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Electronic mechanisms of instability in semiconductor structures

Semiconductor crystals are difficult dynamic systems in which emergence of electric not stability is possible (failure of current, spontaneous fluctuations of current or tension, switching and a hysteresis in volt — the ampere characteristic, etc.). This instability meets in many materials, in different temperature areas and at various levels of excitement. In article instability of some branches of volts — the ampere characteristic of semiconductor devices — existence of the negative differential conductivity (NDC) of S-and N-of types is considered. It is shown that NDC are connected with not stability operated by tension or current. The main electronic mechanisms resulting in negative differential conductivity are considered.

Key words: a semiconductor crystal, instability, negative differential conductivity, volt — the ampere characteristic.

The semiconductor which is under strong external influence finds essential nonlinear behavior: emergence of considerable deviations from a linear ratio between current and tension (violation of the law of Ohm), emergence of not stability is possible (interruptions of current, fluctuation and a gallop of current switching and a hysteresis in the volt-ampere characteristic, etc.).

Big electric and magnetic fields, high level of current injection and light excitement can be external influences.

Listed above instability meet in many materials, in different temperature areas, at various levels of excitement [1–3]. Often they have negative impact on characteristics of semiconductor devices, but in certain cases they are used for the special purposes. For example, for generation of microwave radiation in the range from 0,1 to 1000 GHz, for strengthening in the gigahertz range of frequencies i.e. where ordinary transistors can't be used [3, 4].

It is known that the volt-ampere characteristic of the $I(U)$ semiconductor which is measured in stationary conditions, most fully reflects nature of transfer of carriers of a charge. This characteristic depends on microscopic properties of volume of the semiconductor. These properties define dependence of density of current of j on local electric field E and from parameters of contacts. It is often possible to be limited to a local static scalar product of $j(E)$.

If dependence of $j(E)$ has area of the negative differential conductivity (NDC)

$$\sigma_{\text{дифф}} = \frac{dj}{dE} < 0, \qquad (1)$$

that is, if density of current decreases with growth of electric field (or increases at reduction of a field), respectively stationary states will be unstable. In this case the size of current will depend on other chain which part even in the absence of external load resistance resistive and jet elements surely are (resistance and inductance of wires, mutual inductance and capacity).

Depending on what of letters of the Latin alphabet — N or S — reminds the form of the characteristic of $j(E)$, distinguish NDC N-or S-of type. The characteristic type of the specified characteristics is given in figure 1.

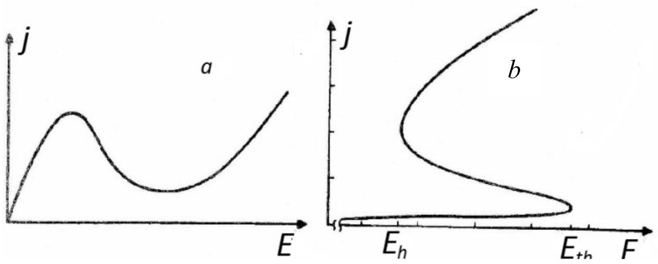


Figure 1. Dependences of *j* (*E*) for NDC of *N*-type (a) and *S*-type (b)

The tunnel diode and Gunn diode belong to devices with NDC *N*-of type. The avalanche-transit (ATD) diode, multilayered devices such as thyristor, as p-n-p-n-and p-i-n-diodes, thermal and electro thermal switches, switches on elements Ovshinsky ovonic memory in the type NDC *S*-type.

NDC N-and *S*-of types are connected with instability which voltage or current. In case of density NDC N-of current is single valued function of a electric field. Thus it is necessary to consider that the electric field is ambiguously: the *E*(*j*) function in a certain area of values *j* has treble coursing [4]. The case of NDC *S*-of type is complementary, i.e. *E* and *j* are interchanged the position. NDC *N*-and *S*-of types are connected with instability which voltage or current. In case of density NDC *N*-of current is single valued function of a electric field. Thus it is necessary to consider that the electric field is ambiguously: the *E*(*j*) function in a certain area of values *j* has treble coursing [4, 5]. The case of NDC *S*-of type is complementary, i.e. *E* and *j* are interchanged the position.

