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Current instability phenomena in a tunnel diode and electron self-organization processes

In the article the mechanisms of electric instability in semiconductors are considered. The origin of negative differential conductivity of different types are described. On the example of functioning of the tunnel diode the mechanism of formation of the concentrated instability in semiconductors resulting in N-shaped volt-ampere characteristic of the diode is considered. It is shown that the «semiconductor structure consisting of two layers of semiconductors with different type of conductivity and an external source of electric energy» system can be considered as an open non-equilibrium thermodynamic system in which self-organization processes are possible. Operation of the tunnel diode in terms of the theory of self-organization in semiconductor structures is analysed. Processes of self-organization are resulted by change of concentration of carriers of a charge in power zones of p- and n-semiconductors of types which make the tunnel diode and therefore the direction of streams of electrons changes. The description of the movement of carriers of a charge in the considered semiconductor structure at various values and external shift is given: in an equilibrium state, at the return shift; at the direct shift and tension which have values less peak value; and tension exceeding «voltage dip». In a thermodynamic non-equilibrium system there can be processes of self-organization of various nature — tunneling and injection of electrons. At the same time the direction of processes of self-organization is defined by features of power ranges of the semiconductors making the tunnel diode and intensity of interaction between system elements.

Keywords: self-organization, semiconductor, electric instability, tunnel diode, negative differential conductivity.

And to the arising oscillatory phenomena in them rather large number of publications and monographs is devoted to a pilot and theoretical study of instability of current in semiconductors [1–3]. Emergence of such number of works is connected with a possibility of practical use of the phenomenon of instability of current in semiconductors for creation of high-frequency generators, amplifiers, etc.

Fluctuations of current in semiconductors arises when the differential conductivity becomes negative. Emergence of the site with the negative differential conductivity (NDC) is possible on volt-ampere characteristic (VACH) with dependence of mobility and concentration of carriers of a charge in the semiconductor from electric field strength.

Differential conductivity σ_d can be written down as [4]

$$\sigma_d = \frac{dj}{dE} = en\mu\left(1 + \frac{dln(n)}{dln(E)} + \frac{dln(\mu)}{dln(E)}\right), \qquad (1)$$

where E — electric field strength; j — electric field strength; n and μ —concentration and mobility of carriers of a charge, respectively; e — electron charge.

As appears from the given expression, σ_d becomes negative if a concentration (or mobility) carrier quickly decreases with growth of electric field strength E. NDC is usually observed on a certain site VACH. At the same time VACH or N-, or S–type are observed. In these cases in VACH appears a so-called «falling» site, i.e. the site with negative differential conductivity.

If the system is on the «falling» site VACH, in a sample there can be an instability. It is usually connected with the concrete origins NDC. For example, if the negative sign third composed in the right part (1) is the reason of instability, the instability is called drift. Its mechanism caused by interval transitions was for the first time explained with Ridley, Watkins and Hilsum [2].

If NDC is connected with the second composed in (1), then it is called concentration. Concentration NDC arises as a result of sharp reduction of concentration of free carriers with increase in the field.

Both origins of NDC lead to N-shaped VACH. And both are connected with a warming up of electronic gas: in the first case the drift speed of carriers decreases with growth of the field at their constant concentration. In the second — NDC arises as result of sharp reduction of concentration of free carriers with increase in the field. There is one more origin of NDC connected with a warming up of electronic gas. Here the cause of NDC is caused by various dependence on temperature of processes of transmission of energy and an impulse to a lattice. Such NDC is implemented on the «falling» site of S-shaped VACH and carries the name of overheating imbalance. The majority of the electric non-stability leading to NDC in semiconductors can be considered as the self-organization arising in an open thermodynamic non-equilibrium system [5]. The «semiconductor structure — a power source» system acts as the last.

In the previous works of authors [6, 7] processes of self-organization in semiconductor structures in the presence in them drift NDC on the example of Gunn's generator and the avalanche and flying diode were analysed.

In the present article in terms of the theory of self-organization processes in the tunnel diode are considered in which the concentration NDC mechanism leading to N-shaped VACH (Fig. 1) is implemented.

