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LOW-DIMENSIONAL SYSTEMS

# The Sharply Nonlinear Current–Voltage Characteristic of a Structure with a Quantum Well Built in the Depletion Region of a Schottky Barrier

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**Abstract**—The heterostructure in which a quantum well is formed in the depletion region of the Schottky barrier is considered. The forward current–voltage characteristic of this structure is calculated and analyzed. It is shown that an N-shaped sharply nonlinear current–voltage characteristic is observed in a wide range of typical values of parameters of the structure under consideration. The characteristic has a clearly pronounced region with a negative differential resistance and a high peak-to-valley ratio.

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Beginning with groundbreaking study [1], semiconductor resonant tunneling structures (RTSs) have been studied over three decades and devices based on these structures have been increasingly widely introduced into practice. At the same time, the characteristics of these devices—in particular, of particularly promising fast (gigahertz and terahertz frequency range) devices—have failed to exhibit a performance that would allow their commercial mass production, despite the impressive results of the solid-state technology. This is one of the main reasons why the number of publications concerned with RTSs remains considerable.

A heterostructure constituted by two potential barriers and a quantum well (QW) between them most frequently serves as an RTS. In the absence of an external voltage, the potential profile of such a standard RTS is symmetric with respect to the vertical plane passing through the middle of the well. Apparently, there exist variations in the mechanism with the use of a standard RTS and somewhat different ways to obtain sharply nonlinear current–voltage ($I$–$V$) characteristics of the resonant tunneling current. For example, an opportunity to observe $I$–$V$ characteristics of this kind in a system in which a standard RTS is placed in a built-in electric field (specifically, in the space charge region of a Schottky barrier; see Fig. 1b) was suggested in [2, 3]. It is clear that the $I$–$V$ characteristics obtained in this system have certain specific features, which were analyzed in [2, 3]. In this communication, we call attention to the fact that systems with sharply nonlinear $I$–$V$ characteristics have, as a variation, a structure in which a QW is formed as done in [2, 3] in the built-in field of a Schottky barrier, but in a somewhat different way (cf. Figs. 1a, 1b).

Since the shape of the potential barrier is not too important, we assume for the sake of simplicity that the potential in the depletion region linearly depends on the coordinate. The potential profile of the corresponding structure is schematically shown in Fig. 1a.

As the resonant level of the QW moves down to below the conduction band bottom of the semiconductor, a portion with a negative differential resistance (NDR) appears in the $I$–$V$ characteristic; this is possible upon application of a forward bias.

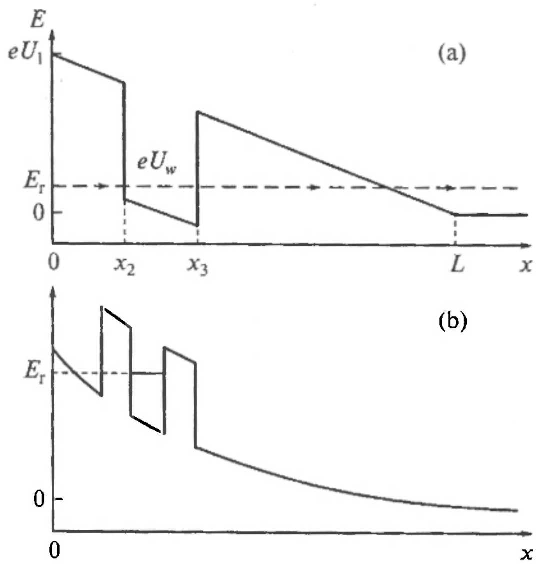


**Fig. 1.** (a) Potential profile of the structure under consideration and (b) that of an RTS examined in [2, 3].

The current density in structures of the type we consider is commonly calculated by the formula

$$j = j_0 \int \frac{dE}{k_B T} D(E) \ln \frac{1 + \exp(E_F - E/k_B T)}{1 + \exp[(E_F + eV - E)/k_B T]}, \quad j_0 = \frac{em(k_B T)^2}{2\pi^2 \hbar^2}, \tag{1}$$

where $V$ is the external potential, $D(E)$ is the tunnel transparency coefficient dependent on the electron energy $E$, and the remaining designations are conventional.

The above calculations disregard such factors as nonparabolicity of the dispersion law, roughness of surfaces, etc., which cannot significantly affect the effect under consideration: observation of steeply nonlinear $I$–$V$ characteristics.

The key parameter affecting the shape of $I$–$V$ characteristics is the transparency coefficient $D$ for electrons passing through the given system. We find it using the method of transfer matrices, according to which

$$D = \frac{m_5 k_5}{m_1 k_1} |T_{11}|^{-2}, \tag{2}$$

where $m_{1,5}$ are effective electron masses in regions 1 and 5, respectively; $k_1$ and $k_5$ are quasi-momenta with $k_{1,5} = \sqrt{\frac{2m_{1,5}E}{\hbar^2}}$; and $T_{11}$ is an element of a transfer matrix $T$ matching solutions to the Schrödinger equation between regions 1 and 5. In the effective mass method in the 1D case, the Schrödinger equation has, for each of the five regions (Fig. 1), the form

$$-\frac{\hbar^2}{2m_n} \frac{\partial^2 \Psi_n(x)}{\partial x^2} + eU_n \Psi_n(x) = E_n \Psi_n(x), \tag{3}$$

where $n = 1, 2, 3, 4, 5$.

