat such devices generators, amplifiers of gigahertz range, high-speed electronic switches, etc.

Volt-ampere characteristic $I(V)$, measured in stationary conditions, most fully reflects of a charge transfer through the semiconductor. This characteristic with difficulty depends on microscopic properties of volume of the semiconductor and parameters of contacts. Density of current of j is defined only by microscopic properties of volume of the semiconductor.

If current density $j(E)$ with growth of electric field decreases, or, on the contrary, grows with reduction of electric field, the semiconductor has negative differential conductivity

$$\sigma_{\text{дифф}} = \frac{dj}{dE} < 0, \tag{1}$$

that is the corresponding stationary states it are unstable. Thus current via the semiconductor depends on resistance of other part of an electric chain: such as inductive and capacitor.

The Negative Differential Conductivity (NDC) happens N-or S-type, depending on what of these letters of the Latin alphabet reminds the characteristic form $j(E)$ (Fig. 1).

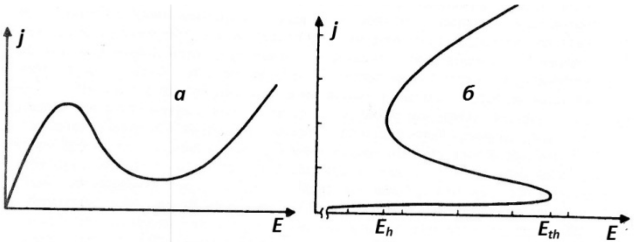

Figure 1. Dependence of density of current of *j* on electric field E
for two types of the negative differential conductivity of N-type (a) and S-of type

Negative differential conductivity of N-and S-types are caused by not stability operated by respectively tension or current.

In case of density NDC N-of current is unambiguous function j (E) of a field, and the field E — is ambiguous function *E(j),* that is in a certain area to one value of density of current there correspond three values of intensity of a field.

The case of DNC of S-type is complementary, that is *E* and *j* are interchanged the position. This duality makes a deep meaning [1].

It is considered to be that negative conductivity arises because of instability of the uniform steady state connected with spatial fluctuation of electric field and concentration of carriers of a charge [1–3]. They lead to spatial non-uniform distributions of density of current and field.

For the analysis of such spatial structures the thermodynamic principle of the minimum production of entropy, fair for systems with Onsager symmetry is inapplicable. As it is known [1, 2], the principle of of Onsager symmetry is fair for the systems which are near an equilibrium state and in approach linear a deviation from it. And negative differential conductivity arises when the system is far from an equilibrium state.

So, NDC *N*-of type arises when the uniform steady state is unstable to formations of moving and motionless non-uniform, layered distributions of a field (domains of a strong field). NDC of *S*-type arises in a case when the uniform steady state is unstable to formation of non-uniform distribution of density of current in the cross section of the conductor (powers cords) [1–3].

NDC N-of type is observed in volt — the ampere characteristics of tunnel, avalanche and flying diodes, Gunn diode, multilayered devices like tiristor [4–6]. The origin of negative differential mobility can be defined both p-n properties — transition and the phenomena in volume of the semiconductor. For example, in the NDC N-tunnel diode of type it is caused by the processes happening in p-n — transition. The tunnel diode is formed by degenerate semiconductors and p-n — transition possesses narrow area of a volume charge (Fig. 2).

Volt-ampere characteristic of N-of type is caused by tunneling of carriers of a charge through a potential barrier of p-n — transition. p-n width – transition between degenerate semiconductors is sufficient is small so — areas tunnel electrons from a zone of conductivity of n on free levels of a valent zone p — area and vice versa. These counter flows are equal in lack of external shift also resultant current through p-n — transition is equal to zero (to Fig. 2 a).

