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A mesoscopic terahertz pulse detector

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We show that under the passage of an electromagnetic terahertz pulse an asymmetric double-barrier device may act as an on/off current switch, depending on the bias. The time-dependent response of the device is discussed. © *1999 American Institute of Physics.* [S0003-6951(99)02536-X]

It is well known that the characteristic frequencies of electronic processes in mesoscopic systems are in the terahertz range. This follows from transition energies that are typically in the meV scale. For example, instabilities in transport through asymmetric double-barrier systems (ADBS) may give rise to terahertz oscillations.[1,2] Other time-dependent processes, such as the charging and discharging of the well in these systems, are also expected to take place in the range of picoseconds. This suggests that an ADBS may react as a fast switch to the passage of a terahertz pulse, a possibility that we explore in this work.

ADBS are characterized by a bistable region of the bias, produced by charge accumulation in the space between the barriers (the well).[3] The collector barrier is made wider with the purpose of increasing the lifetime of the resonance in the well, thus enhancing the amount of charge that is retained when current goes through.[4,5] At a critical bias $V_{c\downarrow}$ the current drops abruptly due to a sudden emptying of the well, driven by an instability that may be understood using a nonlinear model.[1] The dynamics is dominated by the accumulated charge which, in effect, lifts the bottom of the potential well, thus retaining the resonance condition beyond $V_{c\downarrow}$ for ballistic transmission of an incoming electron. There is a point at which this charge is so large that it becomes favorable to spill it out, the well is emptied, and the resonance condition is lost, followed by a large current drop. Similarly, when the well is uncharged it will remain so, even as the bias is decreased to values smaller than $V_{c\downarrow}$. At a second critical value $V_{c\uparrow}$ the resonance condition is fulfilled again and current now flows. This completes the bistable cycle, a signature of which is the fact that $V_{c\downarrow}>V_{c\uparrow}$.

In this work we propose that an ADBS device biased slightly below $V_{c\downarrow}$ will still undergo a transition, triggered by the passage of radiation in the terahertz region. The external field introduces an additional oscillating field that may in effect bring the bias to criticality. We also contend that a radiation field may trigger the onset of resonant transport if the system is biased slightly above $V_{c\uparrow}$. Optical radiation will have no effect in either case since the field then oscillates so fast that the electrons have no time to respond. Only at terahertz and lower frequencies would one expect the system to switch from a state of high current to one of low flow of electrons in the presence of an incident radiation pulse, or vice versa.[6–8]

Consider an ADBS under bias and in the presence of an electromagnetic field polarized along the z axis, the growth direction. In order to study the time evolution of the device we adopt a first-neighbors tight-binding model for the Hamiltonian. The radiation field enters as a space and time-dependent voltage. To a good approximation, the longitudinal degrees of freedom are decoupled from the transverse motion and may be treated independently. The probability amplitude b_j^α for an electron in a time-dependent state $|\alpha\rangle$, to be at plane j along z, is determined by the equation of motion[2]

$$i\hbar\frac{db_j^\alpha}{dt}=\left(\epsilon_j(t)+U\sum_\beta |b_j^\beta|^2\right)b_j^\alpha + v(b_{j-1}^\alpha+b_{j+1}^\alpha-2b_j^\alpha). \tag{1}$$

In this expression $\epsilon_j(t)$ includes the fixed-band contour, the external radiation-induced voltage $\delta E\sin 2\pi\nu t$, and the applied dc bias, the latter represented by a term linear in the spatial coordinate j. The sum over β covers all occupied electron states and v is the hopping matrix element between nearest-neighbor planes. In writing Eq. (1) we have adopted a Hartree model for the electron–electron interaction, keeping just the intra-atomic terms as measured by the effective coupling constant U.[2] As we will show in what follows, this nonlinear term is of key importance in the behavior of the system.

