Observation of a negative differential resistance due to tunneling through a single barrier into a quantum well

H. Morkoç, J. Chen, U. K. Reddy, and T. Henderson
University of Illinois at Urbana–Champaign, Coordinated Science Laboratory, 1101 West Springfield Avenue, Urbana, Illinois 61801

S. Luryi
AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974

(Received 17 January 1986; accepted for publication 15 May 1986)

We have observed a negative differential resistance (NDR) in a single-barrier tunneling structure in which electrons tunnel from a doped semiconductor emitter layer into a quantum well (QW) layer and subsequently drift laterally to a specially designed contact. Pronounced NDR is seen already at room temperature and at 77 K the peak to valley (PTV) ratio in current is more than 2:1. Our results lend support to a recent hypothesis by Luryi [Appl. Phys. Lett. **47**, 490 (1985)] that the NDR in double-barrier tunneling structures is not related to a resonant enhancement of the tunneling probability at selected electron energies, but rather originates from tunneling into a system of electron states of reduced dimensionality. For comparison we have also fabricated a QW structure with two tunneling barriers, in which the parameters of the emitter barrier and the QW are identical to those in the single-barrier structure. In the double-barrier structure we have obtained current densities as high as 4×10^4 A/cm^2 and a NDR with PTV ratios of 3:1 at 300 K and 9:1 at 77 K.

Double-barrier quantum well (DBQW) tunneling structures have recently drawn a great deal of attention because tunneling is the fastest phenomenon observed in semiconductors. Since the first report[1] of tunneling in a DBQW structure, the material quality has improved to the point that negative differential resistance (NDR) can be observed[2] directly in the current-voltage characteristics at 77 K, as opposed to the derivative of the current. The material quality has steadily improved making it possible to observe the NDR at room temperature.[3,4] Recently, peak to valley (PTV) ratios in current as high as 2.3 were obtained at room temperature,[5] in part by introducing lightly doped regions immediately outside the barriers as reported in Ref. 3.

The NDR in DBQW structures is the consequence of two-dimensional confinement of states in a quantum well (QW), and the conservation of energy, and lateral momentum in tunneling. In addition to that, the operation of these structures had often been discussed in terms of resonant enhancement of the transmission probability for electrons incident on the emitter barrier at selected energies—an effect analogous to that in a Fabry–Perot optical resonator. The enhancement occurs when the amplitude of a resonant electronic mode in the QW builds up to the extent that the wave, leaking out in both directions, partially cancels the reflected wave. This physical picture has led to a design strategy intended to optimize the Fabry–Perot resonator conditions in a DBQW structure. In particular, Ricco and Azbel[6] pointed out that achievement of a near-unity resonant transmission requires 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. To counter that, a resonant-tunneling structure was proposed[7] in which a symmetric DBQW was built in the base of a bipolar transistor, and the Fabry-Perot conditions were maintained through the use of minority-carrier injection.

High-frequency operation of DBQW diodes was recently considered by Ricco and Azbel[6] and Luryi.[8] Assuming the Fabry–Perot mechanism, they concluded that the dominant delay results from the resonator charging time, which is of the order of the resonant state lifetime. For a QW bounded by 50-Å-thick AlGaAs barriers, simple estimates[8] gave a frequency limit in the low gigahertz range. At higher frequencies, the amplitude of an electron wave function in the QW cannot readjust itself in response to an external field variation to provide resonant enhancement of the transmission coefficient. These estimates, contrasted with the experimental results of Sollner *et al.*,[2] in which a DBQW structure was used as a detector and mixer of far-infrared radiation at 2.5 THz, have led one of us (SL) to the suggestion that the Fabry–Perot resonant transmission plays only a minor role (if any) in the operation of DBQW diodes. It was shown[8,9] that the NDR can arise solely due to electron tunneling into a system of states of reduced dimensionality. In this picture, electrons subsequently leave the QW by tunneling through the second (collector) barrier, so that their transport through the entire DBQW structure is described by *sequential* rather than resonant tunneling.

Within the sequential-tunneling model, Derkits[10] was able to explain the terahertz results[2] by showing that rectification of an external signal by a DBQW diode requires the readjustment of only the phase of electron wave functions and not their amplitude, so that the operation of a detector is not limited by a Fabry–Perot charging time. Coleman and colleagues at the University of Illinois on the basis of their microwave admittance experiments in the NDR regime of a DBQW diode,[11] proposed an equivalent circuit which may be consistent with the sequential-tunneling model and Derkits's picture of rectification. In that circuit, the small-signal NDR is not shorted out by the DBQW capacitance, which allows detectors to operate at extremely high frequencies, as observed in Ref. 2, while active oscillation frequencies could be limited in a fashion predicted in Ref. 8.