Assuming that the external voltage mostly drops on the depletion region, we write for the potential $U_n$

$$U_{1,5} = 0, \quad x < 0, \quad x > L;$$

$$U_{2,4} = U_1\left(1 - \frac{x}{L}\right), \quad 0 \le x \le x_2, \quad x_3 \le x \le L, \tag{4}$$

$$U_3 = U_1\left(1 - \frac{x}{L}\right) - U_w, \quad x_2 \le x \le x_3,$$

where $eU_w$ is the well depth [the quantities $U_1 = U_0 \pm V$ and $L$ correspond to the height and width of the Schottky barrier (see Fig. 1)]. The coordinate is reckoned from the metal–semiconductor interface along the OX axis, and the energy, from the conduction band bottom of the semiconductor.

We represent the solution to Eq. (3) as

$$\Psi_n(x) = a_n \psi_n(x) + b_n \varphi_n(x), \tag{5}$$

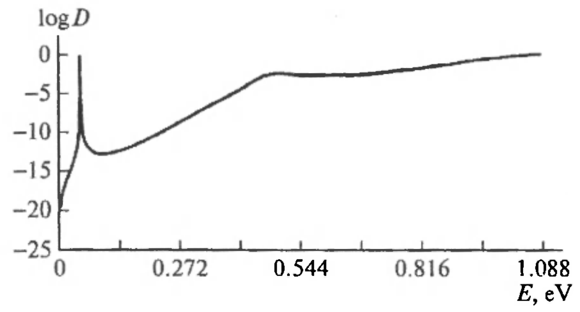


**Fig. 2.** Dependence of the transparency coefficient on the electron energy.

where $n = 1, 2, 3, 4, 5$. In regions 1 and 5, the eigenfunctions are expressed in terms of plane waves, and in the intermediate regions, in terms of Airy functions. The coefficients $a_n$ and $b_n$ can be found by using the standard procedure in which the eigenfunctions and their derivatives are matched (with the difference between the effective masses taken into account; see [4]) at the points corresponding to the heterointerface coordinates. Then, $a_n$ and $b_n$ with different indices are interrelated by the transfer matrix $\hat{M}_s$, where $s = 1$ separates regions 1 and 2; $s = 2$, regions 2 and 3; etc. We have, in particular,

$$\begin{pmatrix} a_1 \\ b_1 \end{pmatrix} = \hat{M}_1 \hat{M}_2 \hat{M}_3 \hat{M}_4 \begin{pmatrix} a_5 \\ b_5 \end{pmatrix} \equiv \hat{T} \begin{pmatrix} a_5 \\ b_5 \end{pmatrix}. \tag{6}$$

The elements of the matrices $\hat{M}_s$ are found in a common way, and the element $T_{11}$ of the matrix $\hat{T}$, which is necessary for calculating the transparency coefficient $D$, is calculated numerically.

Let us briefly analyze the results obtained when calculating the coefficient $D$. Figure 2 shows the dependence of $\log D$ on the electron energy $E$ for the following values of the parameters of the problem:

$$eU_1 = 0.85 \text{ eV}, \quad eU_w = 0.7 \text{ eV}, \quad x_2 = 32 \text{ Å},$$
$$x_3 = 70 \text{ Å}, \quad L = 150 \text{ Å}.$$

The two lowest-in-energy maxima of this dependence correspond to the resonant states of the QW (the further oscillating run of the $\log D(E)$ curve is known to be due to the above-barrier reflection of the electron wave). It can be seen that, at the taken typical and practically acceptable parameters, $D$ reaches large values quite sufficient for providing an effective channel for the resonant tunneling current. For example, for the ground state, with which the appearance of a portion with negative differential resistance in the $I$–$V$ characteristic is commonly associated, $D$ is nearly unity at the chosen parameters.

Figure 3 shows a nearly linear dependence of the resonance energy $E_r$ on $U_1$ (the rest of the parameters

