Electronic Nanosensors Based On Nanotransistor With Bistability Behaviour

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ELECTRONIC NANOSENSORS BASED ON NANOTRANSISTOR WITH BISTABILITY BEHAVIOUR

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Abstract. The creation of a nanosensor aimed at its multiple usage is one of the most important problems in nanotechnologies. In the present work, we demonstrate a possibility of its creation on the basis of a nanotransistor with bistable characteristics. Such a transistor can be a nanostructure including a quantum dot. The reason for the appearance of bistability can consist in the correlation phenomena between current carriers or in their interaction with atoms of the quantum dot.

Keywords: nanodevice, nanosensor, bistability, quantum dot

26.1 Introduction

The problem of the usage of electronic nanounits as sensors for the control over the running of various physical processes in small spatial volumes under a variation of their characteristic parameters on the level of noise is one of the central problems of nanotechnologies. From the basic viewpoint, an electronic nanounit intended for the sensor purposes must consist of two components: the sensor part proper which reads out the information from an object under study and the electronic part for its processing. As for the first component, the situation is sufficiently clear. Indeed, according to the quantum-mechanical description, any change in a state of the molecular aggregate causes necessarily a change of the electrical conduction of the system. Thus, by recording

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a change in the electrical conduction of the testing part of the device, we can get the information about a state of the system under study. The main problem arises if we try to process such information. Here, two basically different approaches are possible. The first approach is related to the output of the information received from the sensor part through nanowires to microelectronic units, where it is processed. The second approach is based on the processing of information directly near the sensor part with the subsequent transfer of the processed information to a registering unit. It is easy to see that, in this case, it is necessary to possess a logical nanounit. A drawback of the first approach is the obligatory presence of nanowires that can and will introduce uncontrolled disturbances into output signals. Ways to solve this problem depend on a specific architecture of a nanodevice, and their general consideration meets difficulties. The usage of the second approach is restricted by the absence of a suitable reliable logical nanounit aimed at the processing of information. As such units, we can take those including quantum dots or quantum wells. But, in this case, it is very important that they will be able to operate in a nonlinear mode. In particular, this mode can be related to the appearance of a bistability in the system due to, for example, the correlation effects between current carriers in a quantum dot [1]. As is shown experimentally, such units can perform logical functions [2]. The second, very important property of nanosensors should consist in the possibility of their multiple use. This property can be decisive for practice. Indeed, the introduction of a nanosensor into an object under study can be, in a number of cases, a complicated task that can become unsolvable if the procedure of introduction must be repeated many times. Within the second approach with the use of nanochips for the direct diagnostics of a state of the sensor part of the device (a probe), such a task seems to be simple.

26.2 Intrinsic bistability of the resonance tunneling

Resonant electron tunneling of particles through a system of double potential barriers is very sensitive to a position of electronic states in a quantum well. This circumstance can be used for effective governing of the tunneling process. For example, it is possible to change potential field in the well by accumulation of electric charge in it under tunneling. This process supposes the existence of a large number of electronic states in the interbarrier space. Actually such a condition requires that the system has a macroscopic size for which a concept of electric capacitance can be introduced. In the case of a small-area quantum well one should consider electron-electron interaction using the quantum mechanical description with an account of its influence on the tunneling. For a limited number of electrons this problem has been considered in Ref. [2]. However, the influence of Coulomb interaction can be increased when the states in the quantum well are degenerated. We consider this problem for the case of N-fold degenerate electronic state when the accumulation up to N electrons in the well is possible. Taking into account the interaction between them one can derive a number of properties, typical of nonlinear tunneling. For instance, that can be an appearance of steplike form of current-voltage characteristics, tunneling bistability and others. We confine ourselves by the consideration of one-dimensional case of tunneling. Studying of fluctuations in these systems shows that they can be virtually suppressed [5]. The latter is typical of double-level systems.

