Frequency limit of double-barrier resonant-tunneling oscillators

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The speed of operation of negative differential resistance (NDR) devices based on resonant tunneling in a double-barrier quantum well structure is considered. It is shown that the intrinsic RC delay of a single barrier limits the frequency of active oscillations to $f_{max} = 1/(2\pi\tau)$, where $\tau = \epsilon\alpha^{-1}(\lambda/c)\exp(4\pi d/\lambda)$ with λ being the de Broglie wavelength of the tunneling electron, d the barrier thickness, ϵ the dielectric permittivity, c the speed of light, and $\alpha \approx 1/137$ the fine-structure constant. The relevance of this estimate to recent experimental results is discussed. An alternative mechanism for the NDR is proposed—not involving resonant tunneling. It should be observable in various single-barrier structures in which tunneling occurs into a two-dimensional system of states. In a double-barrier structure, specially designed experiments are required to distinguish this effect from resonant tunneling.

The study of negative differential resistance (NDR) oscillators based on resonant tunneling in double barrier diodes (DBD) was pioneered by Tsu, Esaki, and Chang.[1,2] Recently, experiments of Sollner *et al.*[3,4] on AlGaAs/GaAs heterostructure DBD's grown by molecular beam epitaxy gave rise to a renewed interest in such devices. These authors have demonstrated[4] active oscillations of a DBD mounted in a resonant cavity at frequencies f up to 18 GHz with the dc to rf conversion efficiency of 2.4%. They suggested that the observed frequency was limited by the coaxial circuits used and that still higher f could be achieved in a different microwave setup. This view is supported by their earlier experiments[3] in which a DBD was used as a detector and mixer of far infrared radiation at $f = 2.5$ THz.

One purpose of the present letter is to provide a simple and easy-to-use estimate for the frequency limit f_{max} of a DBD. This estimate, Eq. (3), is consistent with the results of Ref. 4, but it rules out the possibility of obtaining active oscillations in a GaAs/AlGaAs 50 Å barrier device at terahertz frequencies. Another purpose of this letter is to suggest an alternative interpretation—not involving resonant tunneling—for the observed NDR effect in quantum well diodes.

The operation of a heterostructure DBD is illustrated schematically in Fig. 1. It is best understood by the analogy with a Fabry–Perot resonator. At a sufficiently low temperature the diode current is due to electron tunneling from the emitter to the quantum well (QW) base and then to the collector. At a certain applied voltage V (of order $2E_0/e$, where E_0 is the energy of the lowest subband in the QW) one can expect a resonant enhancement of the tunneling current. This occurs when the energy of an incident electron (one near the Fermi level in the emitter) matches that of an unoccupied state in the QW corresponding to the same lateral momentum. Under such conditions, the amplitude of the resonant electronic mode builds up in the QW to the extent that the wave, leaking out in both directions, partially cancels the incident wave and enhances the transmitted one. Ricco and Azbel[5] have recently pointed out that in order to achieve maximum resonant transmission one needs equal transmission coefficients for both barriers at the operating point—a condition not fulfilled for barriers designed to be symmetric in the absence of an applied field.[6]

Ricco and Azbel[5] have also given a lucid discussion of time development in resonant tunneling—the question which concerns us in this letter. In particular, they pointed out that the enhanced resonant transmission corresponds to a steady state in which the electron wave function has already attained an appropriate amplitude in the QW. The establishment of such a stationary situation (say, in response to a suddenly imposed external field) must be preceded by a transient process during which the amplitude of the resonant mode is built up inside the well. The transient time τ_0 is of the order of the resonant-state lifetime and hence can be expected to increase exponentially with the barrier phase area. We believe (in agreement with Ref. 5) that it is this transient time which gives the fundamental speed limit in most practical DBD's. A simple estimate for τ_0 is derived by regarding the transient process as a modulation of charge in the "quantum capacitor" formed between the base QW and the controlling electrodes. During the operation of a DBD, this capacitor is being charged or discharged by the tunneling current.

Indeed, consider a small-signal oscillation of the diode. As the operating point moves up and down the NDR region of its I-V characteristic, the amount of charge stored in the resonant state inside the QW varies. During the operation of a DBD, this charge (which equals $e\int_{z_1}^{z_2}|\Psi|^2\,dz$, see Fig. 1) is readjusted all the time by a transient difference between the emitter and the collector currents. Even for a single electronic mode it is permissible to speak of a "capacitor" and its RC time constant, since any change in $|\Psi|^2$ is accompanied by a displacement current. It is essential to realize that this capacitor is being charged not by a resonant tunneling current but by the ordinary tunneling through a single barrier. By Gauss' law, in the parallel-plate geometry of a DBD, the variation $\delta|\Psi|^2$ is linearly related to the voltage variations across each barrier. For simplicity, I shall assume that during the part of the cycle when $|\Psi|^2$ in the well is waxing, the emitter current charges the base-emitter capacitance—ignoring the concomitant electron leakage through the collector barrier as well as the displacement current in that barrier—and vice versa for that part of the cycle when $|\Psi|^2$ in QW is on the wane. This should produce a slightly enhanced estimate for f_{max}.