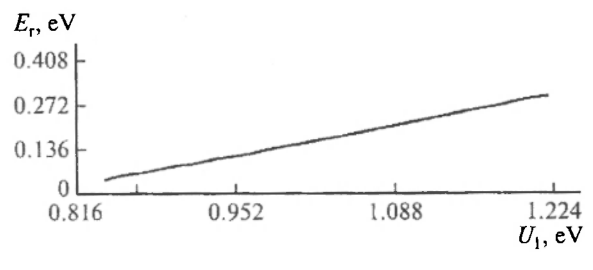


**Fig. 3.** Dependence of the resonance energy $E_r$ on $U_1$.

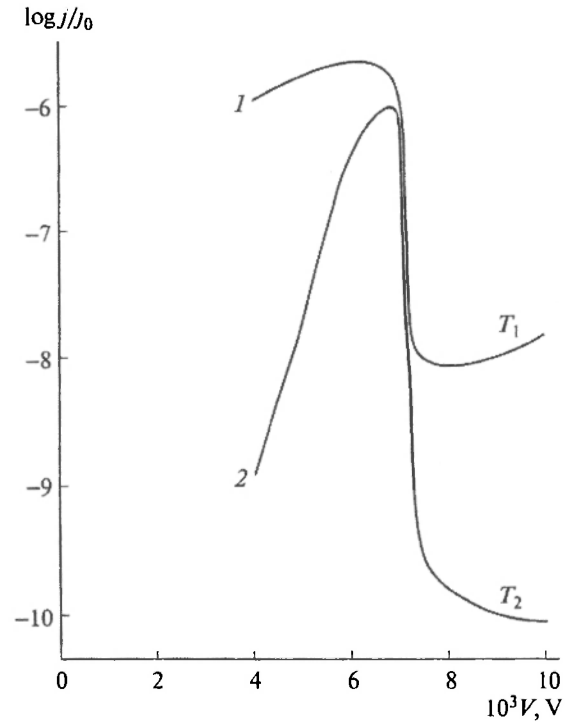


**Fig. 4.** Fragment of the $I$–$V$ characteristic of the structure under consideration.

have the same values as above). The following fact is also noteworthy. As calculations show, the parameters of the structure under consideration can be easily chosen in such a way that the transparency coefficient attains the maximum value immediately before the resonant level moves to below the conduction band bottom of the semiconductor ($E_r \longrightarrow 0$). This provides the largest peak current before the dropping portion in the NDR region of the $I$–$V$ characteristic.

As for the important parameter affecting the resonant tunneling current, i.e., the half-width $\Gamma$ of the resonant level, it is $\Gamma \approx 5 \times 10^{-4}$ eV at the chosen values of the parameters. This value of $\Gamma$ appears to depend on many parameters of the problem, but, as calculations show, this dependence is weak (naturally, within the practically acceptable variation ranges of the parameters of the problem).

Figure 4 shows how the current density depends on the external voltage for the above values of the parameters for two temperatures: room temperature (curve *1*) and liquid-nitrogen temperature (curve *2*). In the calculation, we took into account, in addition to the resonant tunneling current, the direct tunneling current and its above-barrier component. It can be seen that the structure under consideration does have an N-shaped sharply nonlinear $I$–$V$ characteristic with a clearly pronounced portion of a negative differential resistance. One of the main parameters of a $I$–$V$ characteristic with an NDR, its peak-to-valley current ratio, attains large values exceeding $10^3$. Our calculations show that this is true for a wide range of parameters of the problem; in particular, large peak-to-valley ratios may occur at not only low, but also high, temperatures (Fig. 4). It is noteworthy that the cutoff voltage is controlled by different parameters of the structure, such as $U_w$, $x_2$, etc. It is known that such large values of the peak-to-valley ratio are also obtained in calculations of $I$–$V$ characteristics for a number of other RTSs (in particular, these values are on the same order of magnitude for the structure considered in [2, 3], and an order of magnitude larger, as calculated in [5]). However, the ratios obtained in practice are more than two orders of magnitude smaller, the cause of such an important discrepancy still not being quite clear. The answer to the question as to which kind of structure gives the best peak-to-valley ratio can be, in the end, given only by an experiment.

That the structure considered here provides the best current stability should be considered an advantage: the known problem of charge storage in accumulating layers of standard RTSs is alleviated because of the small number of these layers. It is also worth noting that the given structure has a smaller number of heterointerfaces the imperfection of which commonly adversely affects the characteristics of the resonant tunneling current.

Let us, finally, consider the following circumstance. It is advantageous to fabricate RTSs in the first place from such semiconductors as silicon and germanium, the technology of which is very well developed. It is known, however, that attempts to use these semiconductors encounter certain difficulties. The structure considered in this study is more promising in this regard compared with the standard RTS. For example, let us assume that the resonant level is formed by deep impurity states, rather than by the QW (states of this kind can be, e.g., created by impurity sheets introducing deep levels [6]). In this case the specific configuration of the potential barrier in the structure under consideration strongly facilitates the choice of the optimal parameters of Si- and Ge-based RTSs, compared with the standard structure. This primarily refers to selecting a suitable energy $E_r$ of the resonant level, which can be rather flexibly controlled by taking a required impurity and also by varying the electric field strength in the depletion region and the spatial localization of the impurity ($U_0$, $L$, and the distance between the impurity and the metal–semiconductor interface). Of practical importance in this regard is the fact that the required depth of the impurity level is substantially smaller than this depth in the case of the standard RTS (and, accordingly, lower voltages are necessary for reaching the NDR portion of the $I$–$V$ characteristic).

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