Observation of Intrinsic Bistability in Resonant-Tunneling Structures

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A simple quantum system, the semiconductor-based double-barrier resonant-tunneling structure, exhibits intrinsic bistability which we attribute to the feedback dependence of the energy of the electronic states in the well on the tunneling current density.

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The phenomenon of resonant tunneling of electrons through structures consisting of a quantum well confined by two penetrable barriers provided one of the first observations of two-dimensional (2D) electronic states in semiconductor-based heterostructures.[1] The material quality has been improving steadily and recently workers in the field reported observations of negative differential resistance (NDR) in double-barrier resonant-tunneling structures (DBRTS) with current peak-to-valley ratios as high as 3.5:1 at 300 K[2] and 13:1 at 77 K,[3] and of resonant tunneling of holes.[4] The tunneling is the fastest charge-transport mechanism in semiconductors; DBRTS were shown to oscillate at 18 GHz and to respond to far-infrared radiation with frequencies of up to 2.5 THz.[5]

The original Tsu-Esaki picture of the DBRTS as a Fabry-Perot resonator for electrons was developed further by Ricco and Azbel.[6] In this essentially one-dimensional approach, the resonant enhancement of the transmission coefficient occurs when the incident electron energy coincides with the energy of the bottom of the subband in the well.[7] Recently, however, it has been pointed out by Luryi[8] that the NDR in DBRTS can be explained as due solely to the tunneling of electrons from the three-dimensional states in the emitter to the 2D states in the well since the component of the electron momentum transverse to the direction of tunneling is conserved. Subsequently, the electrons leave the well by tunneling through the collector barrier. Other recent contributions included two self-consistent models which took into account the space-charge regions formed in the biased DBRTS within the Fabry-Perot–resonator[9] and the sequential-tunneling[10] pictures.

In this Letter we report the observation of intrinsic bistability in DBRTS[11] and show that it arises from the feedback of the electrostatic field, produced by the electrons in the well, on the tunneling current.

Our DBRTS were grown by molecular-beam epitaxy on an n^+ ⟨100⟩ GaAs substrate and have a 56-Å GaAs well sandwiched between two 85-Å-thick $Al_{0.40}Ga_{0.60}As$ barriers. The GaAs emitter and collector regions have net donor concentrations $\sim 2\times10^{17}$ cm^{-3}. The devices were defined by AuNiGe Ohmic contacts which served as masks for mesa etching.[3] Figure 1(a) shows the current-voltage (I-V) characteristics of a DBRTS device (area 4.5×10^{-6} cm^2) measured at 4.21 K with and without a capacitor. The equivalent experimental circuit consists of a voltage source, series resistance R, inductance of the connecting wires L, and the DBRTS. The bias applied to the DBRTS is swept at a rate of ~ 0.1 mV/sec and is measured in the pseudo four-terminal technique in order to eliminate the voltage drop IR.[12] The series impedance ωL, however, does not allow us to maintain a constant bias across the DBRTS on a short time scale $\sim \omega^{-1}$ at the NDR region of the I-V curve, and the biasing circuit oscillates.[13] We can, however, maintain V constant on a time scale LC by connecting a capacitor C in parallel to the DBRTS; on the longer time scale the impedance ωL is small enough not to cause oscillations. The "real" I-V curve displays two bistable regions of V, shown in detail in Fig. 1(b). The I-V curve does not change appreciably as the temperature is lowered to 1.6 K. Very similar I-V curves were measured on several devices, with areas as large as 1×10^{-4} cm^2, for both polarities of V.

In Ref. 10 we have considered the formation of the accumulation and depletion layers in the emitter and collector electrodes, respectively, in the biased DBRTS as well as the space charge in the well created by the tunneling electrons [Fig. 1(c)]. The depletion layer reduces the electric field in the barriers and the well, thus increasing the bias required to align E_{BSB} (the energy of the bottom of the subband in the well) and the emitter E_F. The accumulation layer lowers the conduction-band (CB) edge in the emitter close to the barrier, thus lowering E_{BSB} relative to E_F in contrast to the effect in the depletion layer, and also extends the range of energies from which the electrons can tunnel. In the sequential-tunneling picture the tunneling current density, J, at a given bias V can be calculated within the stationary-