The time-dependent Eq. (1) is solved using a half-implicit numerical method which is second-order accurate

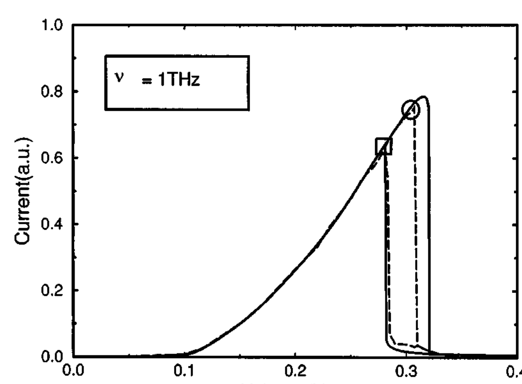

FIG. 1. Current–voltage characteristic for $\delta E=0$ (solid line) and $\delta E=10$ meV (dashed line) at $\nu=1$ THz.

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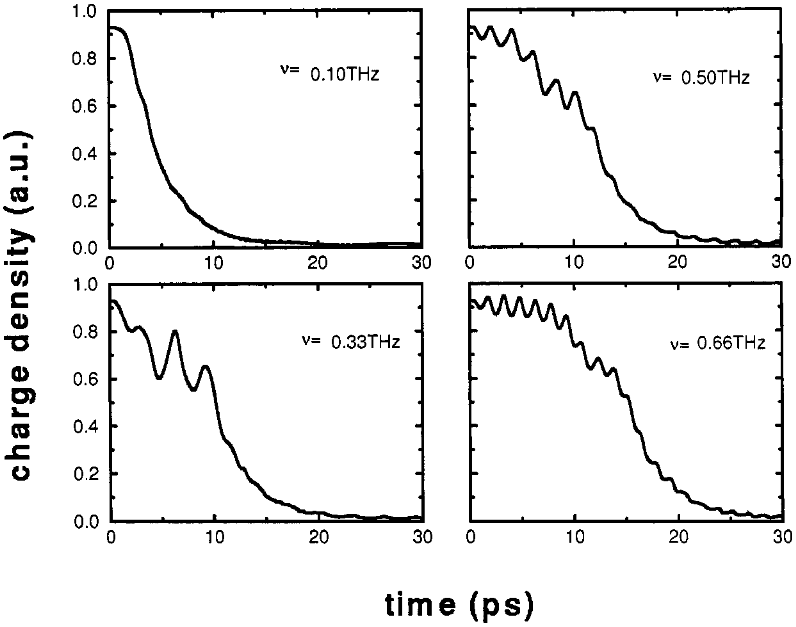

FIG. 2. Time evolution of the charge density in the center of the well at $V=0.310$ V and frequencies 0.10, 0.33, 0.50, and 0.66 THz.

and unitary.[2,9] Boundary conditions must be specified at the left $(z=-L)$ and right $(z=L)$ edges of the structure. The approach taken here assumes that the wave function at time t is given outside the structure by[2,9,10]

$$b_j^\alpha(t)=[Ie^{ik_\alpha z_j}+R_j(t)e^{-ik_\alpha z_j}]e^{-i\epsilon^\alpha t/\hbar}, \quad z_j\leqslant -L, \tag{2}$$

$$b_j^\alpha(t)=T_j(t)e^{ik'_\alpha z_j}e^{-i\epsilon^\alpha t/\hbar}e^{-i\delta E\cos(2\pi\nu t)/h\nu}, \quad z_j\geqslant L. \tag{3}$$

Here, k_α and $k'_\alpha=\sqrt{2m^*[\epsilon^\alpha-\epsilon_L]}/\hbar$ are the wave numbers of the incoming and outgoing states, respectively, with $\epsilon^\alpha=-4v\sin^2(k_\alpha a/2)$ the energy of the incoming particle. To model the interaction with the particle reservoir outside the structure, the incident amplitude I is assumed to be a constant independent of the coordinates. The envelope function of the reflected and transmitted waves, R_j and T_j, are allowed to vary with j, however. Since far from the barriers these quantities are a weak function of the coordinate z_j, we restrict ourselves to the linear corrections only. This approximation is appropriate provided the time step δt does not exceed a certain limiting value. For the results presented here, a value of $\delta t=3\times10^{-17}$ s was found sufficient to eliminate spurious reflections at the boundary while maintaining numerical stability up to 40×10^{-12} s. In our numerical procedure the coefficients obtained without electromagnetic field for a given dc bias are used as the initial condition when the THz radiation is turned on. With $b_j^\alpha(t)$ known, the time-dependent current at site j is obtained numerically from[9]

$$J_j(t)=\frac{e}{\hbar}\int_0^{k_f}\mathrm{Im}\{b_j^{*\alpha}(b_{j+1}^\alpha-b_j^\alpha)\}(k_f^2-k_\alpha^2)dk_\alpha, \tag{4}$$

where $k_f=\sqrt{2m^*\epsilon_f}/\hbar$, with ϵ_f the Fermi energy.

