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St Petersburg, Russia, June 18–22, 2001

Dynamical nature of peculiarities of RTD static V–I characteristic

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Significant achievements in the way of creating nanostructures and studying physical phenomena in these ones are generally acknowledged by now. However the transition to creating nanoelements with definite functional properties goes forward slowly. One of the reason of such situation is the necessity to take into account the dynamic processes running in nanoelements [1].

An example, when the static characteristics are a consequence of dynamic behaviour nanoelements, is a bistable state of resonant tunneling diodes (RTD). This state shows that in the field of negative differential resistance (NDR) at the same bias voltage through the diode the current can have one value, or another [2]. And, as the function from a bias voltage, this phenomenon carries the brightly expressed hysteresis character. Except for hysteresis section there is also horizontal section in area NDR, which can be bent upwards or fall downwards. Usually this section is called "plateau" and connects to a generation of oscillations. Carried out by a number of the authors the numerical modeling of the behaviour of resonant-tunneling structure has shown a presence of current oscillations inside structure [2]. And the frequency of oscillations had very high values ($\sim$2.4 THz). The internal oscillations are connected with a presence of "plateau". As to hysteresis loops, the question remained open, as the authors of work [2] connected it to redistribution of a charge between the emitter and quantum well only.

It is natural, that the oscillations are connected to presence of an inductive element inside resonant-tunnel structure. Such element is the part of the emitter directly contiguous to the barrier (see Fig. 1). In view of an inductive element the authors of the considered works have given the equivalent circuit of RTD, submitted in Fig. 2(a). However, they could not use it for an explanation of anomalies in I–V characteristic as such circuit can not generate oscillation at all.

In [2] dynamic equations describing oscillation in resonant-tunneling structure are received also. The equations describe occurrence of small fluctuations that correspond to birth at dynamic system of a limiting cycle from the critical point in its some small area determined by some small parameter. The offered dynamic model describes occurrence of "soft" generation and by virtue of small amplitudes of oscillations explains the presence of "plateau" in I–V characteristic of resonant-tunneling structures only qualitatively. We offer the equivalent circuit of RTD, enabling to investigate dynamic processes more widely and to give an interpretation of "plateau" and hysteresis loops from the uniform point of view, namely from the point of view of oscillatory process, which in area "plateau" has the character of a "soft" mode of oscillations, and in area hysteresis loops — "rigid" mode.

The equivalent circuit, considered by us, is submitted in a Fig. 2(b). As a matter of fact it differs by one, but very important detail. A current source $i_0(v)$ is shunted by the capacity C, which reflects a presence of a quantum well containing a charge. The addition of this capacity, even as much as very small, causes the oscillations of high frequency in an internal contour formed by elements L, C and $i_0(v)$, which are shunted by capacity C_0.

For analysis of the limiting cycles the analytical and topological criteria allowing to estimate the number of limit cycles, their characteristics and their uniqueness are developed.

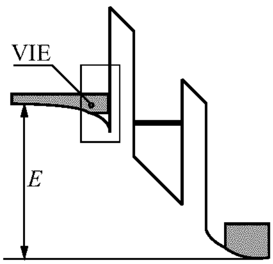

Fig. 1. Schematic band-edge diagram of the RTD under bias with virtual inductive element (VIE) marked by the frame.

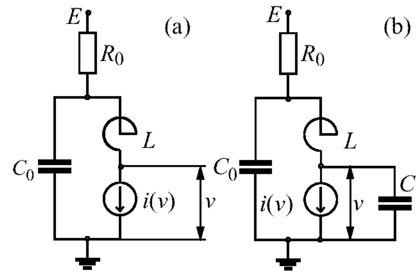

Fig. 2. (a) BJ model [2] of RTD equivalent-circuit; (b) proposed equivalent-circuit.

Here we shall present the simplified criterion of existence of limit cycles for the certain dynamic system, corresponding to the resonant-tunneling structure.

Let oscillatory system is described by the differential equations

$$\frac{\mathrm{d}i}{\mathrm{d}t} = a(E - v), \qquad \frac{\mathrm{d}i}{\mathrm{d}t} = i - i_0(v),$$

where a is constant, $i_0(v)$ is I–V static characteristic of oscillatory system, and E is bias voltage. Let $i_0^*(v) = i_0(2E - v)$. If the curves $i_0(v)$ and $i^*(v)$ are intersected in n points $(v_1, i_l) \dots (v_n, i_n)$ for $v < E$, then the system has n limit cycles, and the voltage amplitude of k limit cycle v_{0k} satisfies to an inequality:

$$E - v_k < v_{0k} < E - v_{k+1}, \qquad 1 \le k \le n, \qquad v_{n+1} = -\infty.$$

If $i_0'(E) > 0$, the odd limit cycles will be unstable, and even — steady.
If $i_0'(E) < 0$, on the contrary.

More accurate formulation of criteria of limiting cycles presence and absence for considered and more complex dynamic systems can be found in [3].

