The Effect of Both Abrupt and Strong Enhancement of Current in the Semiconductor System: Schottky Barrier Containing a Double Barrier Resonant-Tunneling Structure

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The current–voltage characteristics for the double barrier resonant-tunneling structure incorporated into the depletion region of a Schottky barrier, are evaluated and analyzed. It is demonstrated that the Schottky barrier can block or unblock (depending on the parameters of the problem involved) the resonant-tunneling current effectively. Hence both a very sharp and strong enhancement of current through the structure considered takes place for forward bias.

1. Introduction

Various semiconductor structures are investigated widely now giving interesting results. One of these results refers to the current–voltage characteristics (IVC) which occur to reveal unordinary features. Here, we evaluate and analyze the IVC for a resonant-tunneling structure (RTS) incorporated into a depletion region of a Schottky barrier (SB). One can find a proposition in literature to locate the RTS in the SB and it is not very demanding to the technological processes. North et al. [1] have studied effects associated with the electron reflection at the semiconductor–metal interface of the Schottky collector. Resonant-tunneling spectroscopy of quantum dots has been performed in [2, 3]. Structures consisting of the double barrier RTS (DBRTS) located in the SB (named Schottky collector resonant-tunneling diode) have been considered in [4–6]. It has been demonstrated in these references that one can improve the frequency characteristics of the resonant-tunneling diode (RTD) using a Schottky collector in place of the normal Ohmic contact. Note that a region of negative differential resistance (NDR) was formed due to dropping the resonant level below the edge of the conduction band in [1, 4–6] (as in the standard RTD). The authors of [1–6] were not interested in the fact that the SB (namely the top of the SB, not the edge of the conduction band) can serve as an instrument for creation of steep nonlinearities in the IVC. In this paper, we show that the SB can play a principal role in the performance of the structure considered (RTS incorporated into the SB), i.e. that the SB can be used as blocking or unblocking barrier for the resonant-tunneling current (RTC). Due to SB, it is possible to control the RTC effectively enough, hence sharp nonlinear regions in the current–voltage characteristics with both negative and positive differential resistance can be observed.

Consider the contact of a metal with a n-type semiconductor containing the resonant-tunneling structure (RTS) built in the depletion region (resonant-tunneling Schottky barrier – RTSB, Fig. 1). The shape of the IVC depends essentially on the position of

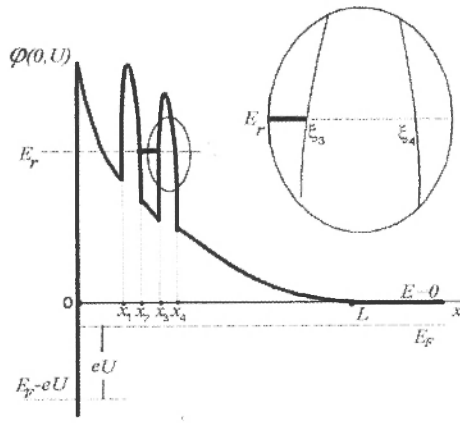[1]) Corresponding author; e-mail: korolam@usuft.kiev.ua

$\varphi(0,U)$

E_r

O $\quad x_1\ x_2\ x_3\ x_4 \qquad\qquad L \qquad\qquad x$

$E-0$

E_F

eU

$E_F - eU$

Fig. 1. The potential shape of the structure considered

the resonant level $E_r(U)$ relative to the top of the SB $\varphi(0,U) = \varphi(x.U)|_{x=0}$ in the starting conditions, i.e. when the applied voltage (U) is equal to zero. There can be two different cases in this initial moment: 1. The inequality $E_r(0) - \varphi(0,0) < 0$ takes place. RT current is blocked by the SB when a small bias is applied. But the growth of the voltage is accompanied by a decrease of the difference between $E_r(U)$ and $\varphi(0,U)$ so that it becomes equal to zero at a certain value $U = U_r$. RTC is unblocked then resulting in an abrupt enlargement of the current through the structure considered. Consequently, this is reflected in the IVC determining its steep nonlinearity in a region of positive differential resistance. 2. In the opposite case — $E_r(0) > \varphi(0,0)$ — the RT channel is unblocked initially, and the forward bias does not change the IVC qualitatively. It is different in the case of back bias where the value $E_r(U) - \varphi(0,U)$ can become equal to zero at a certain value of U. The blocking process of the RTC takes place in this case leading to a region of negative differential resistance in IVC. The problem is to estimate the effectiveness of the blocking role of the SB: is it effective enough to yield both sharp and significant changes in IVC? To answer this question, we have evaluated the IVC for the system considered taking the double barrier RTS (DBRTS) as the resonant-tunneling structure.