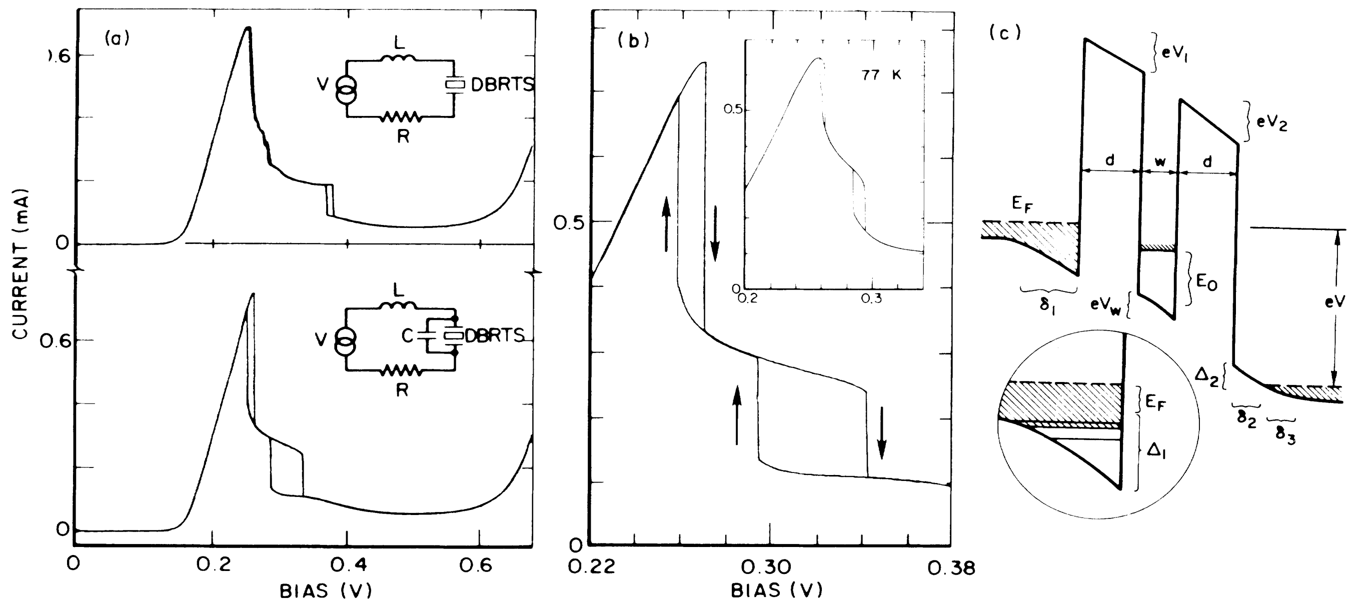

FIG. 1. (a) The I-V characteristics of the DBRTS (area 4.5×10^{-6} cm^2) at 4.21 K measured with and without a 10-nF capacitor in parallel to the device. Equivalent circuits consist of voltage source V, series resistance R (1.6 Ω), and inductance L; the upper circuit oscillates in the bias range $0.25\ \text{V} \lesssim V \lesssim 0.37$ V. I is measured on a 10-Ω resistor (included in R), and V is measured with use of a pseudo four-terminal technique. (b) Same as the lower trace in (a); clearly seen are the two bistable regions (arrows indicate the direction of the voltage sweep, ~0.1 mV/sec). Inset: The I-V curve of the same device at 77 K. (c) The CB energy diagram of a DBRTS under bias. Δ_1 and δ_1 are the parameters of the accumulation layer in the emitter (shown schematically in the inset); Δ_2, δ_2, and δ_3 describe the depletion layer in the collector. The electrostatic potential drops across the emitter barrier, the well, and the collector barrier are, respectively, V_1, V_w, and V_2. The rest of the notation is explained in the text. The hatching shows the electron occupation.