26.2.1 HAMILTONIAN OF THE SYSTEM

As a model of double-barrier tunneling system we take a structure with the energy profile shown in Fig. 26.1. Hamiltonian describing tunneling of electrons through such a structure, can be chosen in the form

$$H = H_0 + H_W + H_T \tag{26.1}$$

The first term of this Hamiltonian is

$$H_0 = \sum_{k\sigma} \varepsilon_L(k) a_{k\sigma}^+ a_{k\sigma}^+ \sum_{k\sigma} \varepsilon_R(k) a_{p\sigma}^+ a_{p\sigma}$$

One describes electrons in the left electrode (source) and in the right electrode (drain). Here $a_{k\sigma}^+(a_{k\sigma})$ and $a_{p\sigma}^+(a_{p\sigma})$ are the creation (annihilation) operators for the electrons in the source and the drain, respectively. $\varepsilon_L(k) = \varepsilon_L + \hbar^2 k^2/2m_L$ is the energy of electrons in the source. $\hbar k$ and m_L are their quasimomentum and effective mass, respectively, σ is the electron spin. For the drain with an account of external potential V, applied across the system we have $\varepsilon_R(k) = \varepsilon_R + \hbar^2 k^2/2m_R - V$, $\hbar p$ being the momentum and m_R the effective mass.

Hamiltonian H_W describes electronic states in the quantum well. We consider the case when there is a N-fold degenerate state in the quantum well. Then H_W can be written in the form

$$H_W = \sum_{\alpha} E_0 a_{\alpha}^+ a_{\alpha} + \frac{1}{2} \sum_{\alpha_1 \neq \alpha_2} V_{\alpha_1\alpha_2} a_{\alpha_1}^+ a_{\alpha_2}^+ a_{\alpha_1} a_{\alpha_2}$$

where $\alpha = (l,\ \sigma)$, σ is the spin number, l is a number of the quantum state, which takes values from 1 to N. An energy of the degenerate state in the well with account of the applied bias is written as follows $E_0 = \varepsilon_0 - \gamma V$, where ε_0 is the energy of the resonant state in the quantum well, and γ is the factor depending on a profile of potential barriers (for identical barriers $\gamma = 0.5$), and $V_{\alpha_1\alpha_2}$ is a matrix element of the electron-electron interaction in the interbarrier space (quantum well). For simplicity, we approximate it a positive constant $V_{\alpha_1\alpha_2} = U$ corresponding to repulsion.

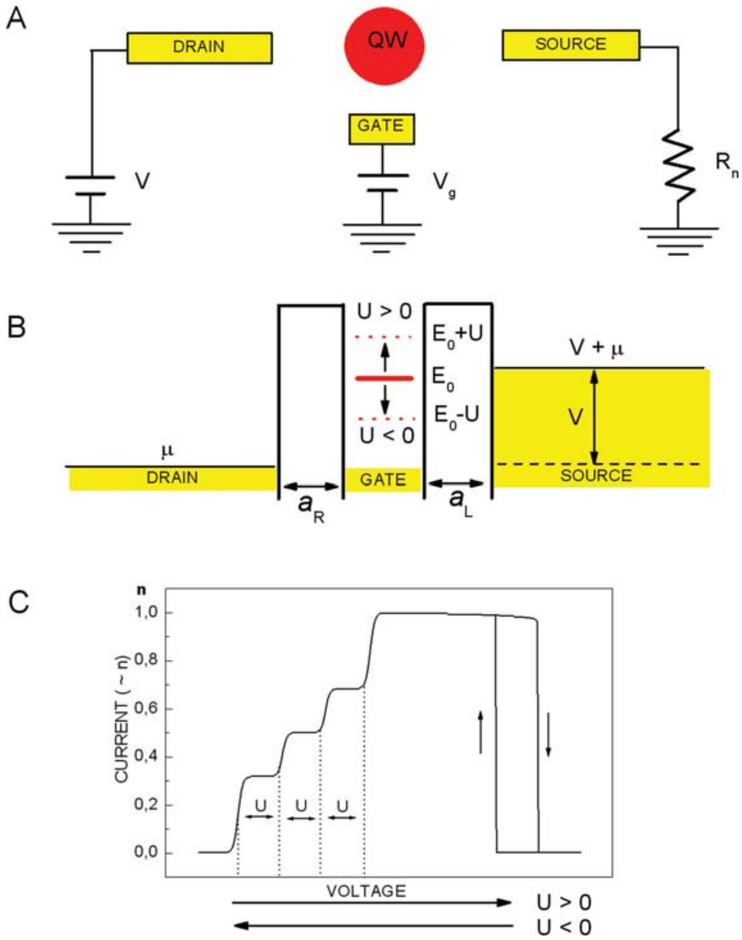

Fig. 26.1. The example of nanotransistor has nonlinear volt-ampere characteristic. (A) Schematic drawing of a nanotransistor. (B) The energy level diagram of the nanodevice showing resonant tunnelling phenomena through degenerated energy states with electron correlation U. (C) Theoretical prediction of current-voltage (I-V) curves. I-V characteristics depend on the sign of U. Applied voltage for positive (negative) U affects the right (left) direction of the shift in I-V curves in (C).