One must note that there are certain essential differences between the performance of the RTSB and the standard RTD (where RTS is located between two n-doped semiconductors). One of these differences is that the collector of RTSB — the metal for $U > 0$ and the semiconductor in the opposite case — accepts only a part of electrons flowing from the emitter, namely a part that flows over the SB. These electrons have greater energies than those responsible for the arising of nonlinearity in the standard RTD, whose energy lies within the interval $[0, E_F]$, E_F being the Fermi level of the semiconductor.

We would like to note also that the effect described in this report — the sharp nonlinearity obtained for the forward-biased RTSB due to the blocking abilities of the SB—can be observed in the case where the RTC exceeds the current of direct tunneling as well as the overbarrier current. Results presented further refer to values of parameters well satisfying this condition.

2. Evaluation and Results

The current density is evaluated by the known formula

$$j = j_0 \int_0^\infty \frac{\mathrm{d}E}{k_B T}\, D(E) \ln \frac{1 + \exp\left[(E_F - E/k_B T)\right]}{1 + \exp\left[(E_F + eU - E)/k_B T\right]}, \tag{1}$$

$$j_0 = e m_s (k_B T)^2 / 2\pi^2 \hbar^3, \tag{1a}$$

where k_B is the Boltzmann constant, T the temperature, $D(E)$ the transmission coefficient depending on the electron energy E, m_S effective mass of an electron in the bulk of the semiconductor. In the evaluations below, we do not take into account the factors which cannot influence qualitatively the effects described, such as the nonparabolicity of the dispersion law, the charge accumulation, etc. The quantity $D(E)$ is expressed via the rates of transparency for the depletion region $D_S(E)$ and for the DBRTS $D_r(E)$. Suppose further that it is equal to the product of $D_S(E)$ and $D_r(E)$. This approximation implies that the tunneling through the DBRTS and the Schottky barrier is incoherent [7]. The probability of incoherent tunneling to take place is high enough due to scattering processes caused by doping impurities of high concentration (note also that we consider the case of room temperatures here).

Since this problem deals with a lot of the parameters involved (they are presented further) the pure numerical calculations of the current are not convenient enough to carry out the analysis. (Add also that the observation of nonlinearities demands a very accurate choice of the values of these parameters.) Therefore, we have evaluated the analytical expressions for the current using the modified WKB method for the determination of $D_r(E)$ (see Appendix). This modified WKB method is non limited to the case of small values of $D_r(E)$ only (as for a standard WKB method); also, it allows for explicit account of the difference between the effective masses in different regions of the multilayer structures. The expression for $D_r(E)$ is obtained in the Appendix; since it is cumbersome we present in brief here the analysis of $D_r(E)$ from Eq. (A3) for a simplified case: $m_s = m_b = m^*$, m_b is the electron effective mass in the barrier regions of the DBRTS. We have then $\gamma = 1$ and (see also [8, 9])

$$D_r \cong [\cosh^2 (\delta_1 + \delta_3 + \ln 4) \cos^2 (\delta_2) + \cosh^2 (\delta_1 - \delta_3) \sin^2 (\delta_2)]^{-1}, \tag{2}$$

$$\delta_i = \frac{1}{h} \sqrt{2m^*} \int_{\xi_i}^{\xi_{i+1}} \sqrt{|E - \Phi(x)|} \, dx, \tag{3}$$

where ξ_i are nearest to the x_i classical turnpoints, the distances x_i are designated in Fig. 1, $x_{i-1} = x_i + d_i, i = 1, 2, 3$; $\Phi(x)$ is the potential energy of the structure considered. Expression (2) has sharp maxima at the energies $E = E_n$, determined by the following condition:

$$\delta_2(E_n) = (n + 1/2) \pi, \qquad n = 0, 1, 2 \ldots \tag{4}$$

These maxima correspond to the resonant energy levels.