state, free-electron model.[14] At low temperatures,

$$J \simeq e\int_0^\infty T_1 N(E_\parallel)dE_\parallel, \tag{1}$$

where T_1 is the transmission coefficient of the emitter barrier, $E_\parallel = (\hbar^2/2m^*)k_\parallel^2$, $k_\parallel$ is the component of the electron wave vector parallel to the direction of tunneling, and $N(E_\parallel)$ is the supply function. The conservation of $k_\perp$, the transverse component of the wave vector, implies that the tunneling is possible only from the electronic states in the emitter having $E_\parallel = E_F + \Delta_1 - \Delta E$, where $\Delta E \simeq \Delta_1 + e(V_1 + \frac{1}{2}V_w) - E_0$ [see Fig. 1(c)] is the energy separation between the emitter E_F and E_{BSB} (we neglect the inelastic tunneling). For tunneling from 3D states, therefore,

$$N(E_\parallel) = E_\parallel \delta[E_\parallel - (E_F + \Delta_1 - \Delta E)] \times (m^*/2\pi^2\hbar^3)\int_0^{\Delta E} dE_\perp, \tag{2}$$

where $E_\perp = (\hbar^2/2m^*)k_\perp^2$. Substitution of Eq. (2) into Eq. (1) yields[15]

$$J \simeq (em^*/2\pi^2\hbar^3)T_1\Delta E(E_F + \Delta_1 - \Delta E). \tag{3}$$

This equation has to be solved self-consistently, since T_1, ΔE, and Δ_1 all depend on both V and J [cf. Eqs. (4) and (5)].

The origin of the intrinsic bistability in the DBRTS appears to be quite simple and basic. The tunneling electrons are dynamically stored in the well, thus creating a space-charge layer.[10] Once an electron has tunneled into the well, it occupies a resonant state with kinetic energy just above E_0. If we denote the transmission coefficient of the collector barrier as T_2, then the lifetime in the well is $\tau \simeq \hbar/T_2E_0$. Since the number flux of electrons passing through the well in the steady state is $-J/e$, the areal concentration of the electrons in the well is $n_w \simeq \hbar J/eT_2E_0$, and the areal space-charge density in the well is

$$-\Sigma \simeq -\hbar J/T_2E_0. \tag{4}$$

Consequently, the electric field in the collector barrier, V_2/d, is appreciably greater than that in the emitter barrier, V_1/d [see Fig. 1(c)]. From Gauss's law

$$V_1 = V_2 - (4\pi/\varepsilon)d\Sigma \simeq V_2 - (4\pi/\varepsilon)d\hbar J/T_2E_0, \tag{5}$$

where ε is the static dielectric constant of GaAs. The voltage drops across the different regions of the structure must add up to V; therefore, both V_1 and Δ_1 decrease (at a fixed V) as J increases. That is, the separation ΔE depends on J through this electrostatic feedback mechanism. Since J is determined by ΔE [cf. Eq. (3)], two

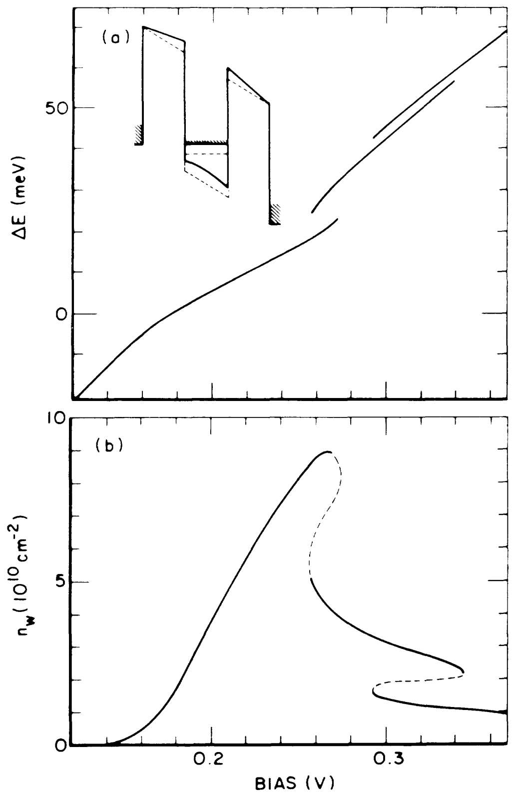

FIG. 2. (a) The energy separation between the bottom of the subband in the well and the emitter E_F, ΔE, as a function of bias V, and (b) the steady-state electron concentration in the well, n_w, vs V, calculated with use of the I-V curve of Fig. 1(b), as described in Ref. 10. The high- and the low-J states of the DBRTS are shown schematically by solid and dashed CB energy diagrams in the inset.

stable states of the DBRTS occur at certain biases [cf. inset in Fig. 2(a)].

