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Dynamics and stability of lateral current density patterns in resonant-tunneling structures

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Abstract. We study lateral current density patterns in a double-barrier resonant tunneling structure with a bistable Z-shaped current-voltage characteristic. It is shown that for a positive load the external circuit provides a positive feedback upon the dynamics of the current pattern. This leads to accelerated motion of lateral switching fronts which switch the device from the low–conductivity to the high–conductivity state, and vice versa. Negative feedback and stabilization of a stationary front can be achieved by implementation of an active external circuit simulating a negative load.

Dynamical charge accumulation within the potential well of a double barrier resonant-tunneling structure (DBRT) leads to an electrostatic feedback mechanism which increases the energy of the quasi-bound state supporting resonant tunneling conditions for higher applied voltages. This mechanism may result in the intrinsic bistability of the DBRT where a high current and a low current state coexist for the same applied voltage u, and the current-voltage characteristic becomes Z-shaped, instead of N-shaped, thus exhibiting hysteresis upon voltage sweep [1]. Recently it has been pointed out [2, 3] that such bistability provides the basis for lateral pattern formation in the DBRT. Lateral current density patterns are characterized by a current density profile which varies in the plane perpendicular to the current flow reflecting spatial coexistence of the two stable states. The formation of such patterns is similar to the appearence of stationary current filaments and travelling fronts in the case of an S-shaped current-voltage characteristic [4]. It is known that the stability and dynamics of current density patterns in bistable semiconductors cannot be understood without taking into account the circuit conditions [4, 5, 6]. In this contribution we analyze lateral current density patterns in the DBRT and their dependence upon the feedback provided by the external circuit.

For a given applied voltage u the internal state of the DBRT can be parameterized by the electron concentration $n(x, t)$ in the quantum well described by the continuity equation [7]

$$\frac{\partial n}{\partial t} = \frac{1}{e}\left(J_{\mathrm{ew}}(n, u) - J_{\mathrm{wc}}(n)\right) + D(n)\frac{\partial^2 n}{\partial x^2}, \qquad (1)$$

where J_{ew} and J_{wc} are the emitter-well and the well-collector current densities, respectively, corresponding to vertical transport (along the z-axis), and the last term describes lateral transport (in the x-direction parallel to the quantum well plane; the width w of the sample along the other lateral direction is supposed to be small). Generally, the combination of lateral diffusion and drift in the well plane effectively results in a term with a nonlinear diffusion coefficient $D(n)$ [7, 2, 3]. We have derived approximate expressions for J_{ew} and

J_{wc} for a symmetric structure assuming sequential tunneling:

$$J_{\mathrm{ew}}(n,u) = \frac{e}{\hbar}\Gamma_L \cdot \left[\varrho\Delta\frac{\arctan(2\Delta/\Gamma) - \arctan(2\Omega/\Gamma)}{\pi} + \varrho\frac{\Gamma}{4\pi}\ln\frac{\Delta^2 + (\Gamma/2)^2}{\Omega^2 + (\Gamma/2)^2}\right] \cdot f_W,$$

$$J_{\mathrm{wc}}(n) = \frac{e}{\hbar}\Gamma_R \cdot n, \tag{2}$$

$$\Delta \equiv E_F - E_W + \frac{u}{2} - \frac{en}{C_{\mathrm{int}}},\ \ \Omega \equiv \frac{u}{2} - \frac{en}{C_{\mathrm{int}}} - E_W,\ \ C_{\mathrm{int}} \equiv \frac{\varepsilon\varepsilon_0}{d},\ \ \varrho \equiv \frac{m}{\pi\hbar^2},\ \ f_W \equiv 1 - \frac{n}{\varrho\Delta}.$$

Here E_F is the Fermi level in the emitter, E_W is the energy of the quasibound state in the well with respect to the bottom of the well, Γ is the total broadening of the quasibound state, Γ_L and Γ_R are the linewidths corresponding to escape via the emitter and collector barriers, respectively, ρ is the two-dimensional density of states, ε and ε_0 denote the relative and absolute permittivity, respectively, m is the effective electron mass, C_{int} is the capacitance of the well, d is the effective thickness of the barriers, and f_W is the effective filling factor of the states in the well. Δ and Ω denote the energy of the quasibound state with respect to the Fermi level and bottom of the conductance band in the emitter, respectively. The corresponding spatially homogeneous current-voltage characteristic $J(u) = J_{\mathrm{ew}} = J_{\mathrm{wc}}$ is shown in Fig. 1(a).

