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Terahertz switching action of a double-barrier resonant tunneling device

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The response of an asymmetric double barrier resonant device to the passage of terahertz radiation is discussed. Within the bistable region the radiation is able to turn the current flowing through the system on or off, with an onset that depends on the bias, the strength of the incoming radiation, and its frequency.

Resonant tunneling through double-barrier structures has been the subject of much interest for their physical properties and applications as electronic devices.[1] Besides a peak due to simple resonant transmission, an intrinsic dynamical bistability and hysteresis in the negative differential resistance region of the current-voltage characteristic has been reported.[2–7] The interior of the bistability has been reached experimentally by employing a load line with positive slope, which turns the characteristic into a Z-shaped tristable curve.[8] The effect is currently understood in terms of the Coulomb repulsion experienced by the incoming electrons from the charge buildup in the space between the barriers.[3] In support of this interpretation is the fact that the width of the bistable region is enhanced by making the collector barrier wider, thus allowing for a more efficient trapping of electrons in the well.[9] A magnetic field along the device provides an additional enhancement and may introduce more complex instabilities.[5,7,10] The effect has also been detected in triple barrier structures.[11]

Since the work of Sollner *et al.*[12] much experimental work has been devoted to the study of the effect of a time-dependent potential in resonant tunneling through semiconductor microstructures. Recently Chitta *et al.* have studied the far-infrared response of double barrier structures.[13] There is also theoretical work reported, although most of it ignores the electron-electron interaction. We have shown recently that for an external bias near the edges of the bistable region in the I-V curve the interacting system becomes unstable under the passage of terahertz electromagnetic radiation.[14] The device can thus act as a detector of radiation in this frequency range, or as a current switch triggered by the passage of radiation. Our results were obtained by direct integration of a Schrödinger equation including a nonlinear Hartree-like term, which gave rise to numerical instabilities and the impossibility of exploring the long-term behavior of the system.

In this paper we apply a rate-equation approach to the problem. Tunneling is modeled as a sequential process[15] in which the electrons are transmitted through the double barrier in steps, first from the emitter into the well, and then, from the well into the collector region. Calling k, q, and p the quantum numbers characterizing the state in the emitter, well, and collector regions, respectively, the rate equation for the occupancies f_k and f_q of the emitter and well states, respectively, are[15]

$$\frac{df_q}{dt}=\sum_k f_k W_{qk}-\sum_p f_q W_{qp}, \tag{1}$$

where W_{qk} and W_{qp} are the transmission rate from the emitter to well and from the well to the collector region, respectively. We obtain the stored charge density from $n_e=(e/A)\Sigma_q f_q$, where A is the interfacial area. Summing Eq. (1) over q and multiplying the result by (e/A) we get the equation of continuity for the charge

$$\frac{dn_e}{dt}=J_L-Rn_e, \tag{2}$$

where $J_L=(e/A)\Sigma_{k,q} f_k W_{qk}$ is the current from the emitter region, and $R=\Sigma_p W_{qp}$ is the escape rate from the collector barrier. We have assumed that W_{qp} does not depend on q, based on the fact that in the well there is a quasibound state associated with motion along the growth direction, the only degrees of freedom left being those along the perpendicular plane, which do not affect the transmission probability. Neglecting the energy resonance width we obtain[16]

$$J_L=\frac{e}{Ah}\theta(\varepsilon_r)\theta(\varepsilon_f^L-\varepsilon_r)(\varepsilon_f^L-\varepsilon_r)T_L, \tag{3}$$

$$R=\frac{v_r}{2d}T_R, \tag{4}$$

where h is Planck's constant, ε_r is the position of the resonance level when the system is under the effect of the applied potential, $\theta(x)$ is the step function, ε_f^L is the Fermi level in the emitter region, and d is the width of the well. The quantum-mechanical transmission coefficient through the left (right) barrier, $T_L(T_R)$, is dependent of the barrier height and width ε_r and the applied bias.[17] The semiclassical velocity of the electron as it passes through the well is given by

$$v_r=\sqrt{\frac{2(\varepsilon_r+\beta\Delta V_o)}{m^*}},$$

where m^* is the electron effective mass, ΔV_o is the external dc voltage, and β is the fraction of the potential drop at the well defined below. All energies are measured with respect to the bottom of the conduction band at the emitter.