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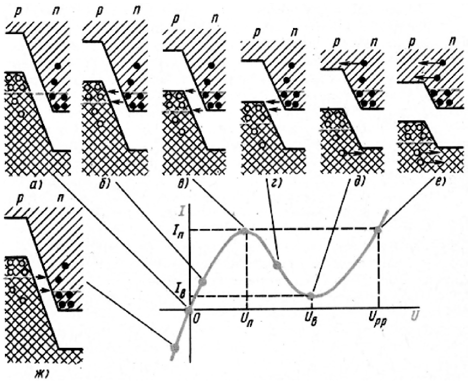

а) in the absence of voltage; б) — at a small direct voltage; в) at a peak point voltage;
г) at a voltage corresponding to negative differential resistance;
д) at a valley voltage е) — at a solution tension; ж) — at the return voltage

Figure 2. Volt-ampere characteristic and charts of the tunnel diode

Four main mechanisms of emergence of negative differential conductivity $dj/dE < 0,$ are known caused by properties of volume of the semiconductor: nonlinear dependence of mobility of carriers of a charge on an electric field — drift instability; nonlinear dependence of concentration of carriers of a charge on electric field — generation-recombination instability; nonlinear dependence of electronic temperature on electric field — peregrevny instability; nonlinear dependence of temperature of a crystal lattice on electric field — electrothermal instability [1].

One of the examples illustrating use of drift not stability in semiconductors is Gunn effect. On its basis Gunn generator which work is based on effect of emergence of periodic high-frequency vibrations in a semiconductor sample with N — the Figurative volt-ampere characteristic [4–6] is created. Feature of power structure of the AsGa semiconductor (Fig. 3) is the cornerstone of functioning of Gunn generator.

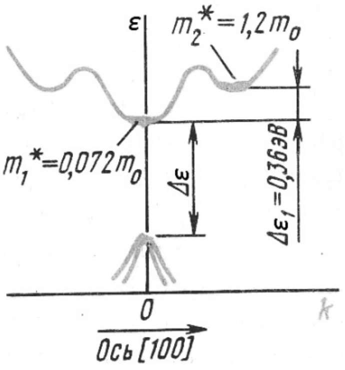

Figure 3. Structure of power zones in the crystallographic direction

The power chart AsGa [4] constructed in space of quasi-momentums in the crystallographic direction [111] has some minima — some power valleys (Fig. 3). In such semiconductor there can be electrons with various mobility — «easy» and «heavy». The ratio between concentrations of «easy» The ratio between concentration of «easy» n_1 and «heavy» n_2 electrons can spontaneously change depending on intensity of external exciting electric field. It leads to spontaneous emergence of some features of transfer of a charge via the semiconductor which makes a basis of the principle of operation of Gunn generator. Thus the following is essential. If energy of an external source of excitement is small, about $\Delta\varepsilon_1$, that electrons, having passed from a valent zone into a conductivity zone without change of a quasi-momentum, generally will appear in lower — the central power valley, i.e. the inequality will be carried out $n_1 >> n_2$. Thus the part of the electrons which passed into a conductivity zone will come back to a valent zone, i.e. the return process will proceed. Thus, at action of external exciting force electrons in the semiconductor Thus the part of the electrons which passed into a conductivity zone will come back to a valent zone, i.e. the return process will proceed.

Thus, at action of external exciting force electrons in the semiconductor *AsGa* will be continuously, randomly to pass in the direct and return directions.

With increase in intensity of an external source of excitement (at the intensity of a field exceeding a certain threshold value $E > E_{пор}$) electrons, gaining additional energy, big $\Delta\varepsilon_1$ (Fig. 3), pass into side valleys and become "heavy" (naturally, at change of a quasi-momentum of electrons because of collision with phonons). If there is no noticeable shock ionization, the general concentration of electrons remains invariable and equal equilibrium:

$$n_0 = n_1 + n_2. \tag{2}$$

If we designate mobility of easy and heavy electrons as μ_1 and μ_2, for current density in the semiconductor we have:

$$J = q(n_1\mu_1 + n_2\mu_2)E. \tag{3}$$

In weak electric fields of ($E < E_{пор}$) practically all electrons are in the central valley of $(\kappa = 0,\ n \approx n_1)$, and density of current is defined by a ratio

$$J = qn_0\mu_1 E. \tag{4}$$

To the last ratio (3) there corresponds the site of 1 volt-ampere characteristic (VAC) of the semiconductor

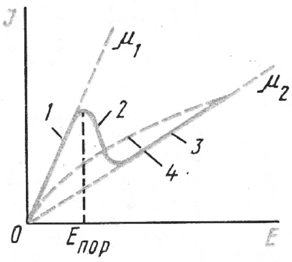

Figure 4. Dependence of density of current via the semiconductor
with multivalley structure of a band of conductivity
from intensity of electric field [4]

In strong electric fields ($E >> E_{пор}$) practically all electrons can gain additional energy $\Delta\varepsilon_1$ and appear in the side valley. In this case $n_2 = n_0$ и

$$J = qn_0\mu_2 E. \tag{5}$$

The ratio (5) defines a site of 3 volts — the ampere characteristic.