According to the model,[8] in DBQW structures the removal of electrons from the QW occurs via sequential tunneling. Other means of electron removal can also be contemplated, for example recombination with holes—if the QW is located in a p-doped material.[12] In this letter we report the first observation of NDR through a single tunneling barrier into a quantum well bounded on the other side by a thick nontunneling barrier, with the electron removal from the QW via lateral drift to a specially provided contact outside the emitter area. The principle of such a single-barrier (SBQW) tunneling structure was first described in Ref. 9.

The structures studied were grown by molecular beam epitaxy (MBE) using conventional growth procedures. In order to make ohmic contact to the quantum well, a special structure as depicted in Fig. 1(a) was grown. The structure of Fig. 1(a) was designed with a 500-Å $Al_{0.3}Ga_{0.7}As$ "collector" barrier to eliminate the possibility of tunneling through this barrier. The 50-Å-thick quantum well was bounded on the top side with a 25-Å tunneling AlAs barrier (undoped). After growing a 315-Å n layer above this tunneling barrier, a 100-Å n^+-doped AlAs etch-stop layer was incorporated. As the last layer on the top, a 0.3-μm-thick n^+ contact layer was grown. For the base contact, the 0.3-μm n^+ cap layer was selectively removed in a GaAs etch followed by the selective removal of the n^+-AlAs layer. The base contact (AuGe/Ni/Au) was then deposited in a self-aligned fashion with the emitter. The contact material was alloyed long enough for the metallization to diffuse from the base region through the nontunneling barrier, thus shorting the base to the conducting layer underneath. The 315-Å n layer remaining between the base contact and intrinsic emitter is designed with a proper doping level so that it is entirely depleted by the surface Fermi-level pinning. Since both GaAs and AlAs etch-stop layers above the tunneling barrier are heavily doped, no rectification or any other spurious non-ohmic effects are expected. In order to make a comparison, we have also examined a double tunneling barrier structure with AlAs barriers as shown in Fig. 1(b).

The current-voltage (I/V) characteristics of the structure of Fig. 1(a), obtained at 300 and 77 K are shown in Fig. 2. As can be seen, there is a pronounced NDR with peak current density of about 3 kA/cm^2 in a device with 75 μm diameter. We believe that the observed NDR is due to tunneling of three-dimensional emitter electrons into a two-dimensional system of states in the QW, as described earlier.[8,9] Since the base contact is shorted to the conducting layer underneath the collector barrier and its lateral distance from the edge of the emitter much exceeds the combined thick-

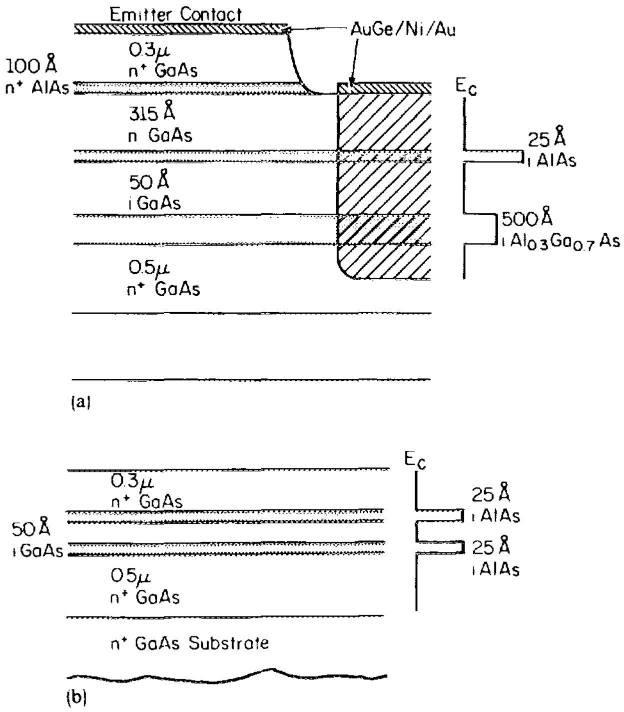

FIG. 1. (a) Cross-sectional view of the single tunnel barrier device structure. The base contact is defined by self-alignment with respect to the emitter. The thin 315-Å-thick n-GaAs layer between the base contact and the emitter is designed to be depleted by the surface Fermi-level pinning, and thus does not short the emitter to the base. Electrons from the 0.3-μm n^+-GaAs emitter region tunnel through the 25-Å i-AlAs barrier into the 50-Å i-GaAs quantum well and are swept by the base contact. (b) Cross-sectional view of the conventional double tunnel barrier AlAs/GaAs resonant-tunneling structure. Electrons from the 0.3-μm n^+-GaAs tunnel through the 25-Å- i-AlAs barrier into the 50-Å GaAs quantum well and subsequently leave the well by tunneling through the second i-AlAs barrier.

