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Ballistic Diodes with Double Quantum Well Segments in Their Bases

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It is shown that a current–voltage characteristic of a ballistic diode with space charge limited longitudinal electron transport through a quantum structure consisting of a double quantum well segment is of a multiextremum character with repeated N-shaped (or Z-shaped) parts.

We examine space charge limited ballistic electron transport in quantum structures formed by segments of single and double quantum wells. Three most interesting versions of such structures which differ in contacting schemes are considered (Fig. 1).

(*a*) A resonant cover structure (RCS) with contacts to the bottom well only is shown in Fig. 1a. Beyond the tunnel resonance condition, a segment of the top well does not affect the electron transport in the bottom well. The situation becomes nontrivial when the tunnel resonance condition holds. In that case the influence of the top well is of a resonant character as a function of the length of the double quantum well segment (DQWS) and the energy of the ballistic electrons in it. Depending on the DQWS length, as well as on the applied voltage across the structure it is possible to affect the current strongly and even to switch it off.

(*b*) A resonant overlap structure (ROS) is presented in Fig. 1b. For this contacting scheme, the current carriers are injected into the bottom well and after preliminary acceleration in the cathode adjacent single quantum well segment (SQWS), they enter in the DQWS. Then the electrons leave the DQWS through the contact to the top well. In contrast to the RCS, this structure is closed if the tunnel resonance is detuned (that is the resonant current is zero). Under the tunnel resonance condition the ROS shows a similar resonant behavior with an effective control of the current by applied voltage.

(*c*) Figure 1.c shows an electron directional coupler. The current flows into the DQWS through the contact to the bottom well and flows out through two anodes which contact with the top well and the bottom well independently. A general operation principle of the coupler is to control currents through two channels providing a complete switching from one to the other. While the total current through the coupler has no peculiarities, the partial anode currents running through each of the anodes oscillate as a function of applied voltage.

The main idea of the operation principle of these devices has been developed in a number of theoretical and experimental works (see [1, 2] for an extensive review of the works dealing with transport in independently contacted DQW structures). A momentum distribution of the ballistic electrons in the DQWS becomes outstretched along the current direction. A transport regime is approaching a single-velocity regime. This

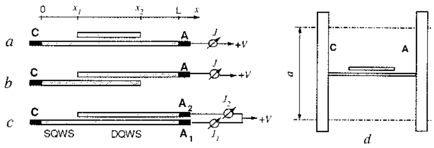

Fig. 1. Three versions of the quantum structures with a double quantum well segments: a) resonant cover structure; b) resonant overlap structure; c) coupler structure with two anodes; and d) model geometry of the ballistic diode used in our calculations (the figure shows the element of the considered structure with spatial periode a)

means that the electron beam consists of electrons of approximately the same velocity. Therefore the path $L(\tau)$, which electrons pass during the time $\tau = h/2\delta\varepsilon$ is also the same (where $2\delta\varepsilon$ is a value of the symmetric–antisymmetric (SAS) splitting in the DQW, $2\delta\varepsilon = \varepsilon_2 - \varepsilon_1 > 0$, and $\varepsilon_{1,2}$ are the energies of two lowest subbands in the DQW). In this manner all the electrons entered in the bottom-well of the DQWS transfer into the top-well at the moment $t = \tau/2$ of their movement in the DQWS passing distance $L(\tau/2)$ from the left boundary of the segment. They return to the bottom-well at $t = \tau$, passing distance $L(\tau)$ etc. The number of the interwell transitions during one passing over the DQWS depends on a mean electron velocity, v_{DQW}. The velocity is conditioned by the applied voltage, V_{D}, which accelerates the electrons. In this manner, V_{D} determines whether the electrons are reflected from the well deadlock (in the bottom-well for the ROS and in the top-well for the RCS). Therefore, the ballistic current in these structures oscillates repeatedly as a function of the applied voltage V_{D}, i.e. the current–voltage (J–V)-characteristic consists of several N-shaped regions.

A distinctive feature of this work is taking into account two different mechanisms of current limitation. The first mechanism is a quantum reflection from the considered inhomogeneous quantum structures. It is determined by the transmission and reflection coefficients, as in the case of linear ballistic conductance for very low voltages. The second mechanism is the space charge limitation. A nonlinear space charge limited ballistic current problem in the considered diodes (Fig. 1,d) stipulates a self-consistent solution of the Poisson equation with two-dimensional (2D) potential and one-dimensional (1D) charge distributions, and the collisionless kinetic equation for 1D ballistic transport in the current-conducting channel.