Also combinations of NDC *N*-and *S*-of types are possible: they can replace each other on the static characteristic at increase of electric field; perhaps eventually transformation of the characteristic from *S*-figurative in *N*-figurative; at last, the static characteristic can have more difficult form, with a complex shapes of current and tension. Also combinations of NDC *N*-and *S*-of types are possible: they can replace each other on the static characteristic at increase of electric field; perhaps eventually transformation of the characteristic from *S*-figurative in *N*-figurative; at last, the static characteristic can have more difficult form, with a complex shapes of current and tension.

The volt — the ampere characteristic of the semiconductor can be calculated, using dependence of *j* from *E*, having carried out integration of density of current of *j* on the flow area s and a field *E* on testing length:

$$I = \int jds; \tag{2}$$

$$U = \int_0^{l_z} E(z)dz. \tag{3}$$

In distinction from dependence of *j*(*E*) which is defined by properties of volume of semiconductor material, volt — ampere characteristic of *I*(*U*) depends also on geometry of a sample, boundary conditions and contacts. However, if the steady state spatially is uniform and resistance of contacts can be neglected in comparison with semiconductor volume resistance, dependences of *j*(*E*) and *I*(*U*) are similar, i.e. can be reduced to one curve by change of scale.

As a rule, NDC connect with instability of a uniform steady state in relation to spatial fluctuations of electric field and concentration of carriers that leads to spatially non-uniform distributions of density of current or field [1, 4]. Thus the usual thermodynamic explanation of such spatial structures is unsuitable as NDC comes when the system is taken far away from a condition of thermal balance.

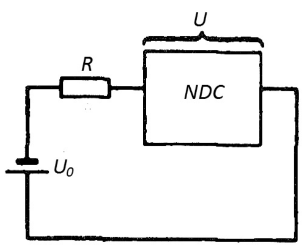


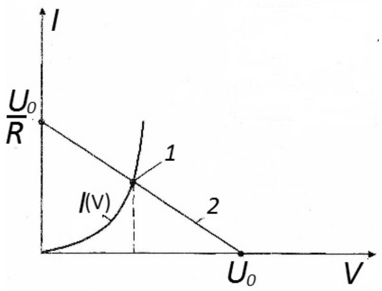
Figure 2. A chain with NDC-an element

The example of the elementary chain with the element having NDC is given in figure 2. NDC – an element is included consistently with the load resistor *R* and a source of tension.

The load line of an element has an appearance (fig. 3)

$$I = \frac{(U_0 - U)}{R}. \tag{4}$$

Crossing of a load straight line about BAX of the device defines a working point on a direct current. Working points at a negative differential indicator of $dI/dU < 0$ often are unstable in relation to heterogeneity of a spatial charge (formation of non-uniform distribution of a field or density of current) and in relation to emergence of the oscillations determined by an external chain.



1 — working point, 2 — a load line on a direct current

Figure 3. Dependence of current on tension on an element with NDC

By the form characteristics of I (U) and to position of the load line can be made the following general conclusions. In case of N-or S-of the figurative characteristic of I (U) three points of intersection of the characteristic of I (U) and the load line are possible. At change of the enclosed tension the load line is displaced parallel to itself and points of intersection move according to the characteristic of I (U). When the load line is tangent to the characteristic, there is a merge of two points of intersection, and at further change there will be a point of intersection — bifurcation of the elementary type. Generally bifurcations are closely connected with loss or change of stability of branches of various decisions.

In the case under consideration it means that one of two merging points of intersection is steady, and another is unstable though in both cases the differential indicator is negative.