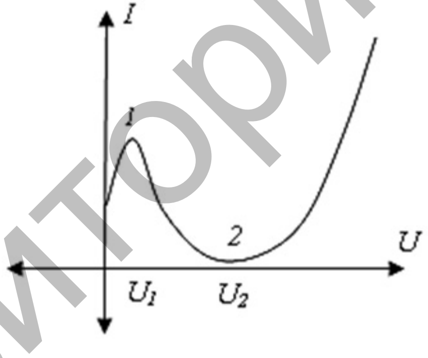

Figure 1. Static characteristic of the tunnel diode. U_1 is the peak tension, i.e. tension characteristic of the maximum current direct direction; the U_2 nd tension of «failure» characteristic of the minimum current

The tunnel diode has the special characteristics distinguishing it from ordinary diodes and stabilitrons. If diodes and stabilitrons well pass current only in one party (in the return — only in the field of breakdown), then the tunnel diode is capable to carry well current in both parties. This property is provided by features of the device of the tunnel diode: very narrow *p-n* transition and significant amount of impurity. It is known that for production of tunnel diodes semiconductors with high concentration of impurity are used — from 10^{18} to10^{20} cm^{-3}. Such semiconductors are called degenerates, actually being semi-metals. In them levels of impurity atoms form the power zones merging with the main resolved zones — valent and a zone of conductivity — the semiconductor. As a result Fermi's levels will be located not in the forbidden zones of *n*-semiconductors and *p*-types, and in their resolved zones, i.e. in a valent zone of the semiconductor of *p*-type and in a zone of conductivity of the semiconductor of *n*-type (Fig. 2).

As appears from the drawing, the bottom of a zone of conductivity of the semiconductor of *n*-type and a ceiling of a valent zone of the semiconductor of *p*-type are divided by very narrow locking layer. Thus, the transition thickness (a potential barrier) in the tunnel diode is very small (about 10^{-2} microns), what are two orders less, than in ordinary semiconductor diodes. Through such thin potential barrier carriers of a charge are capable to tunnel. At the same time resultant current transition will be defined by *p-n-* as the difference of electronic streams from one layer of the semiconductor in another. If to consider the power source and the tunnel diode consisting of the high-alloyed *n*-semiconductors and *p*-types, as an open non-equilibrium thermodynamic system, then the physical processes happening in it will satisfy to the basic principles of synergetic. Namely:

– in an equilibrium state when the diode is not affected by a power source, *n*-semiconductors and *p*-types exchange substance (equal quantities of electrons);

– in the presence of a power source charge carriers in semiconductors at its expense accumulate excess energy on length of a free run and transfer it due to collisions from not an ideal crystal lattice to a crystal. Temperature increase of a crystal which is transferred to the environment results, i.e. the considered system is open and is in a non-equilibrium thermodynamic state.

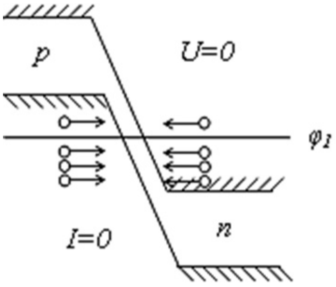

Figure 2. The power chart of the tunnel diode in an equilibrium state. By circles are designated electrons. Shooters noted the electrons capable to pass into an adjacent semiconductor layer

When the return tension is put to the diode, equilibrium state is broken and its power chart (Fig. 3) changes. At the same time there is an increase in a potential barrier and change of provision of level of Fermi: the ceiling of a valent zone of the semiconductor of *p*-type rises, Fermi level φ_{Fp} at the same time is displaced up, at the same time the bottom of a zone of conductivity of the semiconductor of *n*-type falls, and Fermi level φ_{Fn} displaced down. Electrons of a valent zone of the semiconductor of *p*-type which are at the power levels below Fermi level φ_{Fp}, will be located opposite to the free power levels of the semiconductor of *n*-type lying higher than the Fermi level φ_{Fn} (Fig. 3). Current through *p*-*n*- the transition directed from the *n*-type semiconductor to the *p*-type semiconductor results. With growth of the return tension this current increases very quickly as density of electrons in the depth of a valent zone is extremely big and even small increment of potential difference ($\varphi_{Fp} - \varphi_{Fn}$), will be followed by a significant change in a stream of electrons from the p-type semiconductor in the n-type semiconductor.