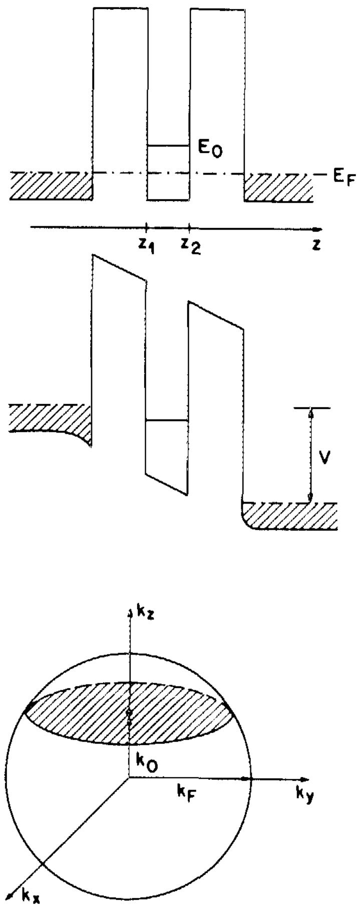

FIG. 1. Illustration of the operation of a double-barrier resonant-tunneling diode. The top part shows the electron energy diagram in equilibrium. The middle displays the band diagram for an applied bias V, when the energy of certain electrons in the emitter matches unoccupied levels of the lowest subband E_0 in the QW. The bottom illustrates the Fermi surface for a degenerately doped emitter. Assuming conservation of the lateral momentum during tunneling, only those emitter electrons whose momenta lie on a disk $k_z = k_0$ (shaded disk) are resonant. The energy separation between E_0 and the bottom of the conduction band in the emitter is given by $\hbar^2 k_0^2/2m$. In an ideal DBD at zero temperature the resonant tunneling occurs in a voltage range during which the shaded disk moves down from the pole to the equatorial plane of the emitter Fermi sphere. At higher V (when $k_0^2 < 0$) resonant electrons no longer exist.

The tunnel resistance of a single barrier of average height Φ and thickness d can be estimated from a WKB expression[7] for the current density:

$$J = (e/2\pi h d^2)\, \Phi \exp(-4\pi d\sqrt{2m\Phi}/h), \tag{1}$$

where h is the Planck constant. The barrier height Φ varies with voltage: for an approximately trapezoidal barrier one has $d\Phi/d(eV_1) \simeq 1/2$, where V_1 is the voltage drop across the (single) barrier. Neglecting variation in the pre-exponential factor, we can express the tunnel resistance per unit area $R \equiv (\delta J/\delta V_1)^{-1}$ in the form

$$R = (2\lambda d h/e^2) e^{4\pi d/\lambda}, \tag{2}$$

where $\lambda \equiv h/\sqrt{2m\Phi}$ is the de Broglie wavelength of an electron tunneling under the barrier. On the other hand, the barrier capacitance per unit area is given by $C = \epsilon/4\pi d$, where ϵ is the dielectric permittivity of the barrier material. Whence we find

$$\tau \equiv RC = \epsilon\alpha^{-1}(\lambda/c) e^{4\pi d/\lambda}, \tag{3}$$

where $\alpha^{-1} = \hbar c/e^2 \simeq 137$ and c is the speed of light. The cutoff frequency is determined from (3) as $f_{max} = 1/(2\pi\tau)$. We can interpret τ as a lifetime of the resonant state. The quantity $\hbar/\tau$ corresponds to a homogeneous broadening of the energy levels in the QW due to electron tunneling in and out.

Let us make numerical estimates for the GaAs/AlGaAs DBD's used in Refs. 3 and 4. We take $m = 0.096\, m_0$ appropriate for $Al_{0.35}Ga_{0.65}As$, and find $\lambda = 88.5$ Å for $\Phi = 0.2$ eV. For 50-Å-thick barriers, Eq. (3) gives $\tau \simeq 40$ ps and $f_{max} \simeq 4$ GHz. This estimate is not inconsistent with the microwave results[4] of Sollner *et al.*, but it is almost three orders of magnitude below the frequency of their detector experiments.[3] One is forced therefore to seek an alternative interpretation of those results. One possible explanation[8] can be related to inhomogeneities in the barrier width and height. It should be interesting to consider the resonant-tunneling problem in the presence of an impurity center in the barrier region. It is also possible that the detector operation is not directly related to resonant tunneling but is rather due to some other rectifying effect. Such an interpretation, however, would have to explain the impressive coincidence[3] between the detector response spectrum as a function of the applied bias and the dc characteristics of the DBD.

