MECHANISM OF OPERATION OF DOUBLE-BARRIER RESONANT-TUNNELING OSCILLATORS

Serge Luryi

AT&T Bell Laboratories
Murray Hill, New Jersey 07974

ABSTRACT

The effect of negative differential resistance observed in double-barrier quantum-well structures is usually attributed to a resonant Fabry-Perot effect. I propose a different mechanism — involving a sequential rather than resonant tunneling through the two barriers. The effect does not require the existence of a second tunneling barrier and it should also be observable in various single-barrier structures in which tunneling occurs into a two-dimensional system of electronic states. Moreover, a similar effect should also occur in the tunneling from a 2D electron gas into a 1-D system of states (a "quantum wire"). This effect underlies the operation of a recently proposed three-terminal negative differential transconductance device.

INTRODUCTION

Recently, a number of workers have demonstrated the microwave activity of negative differential resistance (NDR) diodes based on a double-barrier quantum-well (QW) structure, illustrated in Fig. 1. Since the pioneering work of Tsu, Esaki, and Chang (1) the mechanism for the NDR has been universally attributed to a resonant tunneling effect analogous to that in a Fabry-Perot resonator. This effect is presumed to occur when the energies of incident electrons in the emitter match those of unoccupied states in the QW. Under such conditions, the amplitude of the resonant modes builds up in the QW to the extent that the electron waves leaking out in both directions cancel the incident waves and enhance the transmitted ones.

Sollner et al. (2,3) studied double-barrier diodes (DBD) implemented in AlGaAs/GaAs heterostructures grown by MBE. They demonstrated (3) active oscillation in the 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 the earlier experiments (2) of the same group in which a DBD was used as a detector and mixer of far infrared radiation at $f = 2.5$ THz.

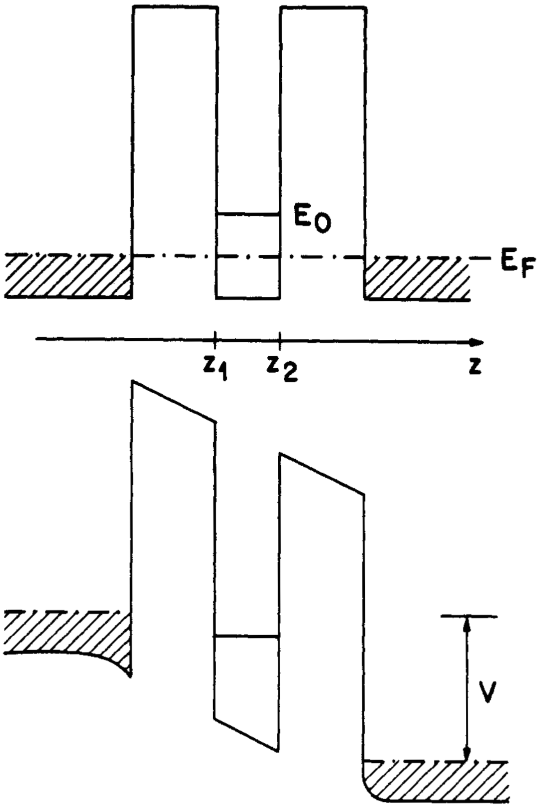

Fig. 1 Band diagram of a double-barrier diode in equilibrium (top) and under applied bias (bottom).

CH2252-5/85/0000-0666 $1.00

In the Fabry-Perot picture of resonant tunneling 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 time required for this process cannot be less than the resonant-state lifetime τ. A simple estimate gives $\tau = \epsilon\alpha^{-1}(\lambda/c)\exp(4\pi d/\lambda)$, with λ being the de Broglie wavelength of the tunneling electron, d the single barrier thickness, ϵ the dielectric permittivity, c the speed of light, and $\alpha \approx 1/137$ the fine-structure constant. This estimate was derived (4) 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. The resultant upper limit $f_{\max} = 1/2\pi\tau$ is substantially *lower* than the observed frequency in GaAs/AlGaAs heterostructure diodes. One is forced, therefore, to seek an alternative explanation for the experimental results.

ALTERNATIVE MECHANISM

I propose a different mechanism for the observed NDR in double-barrier QW structure — not involving a resonant Fabry-Perot effect. Figure 2 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 and E_0 is the bottom of the subband in the QW) tunneling is possible only for electrons whose momenta lie in a disk corresponding to $k_z = k_0$ (shaded disk in the figure), 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. Therefore, one can expect an abrupt drop in the tunneling current. This mechanism of NDR should be experimentally distinguishable from the Fabry-Perot mechanism. 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 also be observable in various single-barrier structures in which tunneling occurs into a two-dimensional system of states.