Hamiltonian H_T describing the tunneling of electrons through the barriers has the conventional form:

$$H_T = \sum_{k\alpha} T_{k\alpha} a^+_{k\sigma} a_\alpha + \sum_{p\alpha} T_{p\alpha} a^+_{p\sigma} a_\alpha + e.c.$$

where $T_{k\alpha}$ and $T_{p\alpha}$ are matrix elements of tunneling through the emitter and the collector, respectively. In general case, they depend on the applied bias.

26.2.2 OCCUPATION NUMBERS FOR QUANTUM STATES IN THE WELL

When we apply constant external bias across the system, nonequilibrium steady-state electron distribution sets in. We assume that the electron distribution functions in electrodes (source, drain) are equilibrium by virtue of their large volumes, but their chemical potentials change. They are connected by the relation $\mu_L - \mu_R = V$ (where μ_L and μ_R are the chemical potentials of the source and the drain, respectively). The electron distribution function $g(E)$ in the quantum well is essentially nonequilibrium. It can be determined from the condition of equality of the tunneling current through the source and the drain. Then distribution function has the form:

$$g(E) = \frac{1}{\Gamma(E)}[\Gamma_L(E)f_L(E) + \Gamma_R(E)f_R(E)], \quad \Gamma(E) = \Gamma_L(E) + \Gamma_R(E)$$

Γ_L and $\Gamma_R$are rates of electron transmission source-QW and QW-drain, respectively. f_L and f_R are electron distribution functions in the source and the drain, respectively. They have Dirac's forms. The occupancy of the QW states ($n_\alpha = \langle a_\alpha^+ a_\alpha \rangle$) in the quantum well can be determined using the following expression

$$n_\alpha = -\frac{1}{\pi}\int dE\, g(E)\; ImG(\alpha, E) \tag{26.2}$$

Where $G(\alpha,E)$ is the Fourier transform from the retarded Green's function. Using the Hamiltonian H_W the Green's function can be calculated exactly. For example, for the state of number N one can obtain

$$G(\alpha) = \frac{1}{(E' - E)}\left\{1 + \sum_{m=1}^{2N-1} \sum_{\substack{\alpha_1, ..., \alpha_m \neq \alpha \\ \alpha_1 \neq \alpha_2 \neq ...\alpha_m}} \prod_{m_1=1}^{m} n_{\alpha_{m_1}} \frac{U}{(E' - E - m_1 U)}\right\} \tag{26.3}$$

with $E' = E + i\eta$ for $\eta \to +0$. Green's function has poles at $E_m = E_0 + mU$, where $m = 0, 1, 2, ..., 2N - 1$. Thus, the electron-electron interaction leads to splitting of states in the quantum well. New states are separated by the gap U. Using a cyclic indices permutation in the formula (26.3) we can obtain Green's functions $G(\alpha, E)$ for all the states of the quantum well.

As it follows from (26.3), the expression for n_α does not depend on the index α. Therefore, mean values of occupation numbers are also independent on the number of the quantum state, and we can assume that $n_\alpha = n$. Thus, finally, we get for n

$$n = F(n) \tag{26.4}$$

Where

$$F(n) = \sum_{m=0}^{2N-1} C_{2N-1}^{m} g_m (1-n)^{2N-1-m} n^m, \qquad C_{2N-1}^{m} = \frac{(2N-1)!}{m!(2N-1-m)!}$$

g_m is $g_m = g(E_m)$. Thus we have obtained the algorithmic equation of power 2N − 1 for occupation numbers n. In general case, this equation can have several solutions in the interval $0 \leqslant n \leqslant 1$. In the case when all $g_m = g$ it follows from (11) that $n = g$, i.e. occupation of electronic states will be defined only by the distribution function $g(E)$.