Negative differential conduction is shown via mechanisms which are defined by p-n-properties of transition, and the phenomena in volume of the semiconductor. These mechanisms are realized in many semiconductor devices (tunnel diodes, diodes Gunn, avalanche-transit diode, etc.). So, in the tunnel diode and in p-n-p-n-the diode NDC mechanisms are caused by the phenomena in p-n-transition.

Operation of the tunnel diode and the mechanism of emergence of type ODP N-in it are in detail considered by authors in [6].

In p-n-p-n-the diode S-the figurative characteristic of I (U) is realized. This device has four-layer structure. Many p-n-p-n-options of structure, including a thyristor or the operated semiconductor rectifier are known. The elementary four-layer structure (a dynistor, a diode thyristor or Shockley diode) consists of three consecutive p-n-of transitions and two ohmic — the anode and the cathode (fig. 4).

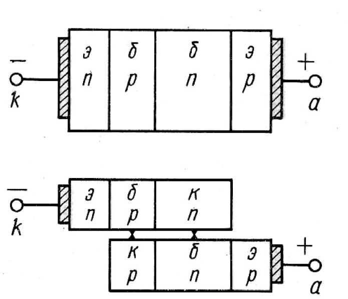


Figure 4. Structure of the Shokley diode

When giving on Shokley diode of direct tension it can be in two steady states: closed and opened. Extreme p-n-transitions are displaced thus in the direct direction (optical transitions), average p-n-transition is displaced in the opposite direction (collector transition). The closed condition of a dynistor corresponds to a site of a direct branch BAX between a zero point and a point of switching (fig. 5, site 1 to CVC). The point of switching is a point to CVC in which differential resistance is equal to zero, and tension on a dynistor reaches the maximum value. The open condition of a dynistor corresponds to a low-voltage and low-impedance site of a direct branch CVC (fig. 5, site 2 to CVC). Between sites 1 and 2 of volts — the ampere characteristic there is transitional a site corresponding to an unstable condition of structure.

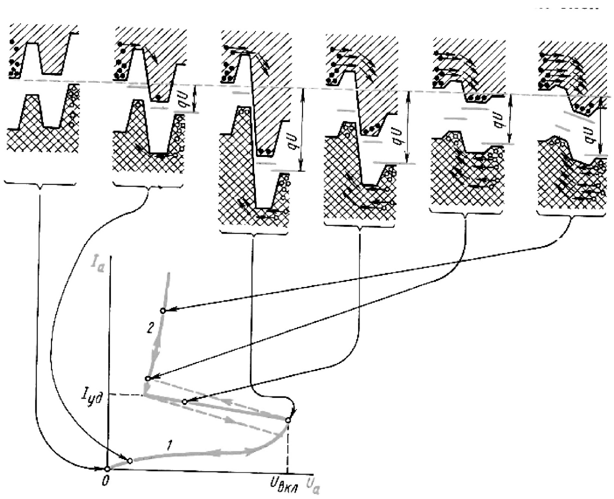


Figure 5. BAX and power charts of Shokley diode (diode thyristor)

The most part of external direct tension falls on collector transition therefore the first site of a direct branch BAX of the Shokley diode is similar to the return branch BAX of the rectifier diode (fig. 5, a site 1 BAX). With increase in the anode tension enclosed between the anode and the cathode direct tension and on emitter transitions increases. The electrons injected from emitter n-in p-base diffuse to collector transition, are involved by a field of collector transition and get to n-base (fig. 5). Further advance of electrons on structure is interfered by a small potential barrier of the right emitter transition. Therefore, part of electrons, having appeared in a potential hole of n-of base, forms an excess negative charge which, lowering height of a potential barrier of the right emitter transition, causes increase in injection of holes from emitter p-in n-base.

The injected holes diffuse to collector transition, are involved by a field of collector transition and get to p-base. Their further advance on structure of the diode is interfered by a small potential barrier of the left emitter transition now. Thus, in p-to base there is an accumulation of an excess positive charge that promotes increase in injection of electrons from emitter n-.