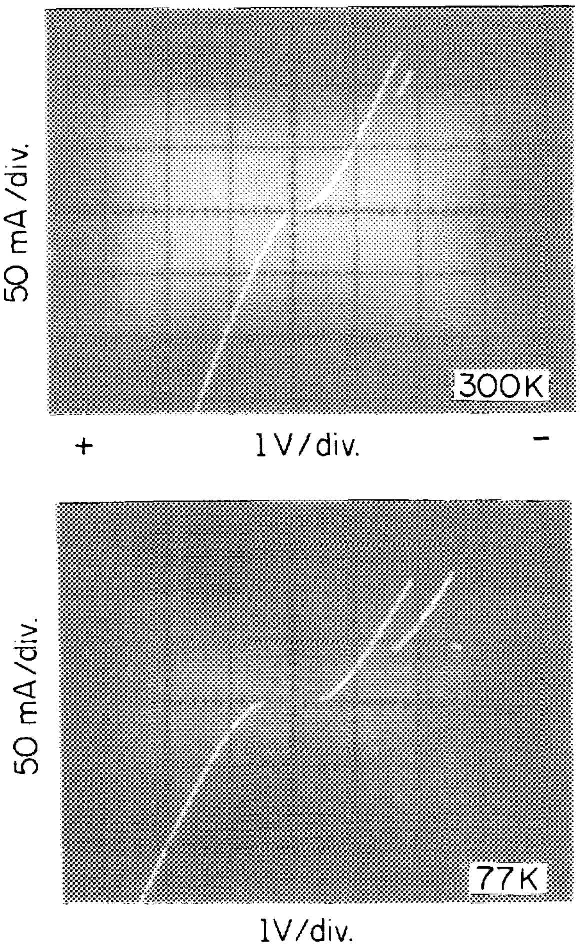

FIG. 2. Typical base-emitter current-voltage characteristics obtained at 300 and 77 K in the single tunnel barrier of Fig. 1(a).

nesses of the two barriers and the QW, application of a base-emitter voltage results in nearly vertical electric field lines under the emitter, which allows us to control by the applied voltage the potential difference between the emitter and the QW. Of course, this control is much less effective (by the lever rule) than it would be if the second barrier were also 25 Å thick.

In order to make sure that there is no tunneling through the 500-Å-thick AlGaAs barrier in Fig. 1(a), we performed a control experiment. By carefully controlling the alloying conditions we fabricated a structure similar to the one in Fig. 1(a) but this time the base and the 0.5-μm n^+ GaAs were not shorted. The base contact was alloyed long enough to diffuse through most of the AlGaAs barrier, nearly but not quite touching the collector layer. This was done to ensure a proper field distribution in the device. The base and collector terminals were tested to verify the fact that the two were not shorted. The I/V characteristics of the control structure obtained at 300 K are qualitatively similar to those shown in Fig. 2 with a peak current density of about 1.7 kA/cm^2 in a device with 75 μm diameter. When subsequently alloyed further so that the drain contact is shorted to the collector layer, the I/V characteristics remained practically the same, the only difference being a slight shift in the position of the peak along the voltage axis. This indicates that the observed NDR is not a result of tunneling through the thick AlGaAs barrier.

For comparison we have also grown and tested a conventional double-barrier structure, which contained a 50-Å well bounded by two 25-Å AlAs tunneling barriers as shown in Fig. 1(b). The doping level on the outside of the tunneling barriers (about 250 Å) was kept low to enhance the PTV ratio, as discussed in Ref. 4. The DBQW I/V characteristics obtained at 300 and 77 K are displayed in Fig. 3. The high quality of the sample is evident in the PTV current ratios of as high as 3:1 at room temperature. Improved material quality reduces the nontunnel valley current associated with the defects in the barrier layers. The best devices when cooled to 77 K exhibit PTV ratios of as high as 9:1. The device dimension here was 6 μm in diameter and the peak current density before the onset of NDR is 30 kA/cm^2, which is only an order of magnitude larger than that obtained in the single tunnel barrier device of Fig. 1(a). The higher peak current in the DBQW structure can hardly be attributed to a resonant enhancement of the tunneling probability, since the application of an external field leads to asymmetric energy barriers and at least partially destroys the Fabry–Perot condition. It is more likely that the higher current is explained by a better uniformity of the transverse electric field across the diode area.