Now on the basis of the presented criterion we shall carry out the analysis of resonant-tunneling structure, with an equivalent circuit submitted in Fig. 2(b). For simplicity we shall consider, that $R_0 = 0$. To give the problem a definite form, let us take the $i(v)$ in form represented in Fig. 3(a). Using criterion and assuming that "time-averaged" current of stable limit cycle equal $(I_p + I_v)/2$, we receive "time-averaged" I–V characteristic represented in Fig. 3(b).

We have I–V characteristic, which is obtained at external measurement. So the experimentally measured static I–V characteristic, exhibiting a plateaulike behavior and double hysteresis, have the dynamic nature:"soft" and "rigid" generation. Let's consider more in detail, that occurs at first at increasing of a bias voltage, and then at its decreasing. When the voltage increases, the dynamic system has only one steady critical point. At achievement of a point **a** the steady critical point turns in unstable and system goes to the stable dynamic state (to the stable limit cycle S_1 (see Fig. 4(a)), where there are the oscillation (so-called "soft" generation). Externally it corresponds to the transition from a point **a** in a point **b** (see Fig. 3(b)). At the further increase of a voltage the mode of "soft" generation is kept, until the point **g** will not be achieved. The further increase of a voltage results in birth from the critical point **O** unstable limit cycle S_2 and transition the system from "soft" mode of generation to "rigid" (see Fig. 4(b). The "rigid" mode is characterized by presence of two steady condition: one static state is represented by a steady critical point **O**, and second — dynamic, represented by steady oscillation (steady limit cycle S_1). As at increase of a bias

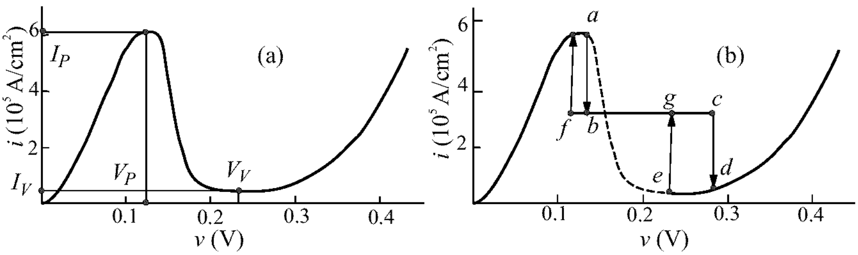

Fig. 3. (a) $i_0(v)$–I–V characteristic used for analyzing of RTD dynamical properties; (b) "time averaged" I–V characteristics of RTD, exhibiting plateaulike behavior and double hysteresis.

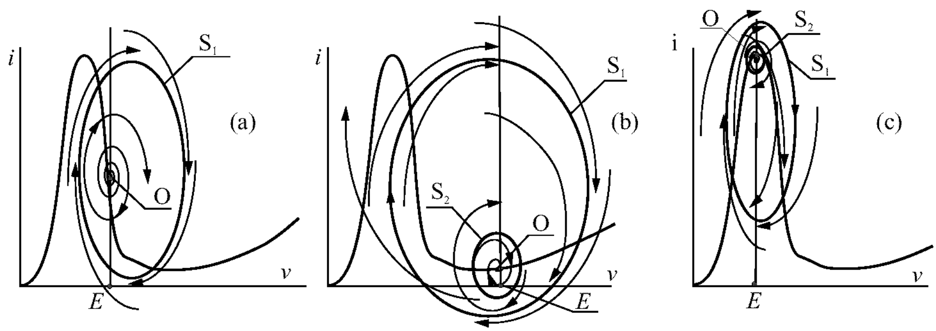

Fig. 4. Phase portraits of dynamical system shown in fig.2(b) for the cases: (a) "plateau"; (b) large "hysteresis" loop; c) small "hysteresis" loop.

voltage the system was in an oscillatory mode, it will continue to keep this state though the system can be transferred in a steady static state. The system will be in "rigid" mode of excitation of oscillations, while the point **c** will not be achieved. At this moment in phase space of system a steady limiting cycle S_1 is merged with unstable S_2 and the system will have only one steady critical point **O**. The system passes in a steady static state, which is represented by transition from a point **c** in **d** (Fig. 3(b)). Now at decrease of a bias voltage the system will be in a steady static state **O**, though it has also steady dynamic state **S** (Fig. 4(b)). It will proceed, while bias voltage will not be lowered up to the point **e**. Here the unstable limit cycle S_2 merges with the critical point **O**, which turns to the unstable critical point. The system passes in a "soft" mode of generation, which proceeds while the point **e** will not be achieved yet. At the further decrease of bias voltage the system will go on a section **bf**, that corresponds to a presence of the system in an excitation state, though it has also the steady static state **O**. Excitation is represented by the steady limit cycle S_1 (Fig. 4(c)). At last, at achievement of a point **f** the system passes in a unique static steady state **O**.

This work was supported in part by the Russian–Ukraine programme "Nanophysics and Nanoelectronics".

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