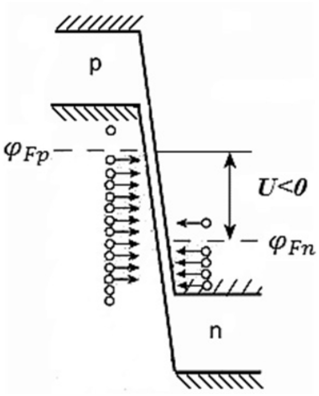

Figure 3. The power chart of the tunnel diode at the return shift

Thus, again there is an exchange of electrons of elements of a system, i.e. in a system the self-organization process having the form of the directed transfer of electric charge between semiconductors with different type of conductivity is observed. At the same time the direction of the self-coordinated process is defined by features of properties of the interacting system elements (features of power structure of semiconductors and the directions of fields of an external power source and the internal field of transition) and the nature of interaction between them. Let's consider processes of self-organization in the tunnel diode when external tension in the direct direction is put to it. The following cases are of interest: when the size of external direct shift does not exceed peak tension, i.e. when $0 < U < U_1$ (Fig. 4), when the condition is satisfied $U_1 < U < U_2$ (Fig. 5), when $U = U_2$ and, at last, when the size of direct shift exceeds tension of «failure» $U > U_2$ (Fig. 6).

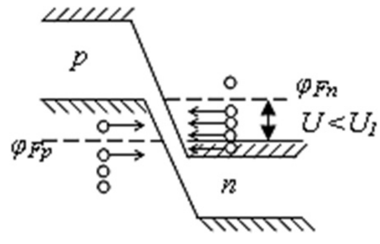

Figure 4. The power chart of the tunnel diode at a tension direct shift, there is less peak ($U < U_1$)

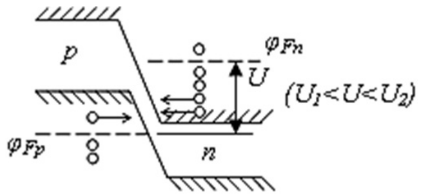

Figure 5. The power chart of the tunnel diode at a tension direct shift $U_1 < U < U_2$

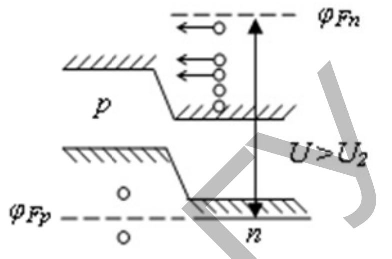

Figure 6. The power chart of the tunnel diode at a tension direct shift, exceeding tension «a failure» $U > U_2$

In the first case (Fig. 4) as a result of decrease in a potential barrier Fermi's level of the semiconductor of *n*-type is displaced up, and the *p*-type semiconductor — down. As a result, a part of electrons of a valent zone of the semiconductor of *p*-type will appear opposite to power levels of the forbidden *n*-type semiconductor zone, and a part of electrons of a zone of conductivity of the semiconductor of *n*-type — opposite to free power levels of a valent zone of the semiconductor of *p*-type. It will lead to decrease in intensity of tunneling of electrons from the *p*-type semiconductor in the *n*-type semiconductor. There will be a primary movement of electrons from *n*- in *p*-area. The direction of process of self-organization changes under the influence of features of interaction of the contacting semiconductors called by action of an external power source.

When Fermi level of the semiconductor of *n*-type φ_ by *Fn*, rising, is compared to a ceiling of a valent zone of the semiconductor of *p*-type, current via the tunnel diode accepts the maximum value (Fig. 1, a point 1). It corresponds to the maximum intensity of process of self-organization.

In the second case when external direct shift exceeds peak tension, but Fermi level of the semiconductor of *n*-type φ_ *Fn* there is less than tension of «failure» (Fig. 5), being displaced up, gets to the area of the forbidden *p*-type semiconductor zone therefore a part of electrons of a zone of conductivity of the *n*-semiconductor appear opposite to power levels of the forbidden *p*-type semiconductor zone. It leads to reduction of current via the diode. On volt-ampere characteristic of the tunnel diode the site with a negative resistance (Fig. 1, site 1–2) appears. Again there is a change of the direction of process of self-organization of the movement of electrons in the tunnel diode.

Further increase in tension of direct shift leads to a bigger decrease in a potential barrier in the field of transition *p*-*n*-. In case the size of shift becomes equal to tension of «failure», the bottom of a zone of conductivity of the semiconductor of *n*-type is compared to a ceiling of a valent zone of the semiconductor of *p*-type. Tunnel current decreases again to zero (Fig. 1, a point 2) as electrons of a zone of conductivity of the *n*-semiconductor are located opposite to power levels of the forbidden *p*-semiconductor zone. It corresponds to reduction to zero intensity of the self-organized transition of electrons from the *n*-type semiconductor in the *p*-type semiconductor.