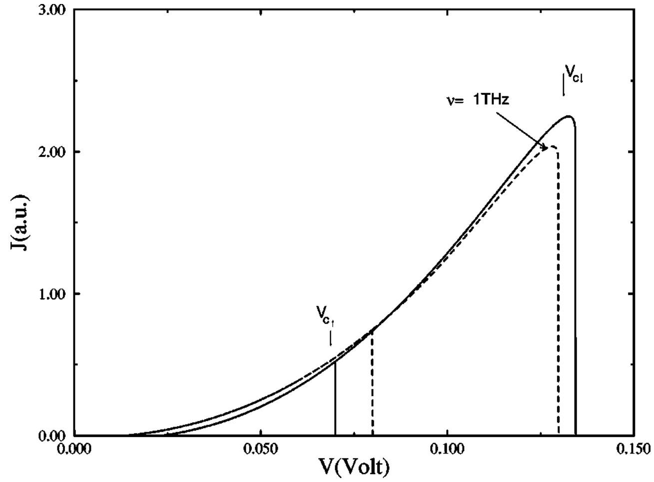

FIG. 1. Current-voltage characteristic for $\delta E = 0$ (solid line) and $\delta E = 10$ meV (dashed line) at $\nu = 1$ THz.

The potential across the device $\Delta V(t)$ includes the external dc voltage ΔV_0, the external radiation-induced ac voltage contribution $\delta E \sin(2\pi\nu t)$, applied between the outside edges of the emitter collector barriers, and the built-in potential profile of the device. We assume that all unbalanced charge is localized at the center plane in the well. The contribution to the potential profile arising from this charge is calculated using Poisson's equation with the boundary conditions $V = 0$ at $z = -(a_L + d/2)$ and $V = \Delta V_0$ at $z = (a_R + d/2)$, with $a_{L,R}$ the widths of the left and right barriers. The overall potential profile modifies the position of the resonance, which is placed at

$$\varepsilon_r = \varepsilon_{ro} - \beta \Delta V(t), \tag{5}$$

where $\varepsilon_{ro} = \varepsilon_o + \alpha n_e$ is the position in the absence of a radiation field, with ε_o the position at zero bias, and

$$\alpha = \frac{(a_L + d/2)(a_R + d/2)}{a_L + d + a_R},$$

$$\beta = \frac{a_L + d/2}{a_L + d + a_R}. \tag{6}$$

We have solved the rate equation numerically using the Runge-Kutta method taking as initial conditions the stationary solutions with no applied ac field. The model is applied to an asymmetric GaAs/AlGaAs double barrier structure, with emitter and collector barrier thicknesses of 1.12 and 3.36 nm, respectively, and a well thickness of 11.2 nm. The second barrier is made wider than the first in order to enhance the trapping of charge in the well. The conduction-band offset is set at 300 meV. For this geometry the first resonance at zero bias occurs at 30 meV. In equilibrium, the Fermi level is taken as 20 meV above the conduction-band edge, so that the zero-bias resonance lies 10 meV above the Fermi sea.

Figure 1 shows the current-voltage characteristic for zero ac field (solid lines), and its temporal average with an applied radiation field of frequency $\nu = 1$ THz and amplitude $\delta E = 10$ meV (dashed lines). The full vertical lines mark the border of the bistable region with no external field. When the bias is turned up, charge accumulates in the well thus keeping the local potential and resonance level within the emitter Fermi sea, up to a bias $V_{c\downarrow}$, where it becomes unstable, the well empties and the current falls abruptly. Turning the bias down does not produce a current since the space between the barriers has no charge and the resonance lies below the bottom of the emitter conduction band, until the lower-critical point $V_{c\uparrow}$, at which, once again, the resonance tunneling is possible and the current state is re-established.[14] Our results show a reduction in the width of the bistability region caused by the electromagnetic radiation, in agreement with previous results.[14,18] The temporal average was taken from 50 to 100 ps, well after transient effects due to the initial conditions had elapsed. Note that in this range one expects about 50 periods of small amplitude oscillations in the current driven by the external field (ringing), a phenomenon we observe clearly in our time-dependent data. Also, with the parameters chosen, our device has a characteristic intrinsic decay time $\tau \sim 3$ ps, measuring how long it takes for unstable accumulated charge in the well to spill out. The dashed vertical lines in the figure mark the boundaries at which the system either makes the transition from a state with current to one with no current, or vice versa, within the first 100 ps from the time at which the radiation field is turned on. This shows the bias range within which an initially stationary state will effect a transition to another state, triggered by the passage of a radiation pulse of the given frequency and amplitude.