26.2.3 THE EXAMPLE: DOUBLE DEGENERATE STATE

An analysis of Eq. (26.4) shows that for N = 2 in the interval $0 \leqslant n \leqslant 1$ it has three solutions under condition $g_0 = g_1 = 0$. These solutions are as follows:

$$n_1 = 0,$$

$$n_{2,3} = -\frac{2}{3}\frac{g_2}{g_3 - 3g_2} \pm \sqrt{\frac{9g_2^2 + 4(g_3 - 3g_2)}{4(g_3 - 3g_2)^2}} \qquad (26.5)$$

Accordingly to the condition $0 \leqslant n \leqslant 1$, expression (26.5) leads to

$$0 < \frac{3g_2}{3g_2 - g_3} < 2$$

$$9g_2^2 - 4(3g_2 - g_3) > 0 \qquad (26.6)$$

Inequalities (26.6) are compatible when

$$g_2 \geqslant \frac{2}{3}(1 + \sqrt{1 - g_3}), \qquad g_3 > \frac{3}{4}$$

Therefore, Eq. (26.4) has three solutions when the values of g_2 and g_3 are close to unity. The two solutions n_1 and n_3 are stable, while the third one, n_2 is unstable. The stable states correspond to the cases, when there are no electrons in the well or there are four electrons occupying levels. The latter is possible since the system is essentially nonequilibrium.

26.3 Bistability-based nanotransistor

Consider an example demonstrating the possibility to use the process of resonance tunneling through degenerate states in a logical unit processing the information obtained from a sensor nanoprobe. Such a unit is, by its structure, a nanotransistor (Fig. 26.1A), whose component is a quantum dot with degenerate energy spectrum. Both the profile of the potential field along the motion

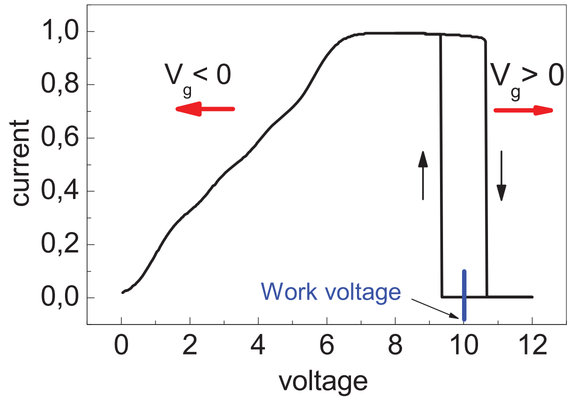

Fig. 26.2. Picture to demonstrate an influence on conductance by the gate voltage.

direction of current carriers and the current-voltage characteristic (CVC) are shown in Figs. 26.1A and 1C.

Depending on the nature of the correlation between current carriers, namely the Coulomb or electron-phonon one, the sections of the hysteresis curve presenting the conduction of a unit have the different directednesses. In the figure, this property is revealed in the behavior of the curve under the increase in the applied voltage. The step-like form of CVC corresponds to the process of elimination of the degeneracy of energy states at the quantum dot due to the correlation. The value of U determines the energy of interaction between two current carriers. Varying the voltage on a gate, one can control the conduction of the system. If the voltage on a gate depends on the potential of the probe, the conduction of such a device will be determined by a state of the probe. In Fig. 26.3, we display the peculiarities of using the property of bistability of the conduction of a nanotransistor for the processing of the information obtained from a probe. When the work voltage is fixed, and its value is in the region of bistability (blue line), a change in the voltage on a gate induces a shift of the profile of CVC. The profile shifts to the right (right red arrow) as the voltage on a gate increases and to the left (left red arrow) as it decreases. If a value of the work voltage leaves the region of bistability on such a shift, the conduction of a nanotransistor changes jumpwise. Thus, if the voltage on a probe is used as the voltage on a gate, such a construction allows one to realize the diagnostics of a state of the probe part of a nanosensor device.