Thus, when giving on p-n-p-n-the diode as whole direct tension two states are possible: with low conductivity (the small size of current is I) and with high conductivity (big size I). In the first case on extreme (optical) transitions direct shift, and on average (collector) transition — blanking offset. In the second case distribution of potential in the device is nonmonotonic dependence and such that on all three transitions shift direct, i.e. unlocking. *S*-the figurative characteristic of the *I* (*V*) is as a result formed.

Lead 4 main mechanisms to emergence of NDC determined by properties of volume. The nonmonotonic dependence of density of current of j on a field E leading to a negative differential condactans in some range E can be caused by nonlinearity of mobility, concentration of carriers of a charge, temperature of electrons or temperatures of a lattice [3, 4].

There are some types of nonlinearity of mobility or drift instability: Gann, and instability, Bragg scattering on border Brillouin zone. Gann nonlinearity of mobility is used in Gunn diode for generation and strengthening of the Microwave radiation frequencies over 1 GHz. NDC mechanism in this case is based on intervalley electron transfer from a state with high mobility in a state with low mobility under the influence of strong electric field (E > 3 Sq/s). As material for production of semiconductor devices with similar structures, connections $A^{III}B^{Y}$, in particular, GaAs gallium arsenide serve. The schematic image of zonal structure of GaAs is given in figure 6.

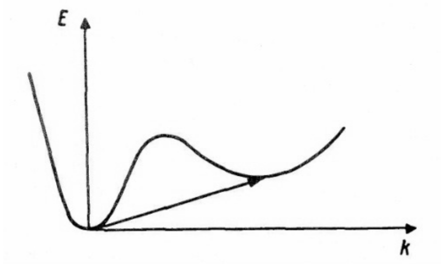


Figure 6. Zonal structure of a zone of conductivity of GaAs

In weaker electric field almost all electrons are in the main minimum where the effective mass of m * is small ($m^* \approx 0{,}07 m_0$, m_0 -the mass of an electron). Therefore, their mobility is great. At increase in a field E electrons "are warmed" and gain the energy sufficient for transition to the side valley with higher energy in a minimum, but with a bigger effective weight and, therefore, with lower mobility. In process of transition of the increasing number of electrons their average mobility sharply decreases, the current density determined by expression $j = en\mu(E)E$ also decreases. Negative differential mobility results. When the majority of electrons appears in the side valley, j will start increasing again. Thus the characteristic with type NDC N-turns out. Other NDC mechanisms connected with nonlinearity of mobility are caused by anisotropy of equivalent side valleys.

Other NDC mechanisms connected with nonlinearity of mobility are caused by anisotropy of equivalent side valleys. For example, Erlbah instability in Ge is caused by not diagonal elements of a tensor of differential conductivity Other NDC mechanisms connected with nonlinearity of mobility are caused by anisotropy of equivalent side valleys. For example, Erlbah instability in Ge is caused by not diagonal elements of a tensor of differential conductivity dj_α / dE_β.

Let there is a case of two equivalent side valleys 1 and 2 which axes of anisotropy have the different directions. Electric field E is enclosed in the direction x, symmetric concerning these two valleys. Then j current will also be directed lengthways x. Further we will assume that the field slightly deviates the direction x so effective weight for conductivity in the valley 1 will exceed that in the valley 2. Speed with which electrons absorb energy of electric field (speed of a warming up of electrons) is inversely proportional to effective weight for conductivity. Therefore in the valley the 2nd electrons will be warmed more strongly, than in the valley 1. By means of intervalley dispersion electrons will pass from hotter valley (the valley 2) in colder. (the valley 1) and in the valley of 1 electrons will become more, than in the valley 2. Reduction of filling of the valley with higher mobility will lead to a negative contribution to current in the direction of y that can result in cross negative conductivity (type NDC N).