It is convenient to represent the coefficient D_r in the form of two addends $D_r = D_t + D_\nu$, the first of which is the Lorenz-like term

$$D_t - \frac{D_1 D_3}{(D_1 + D_3)^2} \frac{\Gamma_n^2}{(E - E_n)^2 + \frac{1}{4}\Gamma_n^2} \tag{5}$$

and is responsible for the resonant-tunneling current. We see that the quantity Γ_n plays the role of the halfwidth of the resonant level E_n, it is equal to

$$\Gamma_n \approx (D_1 + D_3)/\sigma, \qquad \sigma = \frac{\sqrt{2m^*}}{h} \int_{x_2}^{x_3} \frac{dx}{\sqrt{|E_n - \Phi(x)|}}. \tag{6}$$

D_1, D_3 are the transmission rates of the left and right barriers, respectively

$$D_i \simeq \tfrac{1}{4} \exp(-2\delta_i).$$ (7)

From the above expressions, it is clear that integration in (1) results in a step-like function in the $j(U)$ dependence.

Also, to evaluate the current we have to determine the quantity $\Phi(x)$, consisting of two terms: the potential of the depletion region $\varphi(x, U)$ and the potential energy of the DBRTS. The first one is defined as the solution of the Poisson equation

$$\Delta\varphi = -\frac{e}{\varepsilon\varepsilon_0}\varrho(x),$$ (8)

$$\varrho = \begin{cases} eN, & 0 < x < x_1, \quad x_4 < x < L, \\ 0, & x_1 < x < x_4, \quad x > L, \end{cases}$$

(N is the doping impurity concentration, ε the dielectric permittivity in the bulk of the semiconductor, ε_0 the dielectric permittivity of vacuum), with the usual boundary conditions for the depletion region of width L:

$$\varphi(0, U) = \varphi(0, 0) + eU, \quad \varphi(L, U) = \frac{\partial\varphi(x, U)}{\partial x}\bigg|_{x=L} = 0.$$ (9)

As a result,

$$\varphi(x, U) = \frac{Ne^2}{2\varepsilon\varepsilon_0}(x - L)^2 + \frac{Ne^2}{2\varepsilon\varepsilon_0}\begin{cases} (x_4 - x_1)(2x - x_4 - x_1), & 0 < x < x_1: \\ -(x - x_4)^2, & x_1 < x < x_4; \\ 0 & x_4 < x < L: \end{cases}$$ (10)

$$L^2 = \frac{2\varphi(0, U)\varepsilon\varepsilon_0}{Ne^2} + (x_4^2 - x_1^2).$$

The values $U > 0$ refer to the forward bias. DBRTS is located in the coordinate interval $x_1 < x < x_4$. The field strength in this interval is defined as

$$F = -\frac{Ne}{\varepsilon\varepsilon_0}(L - x_4).$$ (11)

Since the integrand in (1) reveals a distinct δ-like shape it is not difficult to obtain expressions for the current which are very accurate in a wide range of parameters.

The quantity $D_s(E)$ necessary for evaluating the current is determined as transparency of the barrier with the potential energy (10) plus potential energy associated with the image forces $\varphi_{im} = -e^2/16\pi\varepsilon\varepsilon_0 x$. In the interval of energies close to the top of the resulting barrier, where the coordinate dependence has parabolic form, the transparency coefficient is of the following form (see e.g. [10]):

$$D_s(E) \simeq \left\{ 1 + \exp\left[\frac{(\bar{\varphi} - E)}{E_0}\right] \right\}^{-1},$$ (12)

$$\bar\varphi = \varphi(0, U) - \frac{1}{2\beta^2}, \quad \beta = \left[\frac{\pi\varepsilon\varepsilon_0}{F(0)}\right]^{1/4}, \quad E_0 = \frac{2\hbar\varepsilon\varepsilon_0}{\sqrt{2m_s}\,\beta^3 e^2},$$

$$F(0) = -\frac{1}{e}\frac{\partial\varphi(x, U)}{\partial x}\bigg|_{x=0}.$$

Note that $D_s(E)$ (12) is a θ-like function with halfwidth $\gamma = \ln(3 + 2\sqrt{2})\,E_0$.