The dynamics of the voltage across the device $u(t)$ is described by Kirchhoff's equation for the external circuit (see [7]):

$$RC\frac{du}{dt} = U_0 - u - Rw\int_0^L \frac{J_{\mathrm{ew}} + J_{\mathrm{wc}}}{2}dx, \tag{3}$$

where U_0 is the applied bias voltage, R is the load resistance, L and w are the lateral sample length and width, respectively, and C is the total differential capacitance of the external circuit and the DBRT.

Eqs. (1),(2),(3) represent an example of a bistable medium with global coupling studied for stationary current density patterns in [6]. For $R > 0$ any stationary pattern in such a system is unstable [6]. Another important class of lateral patterns constitutes of travelling fronts corresponding to the propagation of the high current density state into the low current density state (hot front, front velocity $v > 0$) or vice versa (cold front, $v < 0$), i.e., they describe electronic switching processes between the off and the on state. Previously, we have numerically studied the propagation of planar (1D) fronts in a different semiconductor model (thyristor) with a Z-shaped bistability [9]. The main results of [9] may be applied to the DBRT as well. The $v(u)$ dependence for the DBRT is shown in Fig. 1(b). The speed and the direction of front propagation can be easily controlled by the voltage u. For a certain voltage the velocity is zero, i.e., the front becomes stationary, while for smaller voltages ($v > 0$) the front switches the system to the on state, and for larger voltage ($v < 0$) the front switches the system off. The dynamics of u due to the external circuit Eq. (3) leads to a nonlocal coupling of the front propagation since u depends on the integral value of the current density over the cross-section and, therefore, on the front position. This results in a feedback on the front dynamics. The negative slope $dv/du < 0$ leads to acceleration of both hot (Fig. 1(c)) and cold (Fig. 1(f)) fronts if the DBRT is operated via an external load resistance $R > 0$. Decelerated motion and stabilization of stationary front patterns (Fig. 1(d,e)) can be achieved by an implementation of active external circuits simulating a negative load $R < 0$ and negative capacitance $C < 0$ [8]. The front slows down and eventually becomes stationary. Oscillatory front dynamics is possible for a sufficiently