Generative recombinational instability (instability GR) or instability caused by nonlinearity of concentration of carriers of a charge are characterized by nonlinear dependence of concentration of carriers in a steady state from a field E. It results in nonmonotonic dependence of density of current on a field with NDC N-or S-of types. Such dependence is caused by redistribution of electrons between a zone of conductivity and the connected states in the course of a warming up of electronic gas.

GR — coefficients usually depend on electric field. Especially strong dependence takes place for increase in section of capture of carriers by the impurity centers with growth of a field and for processes of shock ionization of carriers from impurity levels.

Capture of electrons on deep impurity levels demands overcoming of a Coulomb potential barrier by them. Therefore the coefficient of capture increases with a field E. and concentration of free carriers decreases with growth of a field, $dn/dE < 0$, and differential conductivity equal $dj / dE = e\mu\left(n + E dn / dE\right)$ can become negative. In stronger fields the coefficient of ionization increases, and concentration of carriers starts growing with a field. It results in positive differential conductivity. So there is N-figurative $j(E)$ the characteristic. Also shock ionization of carriers from impurity levels (small donors or deep traps) or ionization (avalanche breakdown) can lead to ODP. If the free carrier of current received sufficient kinetic energy in electric field, it can give this energy at collision to the connected carrier. The last then gets to a conductivity zone (electron) or to a valent zone (hole). As a result there is one more free carrier which can make one more act of shock ionization in turn. The fast increase in concentration of free carriers is as a result observed. In the electric fields exceeding threshold values for, necessary for a warming up of carriers to the energy sufficient for ionization, the coefficient of shock ionization sharply increases with growth of a field E. Under certain conditions such processes can lead to type NDC S [7, 8].

The phenomena in volume of the semiconductor leading to NDC are the cornerstone of the avalanche and flying diode and p-i-n-of the diode.

P-i-n-the diode consists of a layer of the not alloyed semiconductor material concluded between layers of p-and n-of types (fig. 7). The majority of switching microwave radiation — diodes has similar structure. If n-a layer of the diode to connect to minus, and p-a layer — to tension source plus, electrons will be injected to the center with own conductivity (i-a layer). Let's say that i-a layer contains the deep centers of a recombination of acceptor type with the big cross section of capture for holes and considerable the smaller section of capture for electrons. Besides, we will assume that in a condition of thermal balance these centers are completely occupied with electrons. Then at the low level of injection for holes there will be «a recombination barrier»: the most part of the injected holes will be taken the recombination centers near injecting transition p-i-. The injected electrons thus will freely pass i-a layer.

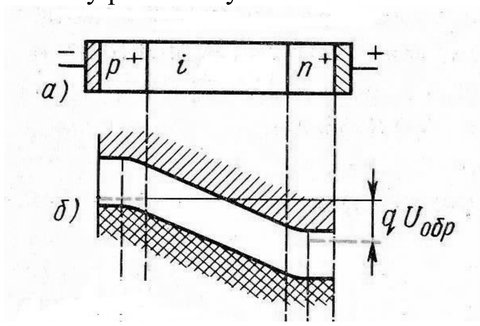


Figure 7. The diode with p-i-n-structure (and) and its power chart

Resultant current of electrons is limited to the volume charge formed by the injected electrons. If concentration of the injected electrons and holes exceeds concentration of the centers of a recombination, i.e. at the high level of injection, on each center of a recombination there is a taken hole, and excess holes just as electrons pass i-a layer. At rather high level of injection of concentration of electrons and holes are approximately identical. In this case current is transferred by quasineutral electronic hole plasma.

Thus, at this size of the enclosed tension two steady stationary states are possible. The first is characterized by the small size of current, thus the recombination centers are occupied with electrons, and current is created by carriers of one sign and is limited by a spatial charge. The second is a state with big current. In this case the recombination centers are filled with holes, and current is caused by the injected plasma. In intermediate states there is NDC.