At the average values of intensity of electric field which are only a little exceeding threshold intensity, density of current is defined by concentration and «easy» and «heavy» electrons (site 2 on Fig. 4).

We will show that functioning of the Gunn generator is connected with synergetic processes [7].

The element of system (uniformly alloyed *AsGa* crystal) possesses the feature leading to development of processes of self-organization in it — spontaneous generation of electric domains. In a zone of conductivity of a semiconductor crystal of *AsGa* the power range of electrons has two minima — central and side. Curvatures of a curve of a power range, corresponding to these minima, are various. Respectively, also the effective mass of electrons which energy lies in vicinities of these minima will be various. If on uniformly alloyed *AsGa* crystal having two ohmic contacts with electrodes (the cathode and the anode) tension creating in a crystal intensity of electric field, a little smaller threshold intensity moves ($E < E_{пор}$),that occurs an exchange of energy between elements of system, that is between a power source and the semiconductor. In weak electric fields practically all electrons which passed from a valence band into a conductivity zone will appear in the central valley $(\kappa = 0,\ n \approx n_1)$, current density in this case is defined by a ratio (4). Transfer of a charge in a crystal will be, generally to be carried out by «easy» electrons and density of current will have the maximum value:

$$J_{\max} = qn_0\mu_1 E_0 = qn_0\upsilon_0. \tag{6}$$

In the semiconductor near areas of the anode and cathode always there are defects. Local intensity of electric field near defects can exceed threshold intensity of electric field. It will lead to increase of energy of the electrons which appeared in this area and will allow them to pass into an overlying side minimum spontaneously. The part of the energy received by electrons from a source will be transformed to thermal energy, i.e. there will be energy dissipation.

Having appeared in a side overlying minimum of a power range electrons from the category of «lungs» spontaneously will pass into the category of «heavy». Thus, reduction of number of «easy» electrons will be followed by increase in number of «heavy» electrons, i.e. the coordinated change of conditions of subsystems of these two classes of electrons will take place. In the considered system the self-organization process caused by feature of structures of subsystems will proceed. Drift speed to the anode of «easy» electrons exceeds the speed of drift of «heavy» electrons. Therefore in the vicinity of defect from the heavy cathode electrons will create negatively loaded layer, and from the anode because of a lack of electrons there will be a layer of the impurity which are positively loaded the donor.

The new structure — the domain is so formed, i.e. during process of self-organization in the considered system there are more difficult and more perfect structures.

The domain consists of two layers: negatively loaded layer formed from the cathode destroyed «heavy» electrons, and from the anode — positively loaded layer formed by ions the donor impurity (Fig. 5). Direction of electric field of the domain $E_{дом}$ coincides with the direction of the exciting field attached to the semiconductor. It leads to that in process of formation of the domain the field grows in it, and outside the domain decreases. The increase in drift speed of «heavy» electrons in the domain and reduction of drift speed of «easy» electrons outside the domain results, that is the coordinated course of processes in system is again observed. In some time point the drift speed of the movement of «heavy» electrons (speed of the movement of the domain) will appear the equal drift speed of the movement of «easy» electrons:

$$\upsilon_1 = \upsilon_2, \tag{7}$$

$$\mu_1 E_1 = \mu_2 E_2, \tag{8}$$

where υ_1 — the drift velocity of the electrons outside the domain; υ_2 — the drift velocity of the electrons inside the domain, that corresponds to the speed of the movement of the domain from the cathode to the anode.