We next apply our model to an asymmetric GaAs/AlGaAs double-barrier structure, with emitter and collector barrier thicknesses of 1.12 nm (2 sites) and 3.36 nm, (6 sites) respectively, and a well thickness of 11.2 nm (20 sites). The second barrier is made wider than the first in order to enhance the trapping of charge in the well. For this geometry

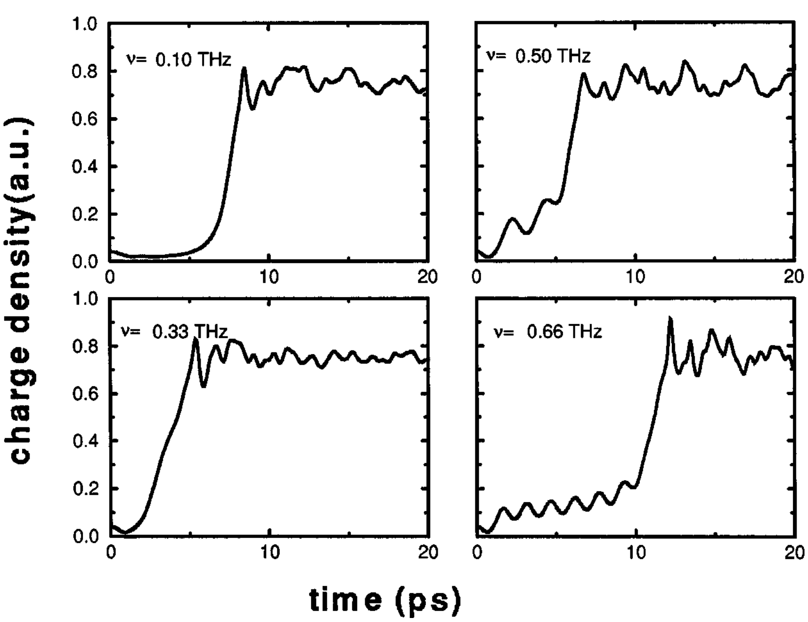

FIG. 3. Time evolution of the charge density in the center of the well at $V=0.285$ V and frequencies 0.10, 0.33, 0.50, and 0.66 THz.

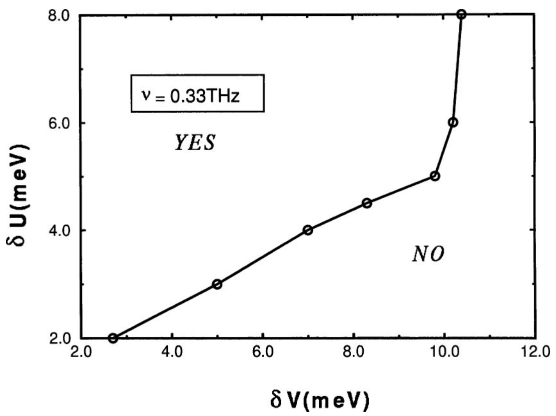

FIG. 4. Boundary separating the region at which switching takes place within 17 ps of the arrival of an external pulse at frequency $\nu = 0.33$ THz, from the region in which the well remains charged beyond that time interval.

the first resonance at zero bias occurs at 30 meV. The conduction-band offset is set at 300 meV. The buffer layers are uniformly doped up to 3 nm from either barrier, so as to give a neutralizing free-carrier concentration of $2 \times 10^{17}\,\mathrm{cm}^{-3}$ at the contacts. In equilibrium, the Fermi level lies 19.2 meV above the asymptotic conduction-band edge, so that the zero-bias resonance lies well above the Fermi sea. The contribution to the potential due to the applied bias is taken into account through a term linear in j, which is assumed to arise from fixed charges. The parameter values in Eq. (1) are set at $v = -2.16\,\mathrm{eV}$ and $U = 100\,\mathrm{meV}$. The latter was chosen phenomenologically so as to fit the experimental $J-V$ characteristic for a GaAs devices.[4] The sample has 400 sites and the normalization of the wave functions is chosen so that charge from the electrons filling up to the Fermi energy exactly cancels the positive charge at the contacts.[5] We solved Eq. (1) using the procedure described above, for an energy mesh appropriate to compute the integral in Eq. (4). Good convergence was found for a mesh of 100 points.