It is clear that the NDR in both the DB and SB structures is of the same nature. The peak current in the SB structure occurs at a voltage which is 5.7 times higher than that observed in the DBQW structure, which is as expected from the lever rule. Of course, in the symmetric DB structure the NDR is seen in both directions of the current, whereas in the SBQW structure it occurs only when the emitter is biased negatively. In as much as the NDR in our single-barrier structure is obtained between the base and the emitter contacts, it is tempting to conclude that no resonant enhancement of the tunneling current is involved. However, such a conclusion would be premature since one can also describe the operation of this structure in terms of a modified Fabry–Perot effect, in which standing electron waves in the QW leaking back into the emitter, cancel the reflected waves and enhance the transmitted ones.

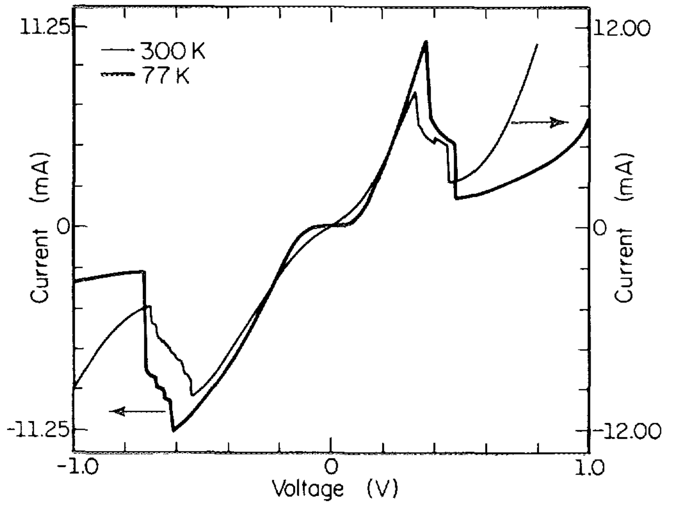

FIG. 3. Typical room-temperature and 77 K I/V characteristics of the double tunnel barrier AlAs/GaAs structure of Fig. 1(b).

In conclusion, we have reported the first observation of a negative differential resistance by tunneling through a single barrier into a quantum well, confirming earlier predictions.[9] It is also shown that the current densities obtained in single tunnel barrier structures are within an order of magnitude of those obtained in double tunnel barrier structures. More studies, both experimental and theoretical, are clearly required to establish conclusively whether or not the Fabry–Perot effect is relevant or important in the operation of quantum well tunneling structures.

The authors would like to thank M. H. Brodsky, F. Capasso, P. Chapin, P. D. Coleman, G. E. Derkits, R. Fischer, J. Gering, A. Kastalsky, R. F. Kazarinov, and M. S. Shur for useful discussions. One of the authors (U. K. Reddy) would like to thank IBM for awarding a post-doctoral fellowship. The work at the University of Illinois was funded by the Air Force Office of Scientific Research.

[1] R. Tsu and L. Esaki, Appl. Phys. Lett. **22**, 562 (1973); L. L. Chang, L. Esaki, and R. Tsu, *ibid.* **24**, 593 (1974).
[2] T. C. L. G. Sollner, W. D. Goodhue, P. E. Tannenwald, C. D. Parker, and D. D. Peck, Appl. Phys. Lett. **43**, 588 (1983).
[3] T. Shewchuk, P. C. Chapin, P. D. Coleman, W. Kopp, R. Fischer, and H. Morkoç, Appl. Phys. Lett. **46**, 508 (1985).
[4] M. Tsuchiya, H. Sakaki, and J. Yashino, Jpn. J. Appl. Phys. **24**, L466 (1985).
[5] T. Tsuchiya and H. Sakaki, Tech. Dig. IEEE Int. Electron Devices Meeting, Dec. 2–4, Washington, DC, 1985, p. 62.
[6] B. Ricco and M. Ya. Azbel, Phys. Rev. B **29**, 1970 (1984).
[7] F. Capasso and R. Kiehl, J. Appl. Phys. **58**, 1366 (1985).
[8] S. Luryi, Appl. Phys. Lett. **47**, 490 (1985).
[9] S. Luryi, Tech. Dig. IEEE Int. Electron Devices Meeting, Dec. 2–4, Washington, DC, 1985, p. 666.
[10] G. E. Derkits (unpublished).
[11] P. D. Coleman, S. Goedeke, T. J. Shewchuck, P. C. Chapin, J. M. Gering, and H. Morkoç, Appl. Phys. Lett. **48**, 422 (1986).
[12] E. A. Rezek, N. Holonyak, Jr., B. A. Vojak, and H. Shichijo, Appl. Phys. Lett. **31**, 703 (1977).