Consider here the forward branch of the IVC only. In a wide range of values of the parameters involved, we have $\gamma \ll \Gamma$, and this enables us to make an approximate estimation of expression (1). When the condition $eU \gg k_B T$ holds the evaluation of current based on (1) yields the following result:

$$j \simeq j_0 \, \frac{2\Gamma}{k_B T} \, \frac{D_1 D_3}{(D_1 + D_3)^2} \, \exp\left(\frac{E_F - E_n}{k_B T}\right) \left[\pi/2 - \arctan \frac{2(\varphi - E_n)}{\Gamma}\right]. \tag{13}$$

Expression (13) is simple enough, hence it is convenient for analysis of special features of the IVC. Using (13) we chose the optimum values of the parameters which allow for observing the effect of abrupt enhancement of current. The accurate calculation of the IVC was carried out using more complicated expressions which account for the difference between the effective masses in the different regions of the RTSB. The corresponding curves for IVC are plotted in Fig. 2 for the following set of the parameters: temperature $T = 300$ K, effective mass of an electron in the barrier and in the well $m_b = 0.1 m_0$, $m_w = m_s = 0.067 m_0$, respectively, m_0 is the free electron mass, widths of the DBTRS barriers $d_1 = d_3 = 2$ nm, width of the well $d_2 = 4$ nm, concentration of the doping impurity $N = 10^{23}$ m^{-3}, $\varphi(0,0) = 0.5$ eV, $\varepsilon = 10.4$, $E_F = 0.011$ eV.

Three curves refer to values of the distance x_1 from the DBRTS to the metal equal to 14 nm, 18 nm, 27 nm. The dashed line shows the dependence of the quantity dj/dU on the voltage U for the second case of the resonant-tunneling channel (18 nm). We see that the "opening" takes place at a certain value of the voltage $U = U_c$, and it is accompanied by an both abrupt and strong enhancement of the current. This sharp growth of the current is realized within a small voltage interval: the current increases by 10 times (approximately) when the voltage changes by 0.01 eV. The "switching voltage" U_c is controlled by various parameters of the RTSB. For example, this quantity can be increased by the enlarging of: 1) the distance from DBRTS to the metal; 2) the doping concentration; 3) the SB height etc.

The calculations performed prove that the blocking properties of the SB can be effective enough. Yet, we would like to emphasize that there are additional technological procedures for further improving the properties mentioned. For example, one can create a thin p-doped layer between the metal and the semiconductor. Depen-
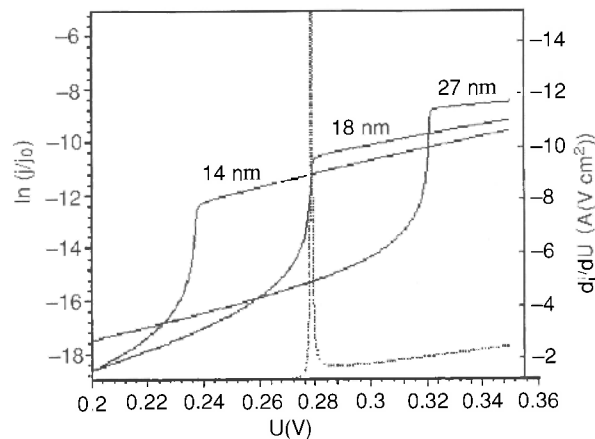

Fig. 2. The quantity $\ln(j/j_0)$ vs. voltage U (solid line). The dashed line refers to the quantity dj/dU dependent on U for a distance from the metal to DBRTS equal to $x_1 = 18$ nm

dent on the doping concentration as well as on the width of this layer it is possible to achieve the optimum profile of the top part of the SB thus improving its blocking abilities.

In conclusion, we show that the Schottky barrier can be used for the effective blocking (unblocking) of the resonant-tunneling current; as a consequence the current–voltage characteristics can reveal sharp nonlinearities. The semiconductor system considered can be used in applications as well as for analytical goals.