26.4 Nanosensor with a bistability-based transistor

In Fig. 26.3, we give the basic diagram of a nanosensor device, in which the above-presented scheme of the processing of information can be realized. The device is a sandwich consisting of dielectric and conducting layers. The work

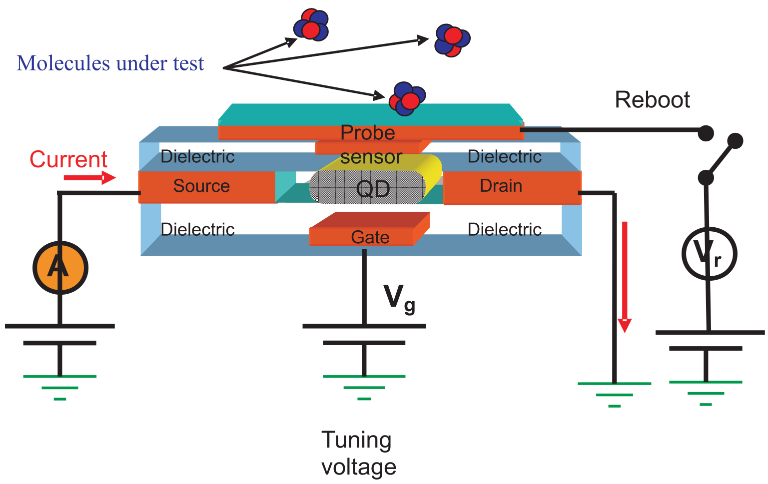

Fig. 26.3. The construction diagram for a electronic nanosensor devices. The function base is a nanotransistor with bistability conduction.

current passes from an emitter to a collector through a quantum dot so that the system is positioned in the conduction bistability region. The voltage supplied in the lower part of the device to the gate V_g allows one to shift a state of the quantum dot to the boundaries of the bistability region. In other words, this voltage is intended for the tuning of the device into the work state. The upper part of the device contains a testing probe that is some small conducting platform joined with an electrode analogous to a gate. On the right part of the device, a system ("reboot") restoring the probe into the working mode is positioned. It allows the necessary voltage to be supplied to the probe in a controlled way. How can such a nanosensor work?

As an example, let us consider its operation in the mode of chemical sensor. In this case, the attachment of tested molecules to the probe can change its potential. The electronic device under consideration does allow one to register such a change. Indeed, while the work voltage is supplied to the quantum dot being in the conduction bistability region, the conduction of the system will depend on the way, in which this voltage is supplied. For definiteness, we choose zero as the initial value of the conduction. In this case, the voltage on a reboot is switched-off, $V_r = 0$. Then, by varying the voltage on a gate V_g, we can shift the current-voltage profile shown in Fig. 26.3 to the right so that the value of work voltage turns out to be near the left boundary of the bistability region. Let now the device be positioned in the gaseous or liquid medium, where some number of tested molecules is present. Then these molecules will touch the probe and, hence, change its potential. In such a way, the potential field around the quantum dot is changed. Therefore, the current-voltage profile will be additionally shifted, which will lead to a jump-like variation of the conduction of the system. There appears the current in the work circuit, and it can be registered with an ammeter. The value of additional shift related to the touching of the probe by a molecule is an individual characteristic of the probe-molecule contact. The voltage on a gate can be selected with regard for this circumstance. Further, even if a molecule leaves the probe, the system remains in the current-conducting state. In other words, the sensor device has remembered the presence of tested molecules in the medium. In order to restore the device in the initial state, it is necessary to switch-on, for some time interval, the recharging voltage V_r, whose value must exceed the width of the bistability region. This will lead to two effects. The current-voltage profile will be shifted to the left by a value exceeding the bistability interval, which transfers the quantum dot into the nonconducting state. In addition, the recharging voltage will repel adhered tested molecules from the probe. That is, there occurs the purification of the probe. After the switching-off of the recharging voltage, the sensor device is in the initial state and is ready again to the testing process.

26.5 Conclusions

Thus, a device consisting of a nanotransistor operating in the bistability interval of voltages and a nanoprobe can successfully fulfill the sensor functions. The above-considered device can be also applied to the testing of pressure variations, acoustic oscillations, etc. To this end, it is sufficient to coat a probe by a substance possessing the piezoelectric properties. However, as a significant obstacle on the way to the fabrication of a similar device, we mention the absence of a suitable nanotransistor with the necessary properties. Eligible can be a transistor using either molecules of rotaxane as a quantum dot or short carbon nanotubes [3, 4]. But, in all the cases, it is basically important to understand the mechanism of the appearance of the property of bistability in nanotransisters [5–8].

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