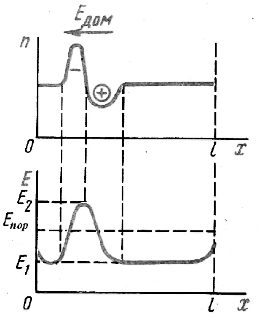

Figure 5. Distribution of concentration of electrons and intensity
electric field in a crystal after formation of the domain [10]

Apparent, $\upsilon_1 < \upsilon_0$, as $E_1 < E_0$. Therefore after formation of the domain density of current decreases to

$$J_{\min} = qn_0\upsilon_1. \tag{9}$$

The minimum value of density of current through a crystal will remain during time of the movement of the domain through a crystal or during flight time

$$t_{прол} = l/\upsilon_2, \tag{10}$$

where l — crystal length.

At achievement of the anode the domain disappears and density of current increases to value $I_{\max}$, corresponding domain. After that at the cathode the new domain is formed, and process repeats (Fig. 6).

The considered mechanism of operation of the device with intervalley transition of electrons corresponds to a flying operating mode. Electric field in the domain grows in this mode during its formation, and outside the domain simultaneous reduction of intensity of electric field is observed. For this reason only one domain as transition of electrons in the side can come from the central valley only in the domain where total intensity of electric field exceeds threshold value can be formed.

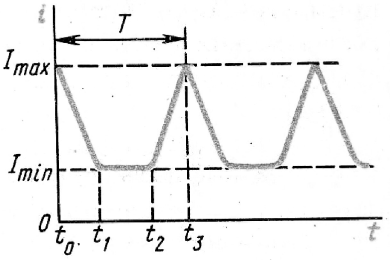

Figure 6. Dependence of the current passing through Gunn generator on time: time corresponding to the beginning of formation of the domain; termination time formations of the domain; time corresponding to the beginning of disappearance of the domain on anode; time of a total disappearance of the domain on the anode and origin of the second the domain on the cathode [4]

Time of formation of the domain is defined by time of a Maxwell relaxation ($\tau = \varepsilon_0\varepsilon\rho$).Time of flight of the domain from the cathode to the anode has to be more time of its formation. Therefore the condition of emergence of fluctuations of current in Gunn generator can be formulated as follows:

$$t_{прол} = l/\upsilon > \varepsilon_0\varepsilon\rho, \text{ или } n_0 l >> \varepsilon_0\varepsilon\upsilon/(q\mu_2). \qquad (11)$$

Thus, in *AsGa* the nonlinear processes leading to emergence of negative NDC gain development.

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Л.В.Чиркова, Э.В.Скубневский, К.Т.Ермағанбетов, Е.Т.Аринова

Шалаөткізгіштердегі бейсызық құбылыстар және орнықсыздықтар

Шалаөткізгіш құрылымдарындағы бейсызық құбылыстар мен орнықсыздықтар қарастырылған. *N* және *S* тәріздес дифференциялық өткізгіштіктерге әкелетін физикалық құбылыстар талданған. Шалаөткізгіштіктерде ығу орнықсыздықтарының пайда болу табиғаты олардың шалаөткізгіштерден жасалған құралдардың жұмысында алатын орны туралы мысал ретінде Ганн құбылысы қарастырылған. Ганн өндіргішінің жұмысы шалаөткізгіш құрылымда өз бетімен жүретін құбылыс тұрғысынан талданған. Ганн өндіргіші жұмысы *AsGa* шалаөткізгішінің энергия спектрінің ерекшеліктері әсерінен туындайтын орнықсыздықтарға негізделетіндігі көрсетілген.

Л.В.Чиркова, Э.В.Скубневский, К.Т.Ермаганбетов, Е.Т.Аринова

Нелинейные явления и неустойчивости в полупроводниках

Рассмотрены нелинейные явления и неустойчивости в полупроводниковых структурах. Описаны механизмы возникновения отрицательных дифференциальных проводимостей *N*- и *S*-типов. В качестве примера образования и использования дрейфовых неустойчивостей в полупроводниках рассмотрен эффект Ганна. Проанализирована работа генератора Ганна с точки зрения развития процессов самоорганизации в полупроводниковых структурах. Показано, что принцип его работы основан на особенностях энергетического спектра *AsGa*.

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