Appendix

In accordance with the WKB approximation, the wave function of an electron in the region $x_j \leq x \leq x_{j+1}$ is of the form $\psi_j = A_j F_j$, where

$$A_j = \begin{pmatrix} a_j \\ b_j \end{pmatrix}, \qquad F_j = \begin{pmatrix} \varphi_j^- \\ \varphi_j^+ \end{pmatrix}, \qquad \varphi_j^\pm(x) = \frac{1}{\sqrt{|k_j(x)|}} \exp\left[\pm \int\limits_{\xi_{j-1}}^{x} k_j(x)dx \right],$$

$$\tag{A1}$$

a_j, b_j are constants, $k_j(x) = \sqrt{2m_j(\Phi(x) - E)}$, m_j is the effective mass in the region j; we have $\xi_j = x_j$ for a case of the barriers with vertical walls. Matrices A_j, which refer to the neighboring regions are connected which each other by the following relationship:

$$A_{j+1} = G_j M_j N_j \,,$$

where

$$G_j = \begin{pmatrix} \frac{1}{2}g_j(1 + g_j^2)e^{i(k_j - k_{j+1})x_j} & \frac{1}{2}g_j(1 - g_j^2)e^{-i(k_j + k_{j-1})x_j} \\ \frac{1}{2}g_j(1 - g_j^2)e^{i(k_j + k_{j+1})x_j} & \frac{1}{2}g_j(1 + g_j^2)e^{-i(k_j - k_{j+1})x_j} \end{pmatrix},$$

$$g_j = \left(\frac{m_{j+1}}{m_j} \right)^{1/4}, \qquad M_j = \begin{pmatrix} e^{-\delta_j} & 0 \\ 0 & e^{\delta_j} \end{pmatrix}, \qquad N_j = \begin{cases} T & (dU/dx)_{\xi_{j+1}} > 0 \\ T^+ & (dU/dx)_{\xi_{j+1}} < 0 \end{cases},$$

$$T = \begin{pmatrix} \frac{1}{2}e^{i\pi/4} & \frac{1}{2}e^{-i\pi/4} \\ e^{-i\pi/4} & e^{i\pi/4} \end{pmatrix}. \tag{A2}$$

Here $\delta_j = \int\limits_{\xi_j}^{\xi_{j+1}} k_j(x)\, dx$, we use Jeffrey's transformations (e.g., [10]) to write T, the matrices G_j were obtained from the condition that both the wave functions and the flux must be continuous at x_{j+1}. The rate of transparency is defined as

$$D = 1 \Big/ \left[\left(\prod_{j=1}^{S} G_j M_j N_j \right)_{11} \right]^2 \tag{A3}$$

for a structure which incorporates S interfaces.

If we ignore the difference between the effective masses, formulae (2) holds for a special case of a double-barrier structure ($S = 4$). Consider another special case where the potential energy $\Phi(x)$ is constant (and equal) in every region, but the effective masses are different in different regions. In such a case the transmission coefficient is of

the following form:

$$D = |e^{-i\omega_2} (\mu_1\mu_2 \, e^{-i\delta_1} + \nu_1\nu_2 \, e^{i\delta_1}) (\mu_3\mu_4 \, e^{-i\omega_3} + \nu_3\nu_4 \, e^{i\delta_3})$$
$$+ \, e^{i\delta_2} (\mu_1\nu_2 \, e^{-i\delta_1} + \nu_1\mu_2 \, e^{i\delta_1}) (\nu_3\mu_4 \, e^{-i\delta_3} + \mu_3\nu_4 \, e^{i\delta_3})|^{-2} \, .$$

where $\mu_i = \frac{1}{2} g_i(1+g^2), \nu_i = \frac{1}{2} g_i(1-g^2)$. In particular, if the masses inside the barriers are equal to m_b and the masses in the well inside the double-barrier structure and in the bulk of the semiconductor are equal to m_s then

$$D = \frac{16g^4}{a^2 + b^2 + c^2 + 2b[a\cos{(2\delta_2)} - c\sin{(2\delta_2)}]} \, ,$$

$$a = [(1+g^2)^4 + (1-g^2)^4]\cos{(\delta_1 + \delta_3)} - 2(1-g^4)^2 \cos{(\delta_1 - \delta_3)} \, ,$$

$$b = 4(1-g^4)^2 \sin{(\delta_1)}\sin{(\delta_3)} \, , \qquad c = 8g^2(1+g^4)\sin{(\delta_1 + \delta_3)} \, ,$$

$$g = \left(\frac{m_b}{m_s}\right)^{1/4} . \tag{A4}$$

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