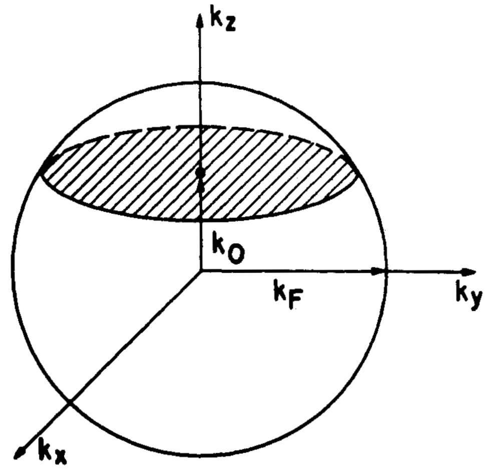

Fig. 2 Illustration of the NDR mechanism in QW diodes. The shaded disk within the Fermi sphere corresponding to a degenerately doped emitter, describes all the electrons which can tunnel into the QW while conserving their lateral momenta. In an ideal diode at zero temperature the resonant tunneling occurs 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* resonant electrons no longer exist.

In fact, it may have already been observed in the tunnel injection experiments. The University of Illinois group (5) studied electron tunneling through a single barrier into a QW located in a *p*-type quaternary material. In these experiments the diode current resulted from the subsequent recombination of tunneling electrons with holes in the direct-gap QW. The observed structure in the dependences of the current and the intensity of the recombination radiation on the applied bias can be explained in terms of the above picture based on the momentum conservation. Extension of this picture to the case of several subbands in the QW is straightforward.

One should also be able to demonstrate the described effect in a unipolar single-barrier structure: Let the emitter be separated by a thin tunneling barrier from a QW which is confined on the other side by a thin but impenetrable (for tunneling) barrier, Fig. 3. The drain contact to the QW, located outside the emitter area, should be electrically connected to a conducting layer underneath. Application of a negative bias to the emitter will result in the tunneling of electrons into the QW and their subsequent drift laterally toward the drain contact. If the drift resistance is made sufficiently small so that there is no steady-state accumulation of electrons in the QW under the emitter, then one can expect to observe an NDR effect in this structure, as described above.

Returning to the double-barrier QW structure of Fig. 1, I would like to stress the essential difference between the Fabry-Perot mechanism of the NDR and the above-described mechanism, which involves *sequential* rather than resonant tunneling through the two barriers. In the instance of a semiconductor superlattice, this difference had been clearly explained in a remarkable paper by Kazarinov and Suris (6). In an ideal superlattice consisting of a large number of equally spaced identical quantum wells, an enhanced electron current must flow at sharply defined values of an external electric field, when the ground state in the n-th well is degenerate with the first excited state in the $(n+1)$-st well. Under such conditions, the current is due to electron tunneling between the adjacent wells with a subsequent de-excitation in the $(n+1)$-st well. In other words, electron propagation through the entire superlattice involves again a sequential rather than resonant tunneling. On the other hand, if the applied field is such that the potential difference, acquired by an electron over many periods of the superlattice, is less than the width of the lowest electron miniband, then one can expect a resonant transmission, analogous to the Fabry-Perot effect, and possibly an NDR due to the Bragg reflections. For the sequential tunneling regime, Kazarinov and Suris had predicted the possibility of a laser action at the inter-miniband transition frequency — an effect not yet observed experimentally in superlattices.

NEGATIVE TRANSCONDUCTANCE TRANSISTOR

We have established that all that is required for the NDR to occur in a resonant tunneling structure is the reduced dimensionality of electronic states. The preceding discussion has dealt with the bulk-carrier tunneling into a 2-D density of electronic states. Recently, F. Capasso and myself proposed a novel device structure (7) in which the QW is linear rather than planar and the tunneling if of 2-D electrons into a 1-D density of states. Figure 4 shows the schematic cross-section of the proposed device. It consists of an epitaxially grown undoped planar QW and a double AlGaAs barrier sandwiched between two undoped GaAs layers and heavily doped GaAs contact layers. The working surface defined by a V-groove etching is subsequently overgrown epitaxially with a thin AlGaAs layer and gated. Application of a positive gate voltage V_G induces 2-D electron gases at the two interfaces with the edges of undoped GaAs layers outside the QW. These gases will act as the source (S) and drain (D) electrodes. At the same time, there is a range of V_G in which electrons are not yet induced in the "quantum wire" region (which is the edge of the QW layer) — because of the additional dimensional quantization. The operating regime of our device is in this range.

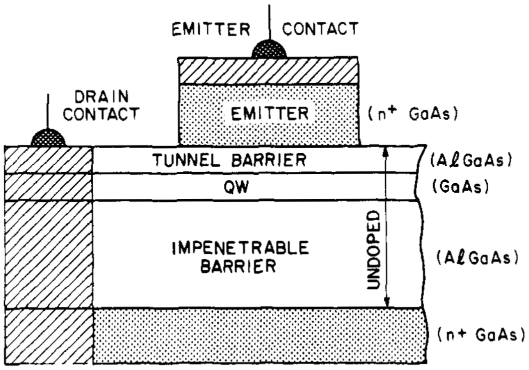

Fig. 3 Illustration of a QW structure which is expected to exhibit the NDR effect similar to that observed in double-barrier diodes. The drain contact is assumed to be concentric with a cylindrical emitter electrode. The "impenetrable" barrier separating the QW from the conducting layer underneath (the latter is shorted to the drain) must be thin enough ($\sim 1000\,\text{Å}$), so that the emitter-to-QW potential could be effectively controlled by the emitter bias.