There exists the following rather intriguing possibility. It can be shown that a negative differential resistance can arise solely due to tunneling into a quantum well—without a resonant Fabry–Perot effect. To see this, we turn again to Fig. 1. The figure at the bottom illustrates the Fermi sea of electrons in a degenerately doped emitter. Assuming that the AlGaAs barrier is free of impurities and inhomogeneities, the lateral electron momentum (k_x, k_y) is conserved in tunneling. This means that for $E_C < E_0 < E_F$ (where E_C is the bottom of the conduction band in the emitter) tunneling is possible only for electrons whose momenta lie in a disk corresponding to $k_z = k_0$ (shaded disk in Fig. 1), where $\hbar^2 k_0^2/2m = E_0 - E_C$. Only those electrons have isoenergetic states in the QW with the same k_x and k_y. This is a general feature of tunneling into a two-dimensional system of states. As the emitter-base potential rises, so does the number of electrons which can tunnel: the shaded disk moves downward to the equatorial plane of the Fermi sphere. For $k_0 = 0$ the number of tunneling electrons per unit area equals $mE_F/\pi\hbar^2$. When E_C rises above E_0, then at $T = 0$ there are no electrons in the emitter which can tunnel into the QW while conserving their lateral momentum. This mechanism of NDR should be experimentally distinguishable from resonant tunneling. In particular, it does not depend on the symmetry of transmission coefficients of the two barriers, and should not degrade, therefore, if the transparency of the second (collector) barrier is enhanced. The effect is conceptually similar to that in the Esaki diode. It should be observable in various single-barrier structures in which tunneling occurs into a two-dimensional system of states. If the NDR mechanism just described is operating,[9] the width of the observed peak in the I-V characteristic should depend on the emitter doping and be given by E_F/e times a geometrical factor ($\gtrsim 2$). This is not inconsistent with the results of Refs. 1–4. It is therefore possible that the mechanism responsible for the NDR in the experimentally studied DBD's is not the Fabry–

Perot effect, as was assumed before,[1–5] but rather the above-described effect involving *sequential* tunneling through the two barriers.

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[9]This interpretation was conceived in a discussion with A. Kastalsky. He also pointed out that the width of the NDR peak can be made extremely narrow at low temperatures, if the tunnel emitter also represents a two-dimensional system.

Magneto-optic determinations of the pressure dependence of band-gap energies and effective masses in strained-layer superlattices

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Pressure-dependent magneto-optic studies on strained-layer superlattices have been performed for magnetic fields up to 65 kG and pressures up to 4 kbar in the temperature range of 1.6–4 K. The experimental pressure coefficients of the band-gap energy and the reduced effective mass in both *n*-type and *p*-type strained-layer $In_{0.2}Ga_{0.8}As/GaAs$ superlattice structures were determined.

We present the first pressure-dependent magneto-optic measurements in semiconductors at high-magnetic fields and low temperatures. These measurements were performed on *n*-type and *p*-type $In_{0.2}Ga_{0.8}As/GaAs$ strained-layer superlattices (SLS) for magnetic fields up to 65 kG and pressures up to 4 kbar in the temperature range of 1.6–4 K. These measurements allow the simultaneous determination of the pressure coefficients for both the band-gap energies and the effective masses. This information is important for determinations of band structures of superlattices.

Using the pressure coefficients for the reduced effective mass from these magneto-optic measurements and the magneto-transport determined conduction-band mass,[1] an estimate of the pressure coefficient for the valence-band mass can also be made. The bulk GaAs pressure coefficients of the band-gap energy[2] and band-effective masses[3] are 12.5 meV/kbar and 0.7 %/kbar, respectively. Pressure-dependent luminescence measurements on lattice matched GaAs/GaAlAs superlattices have been previously reported[4–13] using high-pressure diamond-anvil techniques. These experimental results yielded pressure coefficients of the band-gap energy in the range of 10–12 meV/kbar. Generally, because of the physical dimensions of typical diamond-anvil cells, these types of measurements have precluded the application of the large magnetic fields necessary for the study of magneto-optic effects.

The experimental apparatus and techniques for performing pressure-dependent magneto-optical measurements at low temperatures and high magnetic fields are described in Ref. 14. However, a brief description will be presented here. Hydrostatic pressures up to 4 kbar were generated using isobarically frozen helium[15,16] inside a 0.125-in. inside-diameter BeCu pressure bomb. The [100] face of the SLS was attached to one end of a 100-μ core-diameter quartz fiber using GE 7031 varnish. The sample-optical-fiber combination was inserted into the BeCu pressure chamber and this assembly in turn was placed into the magnetic field region of a 0.75-in.-diam-bore superconducting solenoid. Magnetic fields to 65 kG were provided by the superconducting solenoid and the data were obtained in the 1.6–4 K range by pumping on the helium bath in which the pressure bomb was immersed. The sample was illuminated by the 514.5 nm line of an argon-ion laser through the fiber-optic cable. The luminescence signal, returning through the same fiber, was directed by a beam splitter to a monochromator and a CAMAC-based data acquisition system.[17] The magnetic field direction was normal to the SLS layers.

Two different heavily doped $In_{0.2}Ga_{0.8}As/GaAs$ SLS structures, *n* type and *p* type, were used in these studies. For this In concentration, both the conduction-band minima

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