And, at last, at a tension of direct shift exceeding tension of «failure», the forbidden power zones of *n*-semiconductors and *p*-types become «through» (Fig. 6) and tunnel current disappears. At the same time the coordinated movement caused by tunneling of electrons through a potential barrier stops. Current via the diode increases, but already at the expense of the ordinary mechanism — overcoming by electrons of a potential barrier — injections of carriers of a charge. There is a coordinated transfer of electrons mechanism of which differs from the mechanism of the transfer connected with tunneling process.

Thus, in the thermodynamic non-equilibrium system consisting of semiconductors with different types of conductivity, and a power source there are processes of self-organization of various natures (tunneling and injection of electrons). The direction of processes of self-organization is defined by features of properties of elements of a system (features of power ranges of semiconductors) and intensity of interaction between system elements (the sign and size of external tension).

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Туннельдік диодта тоқтың орнықсыздығы және электрондардың өздігінен ұйымдасуы

Шалаөткізгіш электр орнықсыздығының пайда болу механизмі қарастырылған. Әртүрлі теріс дифференциалық өткізгіштердің пайда болу механизмдері зерттелген. Туннельдік диодтың жұмыс ұстанымын талдау арқылы диодтың N-пішіндес вольтамперлік сипаттамасына әкелетін себептер талданған. Түйіскен шалаөткізгіштер мен энергия көзінен тұратын жүйені өздігінен ұйымдасатын үдерістер, пайда болатын орнықсыздықты ашық термодинамикалық жүйе ретінде қарастыруға болатындығы көрсетілген. Туннельдік диодтың жұмыс ұстанымы синергетика ұстанымдары негізінде түсіндірілген. Өздігінен жүретін үдерістер әсерінен *p*- және *n*-тектес шалаөткізгіштердің рұқсат етілген энергия жолақтарында зарядтасушылардың шоғырлану дәрежелерінің өзгерулері нәтижесінде электрондардың өздігінен тасымалдану бағыттары өзгеріске ұшырайды. Жүйені құраушы элементтердің өзара әсерлесу ерекшеліктеріне қарай электрондардың тасымалдануларында пайда болатын ерекшеліктер мұқият талданған. Қарастырылып отырған термодинамикалық жүйеде пайда болатын өздігінен ұйымдасатын үдерістердің табиғаттары әртүрлі. Өздігіне ұйымдасатын үдерістердің жүру бағыттары шалаөткізгіштердің энергия спетрлерінің ерекшеліктеріне, энергия көзінің қарқынына тәуелді.

Кілт сөздер: өздігінен ұйымдасу, шалаөткізгіш, электр орнықсыздық, туннельдік диод, теріс дифференциалдық өткізгіштік.

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Явления неустойчивости тока в туннельном диоде и процессы самоорганизации электронов

Рассмотрены механизмы электрической неустойчивости в полупроводниках. Описаны механизмы возникновения отрицательных дифференциальных проводимостей различных типов. На примере функционирования туннельного диода рассмотрен механизм формирования концентрационной неустойчивости в полупроводниках, приводящей к N-образной вольт-амперной характеристике диода. Показано, что система «полупроводниковая структура, состоящая из двух слоев полупроводников с разным типом проводимости + внешний источник электрической энергии» может рассматриваться как открытая неравновесная термодинамическая система, в которой возможны процессы самоорганизации. Проанализирована работа туннельного диода с точки зрения теории самоорганизации в полупроводниковых структурах. Показано, что в результате процессов самоорганизации происходит изменение концентрации носителей заряда в разрешенных энергетических зонах полупроводников *p*- и *n*-типов, составляющих туннельный диод, и изменяется направление потоков электронов. Приведено подробное описание движения носителей заряда в рассматриваемой полупроводниковой структуре при различных значениях и знаках внешнего смещения: в равновесном состоянии, при обратном смещении; при прямом смещении и напряжениях, меньших пикового значения; меньших напряжения «провала» и напряжениях, превышающих напряжение «провала». Показано, что в рассматриваемой термодинамической неравновесной системе могут возникать процессы самоорганизации различной природы — туннелирование и инжекция электронов. При этом направление процессов самоорганизации определяется особенностями энергетических спектров полупроводников, составляющих туннельный диод, и интенсивностями взаимодействия между элементами системы.

Ключевые слова: самоорганизация, полупроводник, электрическая неустойчивость, туннельный диод, отрицательная дифференциальная проводимость.

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