Figure 1 shows the current–voltage characteristic in the absence (solid line) and presence (dashed line) of radiation of amplitude $\delta E = 10\,\mathrm{meV}$ at $\nu = 1$ THz. In the latter case we exhibit an average of the current over time. Note that at the chosen values of parameters $V_{c\downarrow} = 0.320\,\mathrm{V}$ and $V_{c\uparrow} = 0.282\,\mathrm{V}$. It is clear from Fig. 1 that the radiation field narrows down the region of bistability, in agreement with previous results by Iñarrea and Platero.[11] This effect is to be expected since the time-dependent field added to the bias brings the system periodically to criticality when the applied dc bias has not reached this condition yet, thus triggering the charging or discharging of the well.

In Fig. 2 we show the time evolution of the charge density at the center of the well for different frequencies of the radiation field at $V = 0.310\,\mathrm{V}$ (empty circle in Fig. 1), a bias slightly below $V_{c\downarrow}$. The condition for resonant tunneling is still met, conduction is allowed, and the well is initially charged. A THz field of the same amplitude as for Fig. 1 is turned on at $t = 0$, and as the radiation passes through the system the well empties, doing so in a few picoseconds time. Two characteristic times are involved in the data: the external radiation period $T_r = 1/\nu$ and the time $T_w \sim 3$ ps it would take for our well to empty if charge is initially in it. When $T_r \gg T_w$ the radiation field essentially acts as an added dc bias and the well empties within the time T_w, while in the other extreme $T_r \ll T_w$ the oscillation is so fast that the electrons cannot respond and the system remains charged and conducting.

Figure 3 shows a situation in which the well is initially empty at a bias of $V = 0.285\,\mathrm{V}$, slightly above the critical value $V_{c\uparrow}$ (empty square in Fig. 1). It is physically reached by lowering the bias after it has gone beyond $V_{c\downarrow}$. Once again the THz field is switched on at $t = 0$. We observe that in all cases exhibited the well begins to charge, and after a transient time the system enters full resonance and current flows.

The above results assumed a radiation field of fixed amplitude $\delta E = 10\,\mathrm{meV}$. One may ask how close to the critical value $V_{c\downarrow}$ must the system be biased in order to act as a switch for weaker radiation fields. This is shown in Fig. 4 for $\nu = 0.33$ THz and assuming the switching to take place at $\tau = 17$ ps time. The bias offset is defined as $\delta V = V_{c\downarrow} - V$. The region above the curve (labeled YES) is where the potential drop takes place within the time τ, while the region below (labeled NO) is where the switching does not take place in that time interval. Within the range of our calculations we found the shape of the curve in Fig. 4 to be generic, shifting upwards as the frequency increases. Close to the origin the dependence is approximately linear and for the chosen frequency follows the relation $\delta E \sim \frac{1}{2}(1 + \delta V)$. Using this expression we get that at a bias $\delta V = 1$ meV our device would switch under radiation of about 50 W/cm^2 and stronger. The sensitivity could be improved using a wider collector barrier, thus having a narrower resonance (longer lifetime T_w). Because of limitations due to numerical instabilities, this ansatz would be best tested experimentally.

In summary, we have shown that an asymmetric double-barrier heterostructure may act as a switch triggered by the passage of electromagnetic radiation at frequencies in the terahertz region and below. The frequency threshold for this switching action depends on the barrier and enclosed well widths. Depending on the applied external bias, the passage of current is turned on or off by the radiation pulse. Our results rely on the current drop as the resonance in the well falls below the emitter conduction-band edge, a feature also present in symmetric double-barrier heterostructures. In the latter case, however, the drop is not an instability of the system and does not take place abruptly, a desirable feature for a switching device.

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