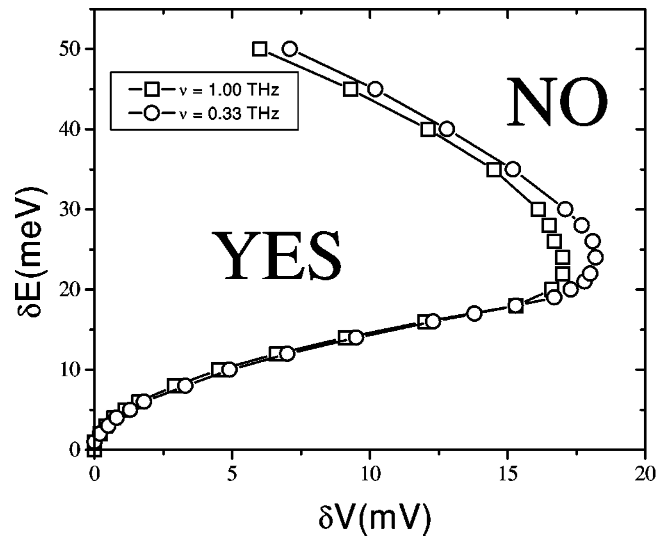

FIG. 2. Phase diagram for switching in the range 50–100 ps at two different radiation frequencies.

As the amplitude and frequency of the radiation field varies, the position of the vertical-dashed lines in Fig. 1 change. In fact the one at lower bias moves approximately linearly with δE to the right, while the one at higher bias first moves to the left narrowing the bistable region, and then moves to the right. We have studied in detail the associated phase diagram using the powerful calculation scheme presented here. Results for a transition between a state where current flows, to one with no current, are shown in Fig. 2 for two different frequencies. Here $\delta V = V_{c\downarrow} - V$ is the external bias offset from the radiation-free critical value $V_{c\downarrow}$. The figure shows the position of the vertical-dashed line (Fig. 1) nearest the latter, for given values of the ac-field amplitude δE at a fixed frequency. The time average was taken in the same interval as for Fig. 1. The region labeled YES is where the transition takes place, while that labeled NO marks the area where the transition will not take place. As expected, the transition never takes place for a bias offset δV larger than δE. Also, as the frequency is decreased, the boundary line moves to the right approaching the dc limit $\delta E = \delta V$, representing the quasistatic regime at which the device just traces the solid line in Fig. 1.

The most remarkable finding exhibited in Fig. 2 is that for frequencies $\sim \tau^{-1}$ the boundary curve bends over in such a way that beyond a critical ac-field amplitude the transition does not take place regardless of how strong the external radiation is. To understand this feature let us follow the behavior of the system as one increases δE at a fixed value of δV, say 10 mV, so that before the radiation arrives, the resonance level ε_r [Eq. (5)] lies about midway across the Fermi sea. At small values of δE the oscillation about ε_r is too small to trigger an instability. Near $\delta E = 14.5$ mV, however, the transition takes place since the system is a fraction $\nu\Delta t = 2\cos^{-1}(1-\delta V/\delta E)/\pi$ of a period out of resonance, either because the effective position of the resonance level ε_r in the well lies above the Fermi sea, in the emitter, or below. The out of resonance time Δt needs to be large enough in relation with the trapping characteristic time τ so that enough charge leaves the well to trigger the instability before the resonance condition is re-established within a period. Note that the onset exhibited by Fig. 2 occurs at a slightly higher value of δE if the frequency is increased, since $\Delta t/\tau$ is then smaller. The instability remains for a range of δE, yet as this quantity continues to grow the current as well as the trapped charge in the well decrease, affecting the strength of the nonlinear interaction. In fact, at about $\delta E = 44$ mV (at $\nu = 1$ THz), and $\delta E = 45$ mV (at $\nu = 0.33$ THz) and beyond, the transition no longer occurs in the interval 0–100 ps. We have checked that the transition in this range does not take place even if one goes up to 300 ps and higher. Within a period the system remains a short time in resonance, and so little charge is stored in the well that its effect in transport becomes negligible.

In summary, we have studied the response of a resonant tunneling device to a THz radiation field, and its action as a switching device. Using a rate equation approach we have been able to follow the time evolution of the system for as long a time as one wishes, without the numerical instabilities encountered in detailed first-principles quantum-mechanical calculations.[14] This allows for a detailed study of the phase diagram for fast switching at any frequency of the external field.

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