We interpret the experimental I-V curve as follows. At low biases, $V \lesssim 160$ mV, the bottom of the subband in the well (E_{BSB}) is higher in energy than the emitter E_F and no resonantly enhanced tunneling is possible. I starts to rise when E_{BSB} is aligned with the emitter E_F,[16] and, as the energy separation between the two, ΔE, increases, I continues to rise [cf. Eq. (3)]. As illustrated schematically in the inset in Fig. 1(c), the electric field in the accumulation layer leads to 2D quantization of the electronic states in the emitter, near the barrier. The higher-lying subbands overlap strongly, however, mostly on account of the energy broadening produced by the ionized donors. These subbands are not resolved and can be treated collectively as 3D states. When V is such that E_{BSB} is just below these 3D states in the emitter, resonantly enhanced tunneling is no longer possible, since $k_\perp$ cannot be conserved in an elastic process, and I drops. The energy separation between the bottoms of the lowest subbands in the accumulation layer is substantial, and

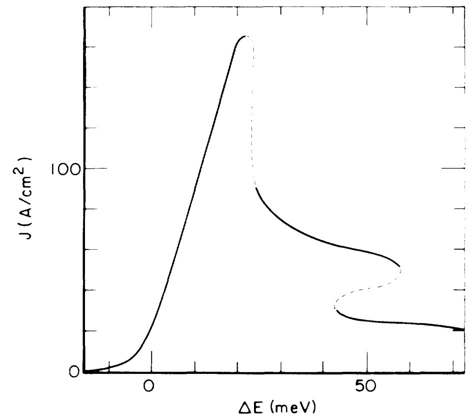

FIG. 3. The experimental current density J vs ΔE [as calculated in Fig. 2(a)]. The dashed portions of the curve are drawn arbitrarily.

one of them is clearly resolved so that there are two bistable regions in the I-V curve in Fig. 1(b).

Figure 2(a) gives the ΔE vs V dependence, which we calculated using the experimental I-V curve, the DBRTS parameters, the material constants, and the approximations described in Ref. 10. Figure 2(b) shows the n_w vs V dependence calculated concurrently, and Fig. 3 shows the experimental J versus calculated ΔE dependence. Although our model calculation is approximate and its accuracy decreases at higher V, we believe that the two-valuedness of J at $\Delta E \simeq 50$ meV is real and is due to the decrease of Δ_1 at lower J (ΔE fixed) and the resulting upward shift of the bottom of the subband in the accumulation layer.

The observation of intrinsic bistability in DBRTS does not, in itself, provide evidence against a modified Fabry-Perot picture of DBRTS. In this approach the bistability can be explained in terms of nonlinear dependence of the effective "resonator length" on the current density, in analogy to the optical bistable devices.[17] The Fabry-Perot approach, however, appears to lead to quantitative discrepancies with the experimental results, which, on the other hand, can be understood thoroughly within the sequential-tunneling approach.

In conclusion, we note that the DBRTS can be considered as a macroscopic quantum system. If the bias voltage is changed adiabatically, the mechanism of bistability does not involve dissipative or incoherent processes (dissipation is present, but only in the collector electrode, after the electrons have tunneled through the collector barrier). An interesting and still unresolved question is how the transition between the low- and the high-current states of the DBRTS occurs.[18]

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[11]We would like to stress the difference between the intrinsic bistability and the bistability of a composite circuit, such as an NDR-displaying device and a series resistance, e.g., Esaki diode or DBRTS [cf. Ref. 2; also M. Tsuchiya and H. Sakaki, Appl. Phys. Lett. **49**, 88 (1986)].

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[15]In the quasiclassical approximation,

$$T_1 \simeq 16\frac{E'}{U}\left(1-\frac{E'}{U}\right)\exp\left(-\frac{4d(2m^*)^{1/2}}{3\hbar eV_1}\times[(U-E')^{3/2}-(U-E'-eV_1)^{3/2}]\right),$$

where $E' \equiv E_F + \Delta_1 - \Delta E$ and U is the AlGaAs/GaAs CB edge discontinuity [cf. I. I. Goldman and V. D. Krivchenkov, *Problems in Quantum Mechanics* (Pergamon, New York, 1961), Chap. 2].

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