Device characteristics can be understood along the lines described above in connection with Fig. 2. In the present case the dimensionality of both the emitter and the base is reduced by 1, so that the emitter Fermi sea becomes a disk and the shaded disk of Fig. 2 is replaced by a resonant segment. Application of a positive drain voltage V_D brings about the resonant tunneling condition and one expects an NDR in the dependence $I(V_D)$. What is more interesting, is that this condition is also

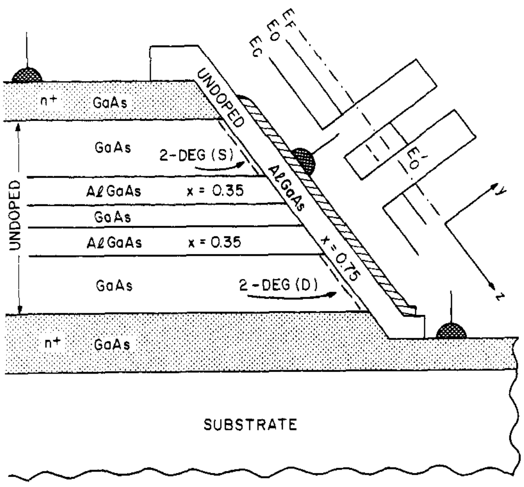

Fig. 4 The negative differential transconductance device (7). E_0 is the bottom of the 2D subband separated from the classical conduction band minimum by the energy of the zero-point motion in y-direction; E_0' is the bottom of the 1-D subband in the quantum wire, separated from E_0 by the confinement energy in the z-direction. In the operating regime the Fermi level E_F lies between E_0 and E_0'.

controlled by V_G. The control is effected by fringing electric fields: in the operating regime an increasing $V_G > 0$ *lowers* the electrostatic potential energy in the base with respect to the emitter — nearly as effectively as does the increasing V_D (this has been confirmed in ref. 7 by solving the corresponding electrostatic problem exactly with the help of suitable conformal mappings). At a fixed V_G having established the peak of $I(V_D)$, we can then quench the tunneling current by increasing V_G. This implies the possibility of achieving the *negative differential transconductance* (NDT) — an entirely novel feature in a unipolar device. An NDT transistor can perform the functions of a complementary device analogous to a p-channel transistor in the silicon CMOS logic. A circuit formed by a conventional n-channel field-effect transistor and our NDT device can act like a low-power inverter in which a significant current flows only during switching. This feature can find applications in logic circuits.

CONCLUSION AND ACKNOWLEDGEMENTS

I have shown that the NDR effect observed in resonant-tunneling structures can arise solely due to the dimensional confinement of electronic states and its observation essentially requires neither the Fabry-Perot mechanism nor the existence of two tunnel barriers. This understanding should have important implications for the design of future resonant-tunneling diodes and transistors.

It is my pleasure to acknowledge useful discussions and collaboration of F. Capasso, G. E. Derkits, and A. Kastalsky.

REFERENCES

[1] R. Tsu and L. Esaki, "Tunneling in a finite superlattice", *Appl. Phys. Lett.* **22**, 562 (1973); L. L. Chang, L. Esaki, and R. Tsu, "Resonant tunneling in semiconductor double barriers", *Appl. Phys. Lett.* **24**, 593 (1974).

[2] T. C. L. G. Sollner, W. D. Goodhue, P. E. Tannenwald, C. D. Parker, and D. D. Peck, "Resonant tunneling through quantum wells at frequencies up to 2.5 THz", *Appl. Phys. Lett.* **43**, 588 (1983).

[3] T. C. L. G. Sollner, P. E. Tannenwald, D. D. Peck, and W. D. Goodhue, "Quantum well oscillators", *Appl. Phys. Lett.* **45**, 1319 (1984).

[4] S. Luryi, "Frequency limit of double-barrier resonant-tunneling oscillators", *Appl. Phys. Lett.* **47**, 490 (1985).

[5] E. A. Rezek, N. Holonyak, Jr., B. A. Vojak, and H. Schichijo, "Tunnel injection into the confined-particle states of an InGaPAs well in InP", *Appl. Phys. Lett.*, **703** (1977).

[6] R. F. Kazarinov and R. A. Suris, "Possibility of the amplification of electromagnetic waves in a semiconductor with a superlattice", *Sov. Phys. - Semicond.* **5**, 707 (1971).

[7] S. Luryi and F. Capasso, "Resonant tunneling of two-dimensional electrons through a quantum wire: a negative transconductance device", to be published.