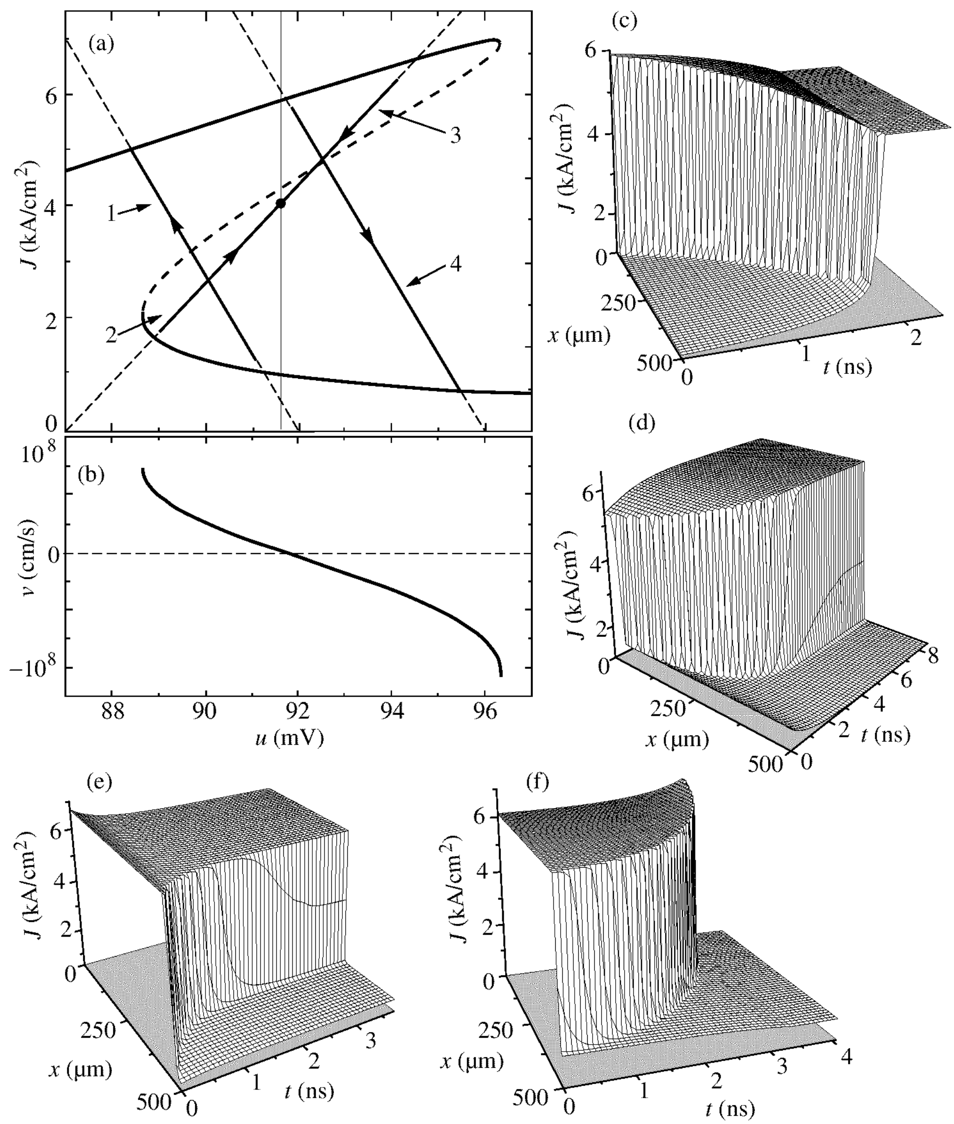

Fig. 1. (a) Current-voltage characteristic $J(u)$ calculated for the DBRT with $E_F = 5$ meV, $E_W = 40$ meV, $\Gamma = 1$ meV, $\Gamma_L = \Gamma_R = 0.5$ meV, $\varepsilon = 12$, and $m = 0.067$ (for GaAs). (b) The dependence of the front velocity v on u for the voltage-controlled regime; $v > 0$ corresponds to a hot front. (c,d) accelerated and decelerated hot fronts for $R > 0$ (load line 1 in the (J, u)-plane: $U_0 = 92$ mV, $RLw = 7.8 \cdot 10^{-11}\,\Omega \cdot \mathrm{m}^2$) and $R < 0$ (load line 2: $U_0 = 87$ mV, $RLw = -1.3 \cdot 10^{-10}\,\Omega \cdot \mathrm{m}^2$), respectively; (e,f) decelerated and accelerated cold fronts for $R < 0$ (load line 3: $U_0 = 87$ mV, $RLw = -1.3 \cdot 10^{-10}\,\Omega \cdot \mathrm{m}^2$) and $R > 0$ (load line 4: $U_0 = 96$ mV, $RLw = 7.8 \cdot 10^{-11}\,\Omega \cdot \mathrm{m}^2$), respectively. In these simulations $RC = 10^{-12}$ s which corresponds to an instantaneous global feedback on front dynamics. Here we assume a diffusion constant $D = D_0 = 1\,\mathrm{m}^2/\mathrm{s}$ inside the well. For different values of D the length and velocity has to be rescaled by a factor $\sqrt{D/D_0}$.

large capacitance C. In conclusion, this offers convenient control of lateral switching in the DBRT.

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