Avalanche-transit diodes have structure $p^+ - n - n^+$ (fig. 8). They work in the mode of avalanche reproduction of carriers of current at the return shift of electric transition having constant and variable components.

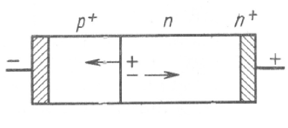


Figure 8. Structure of avalanche-transit diode

When total tension exceeds penetrative, shock ionization — avalanche breakdown begins. Electron-hole couples generated in narrow part of p-n-of transition where intensity of electric field is sufficient for shock ionization are divided by a field. The current caused by the movement of new carriers passes through structure until these carriers don't go beyond transition p-n-.

If to impose an alternating voltage on continuous return shift, emergence of a negative variable conductance if the part of carriers drifts against variation electric field is possible. It corresponds to delay of a phase of current on a corner π concerning tension.

Increase of tension all the time will be followed by reduction of current, and reduction of tension – current growth. It testifies that for this frequency of an alternating voltage during the entire period of fluctuations the condition of a negative conductance is satisfied.

At reduction in the frequency of an alternating voltage current will lag behind tension on a corner, smaller π as time of flight and a lag effect of shock ionization don't change. When with reduction in the frequency of an alternating voltage phase shift between current and tension makes π/2, conditions of a negative conductance will be satisfied only throughout a half of the period, alternating through everyone a quarter of the period with conditions of positive differential resistance. In this limit case on average for the period the avalanche and flying diode won't possess a negative conductance. Thus, in case of avalanche and flying diodes the combination of the effects connected with shock ionization and final time of flight of carriers works.

All mechanisms of emergence of ODP considered in article are purely electronic, based on violation of balance in system of carriers by electric field. At the same time it should be noted that there is rather big variety electro thermal, the ODP acoustoelectric mechanisms, mechanisms connected with instability of the magnetized plasma, etc. which consideration is beyond this article.

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Шалаөткізгіш құрылымдарындағы орнықсыздықтардың электрондық табиғаты

Шалаөткізгіш кристалдар өте күрделі динамикалық жүйе болғандықтан, оларда әр түрлі электр орнықсыздықтар (токтың кенеттен жоғалуы, ток пен кернеудің өз бетімен тербелісі, вольт-амперлік сипаттамаларда гистерезистің пайда болуы т.б.) пайда болуы мүмкін. Орнықсыздықтар көпшілік материалдарда әр түрлі температура аралығында, әр түрлі қоздырғыштардың әсерінен туындайды. Мақалада шалаөткізгіш құралдарының вольт-амперлік сипаттамаларының тармақтарында орнықсыздықтардың пайда болатындығы — S- және N-тектес теріс дифференциациялық өткізгіштіктердің пайда болатындықтары зерттелген. Теріс дифференциациялық өткізгіштіктің пайда болуы кернеу мен тоққа тәуелді орнықсыздықтарға тәуелді болатындығы көрсетілген. Теріс дифференциациялық өткізгіштіктің пайда болуына әкелетін электрондық тетіктер қарастырылған.

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

Электронные механизмы неустойчивостей в полупроводниковых структурах

В статье отмечено, что полупроводниковые кристаллы являются сложными динамическим системами, в которых возможно возникновение электрических неустойчивостей (срыв тока, спонтанные колебания тока или напряжения, переключение и гистерезис в вольт-амперной характеристике и т.д.). Эти неустойчивости встречаются во многих материалах, в разных температурных областях и при различных уровнях возбуждения. Авторами рассмотрена неустойчивость некоторых ветвей вольт-амперной характеристики полупроводниковых приборов — наличие отрицательной дифференциальной проводимости (ОДП) S- и N-типов. Показано, что ОДП связаны с неустойчивостями, управляемыми напряжением или током. Рассмотрены основные электронные механизмы, приводящие к отрицательной дифференциальной проводимости (кондактансу).

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