The anode currents in the considered structures oscillate as a function of the applied voltage, resulting in repeated N-shaped parts of the J–V characteristics, with minimum current values which are practically equal to zero (Fig. 2,a).

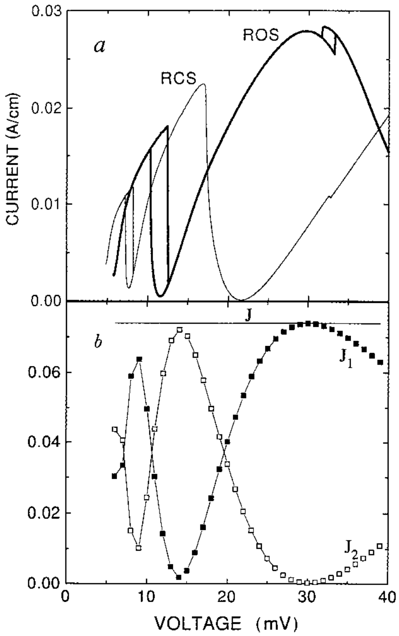

Fig. 2. a) Current–voltage characteristics of the diodes with the ROS and the RCS with the same parameters: $x_1 = 0.125$ µm, $x_2 = L = 0.5$ µm, $a = 0.5$ µm, $\delta\varepsilon = 2.5$ meV, $\mu = 2$ meV (μ is the Fermi energy), $N_{\mathrm{D}} = 1 \times 10^{10}$ cm^{-2}, $m/m_0 = 0.067$. b) J–V and $J_{1,2}$–V characteristics of the diode with the coupler structure: $x_1 = 0.1$ µm, $x_2 = L = 0.5$ µm, $a = 0.5$ µm, $\delta\varepsilon = 2$ meV, $\mu = 3$ meV, $N_{\mathrm{D}} = 5 \times 10^{10}$ cm^{-2}

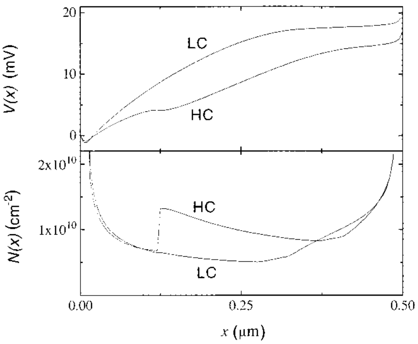

Fig. 3. Self-consistent potential $V(x)$ and concentration distributions $N(x)$ in the diode with the RCS from Fig. 2a for the high current and the low current branches

This is due to oscillations of the transmission coefficients as a function of a mean electron energy in the DQWS. The high current (HC) regime is characterized by the space charge accumulation in the DQWS (Fig. 3) because the DQWS is a resonant cavity (as in the case of either the RCS or the ROS). At the low current (LC) regime the space charge undergoes a redistribution, so that there is no additional charge in the DQWS and the voltage drops mainly across the cathode-adjacent SQWS. At the same time, the HC potential distribution is characterized by the substantially smaller electric field in the cathode-adjacent SQWS. A region with a large field is shifted into the DQWS, and almost the whole anode voltage drops across the DQWS. This redistribution leads to a strong asymmetry of the N-shaped parts with smooth growing branches and sharp falling branches. For a strong tunnel connection in the DQWS this asymmetry leads to Z-shaped parts of the J–V-characteristics and to hysteresis.

In the coupler there is only a modulation of partial anode currents flowing out through each of two anodes which are independently contacted with the bottom-well and the top-well (Fig. 2,b). The space charge increases monotonously with the voltage. We can see that the coupler characteristics provide a complete switching of the current between the channels and provide conservation of the switching current value. Here the switching is in the saturation current regime, that is the total current is not limited by a space charge.

In conclusion we enumerate our main results.

1. The resonant DQWS embedded into the base of the ballistic diode (the ROS or the RCS) lead to multiextrema behavior of the J–V-characteristics with repeated N-NDR.

2. At low voltages these characteristics demonstrate multivalued current behavior and Z-shaped parts.

3. There exists another type of current oscillations vs applied voltage caused by the electron wave reflection from the well deadlocks. It is not discussed thoroughly here. The oscillations can complicate the described picture if they are not suppressed. The suppression occurs when the ballistic beam is sufficiently wide in the energy scale and/or there are noticeable inhomogeneous fluctuations of the DQWS length.

4. A nonresonant coupler structure, displays multiextrema behavior for the partial currents $J_{1,2}$, but does not demonstrate such behavior for the total current.

References

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