Negative transconductance via gating of the quantum well subbands in a resonant tunneling transistor

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Operation of a new resonant tunneling transistor is reported in the AlGaAs/GaAs material system. The device contains an undoped quantum well collector separated from a heavily doped emitter by a thin tunnel barrier. The collector is gated and the gate field controls resonant tunneling characteristics "from behind" via a combination of the generalized Stark effect and the quantum capacitance effect. The common-collector characteristics show negative differential resistance at a fixed gate bias and negative transconductance at a fixed emitter bias. Excellent agreement is found between the measured and calculated shifts of the peaks of the current-voltage characteristics.

The device studied in this work is part of the new but fast growing family of resonant tunneling (RT) transistors. These devices offer an interesting range of potential applications for a variety of logic and analog circuits.[1] After the first proposal of a RT bipolar transistor by Capasso and Kiehl[2] a host of other structures have been proposed and demonstrated.[3–6] One such device was proposed by Bonnefoi *et al.*[3] under the name of Stark effect transistor (SET). The key idea of that transistor was the use of a quantum well collector and the inverted sequence of layers in which the controlling electrode (here referred to as the gate[7]) was placed "behind" the collector layer. It was predicted[3] that the gate field would modify the positions of the collector subbands with respect to the emitter Fermi level and thus modulate the tunneling current. One of us has reexamined the SET structure (Ref. 8, p. 554) revealing its additional possibilities, in particular the existence of negative differential resistance (NDR) at a fixed bias and negative transconductance at a fixed emitter-collector bias. In this letter we report the first demonstration of these effects.

Figure 1 shows the schematics of the device grown by molecular beam epitaxy in the AlGaAs material system. It consists of an undoped quantum well collector separated from an n^+-doped emitter layer by a thin undoped barrier. A thicker undoped barrier on the other side of the well is followed by an n^+-doped gate. The layer thicknesses indicated were measured by transmission electron microscopy; the doping level in the 5000-Å-thick n^+-GaAs layers was nominally 2×10^{18} cm^{-3}. The devices were defined by standard photolithographic techniques and wet etched with a H_3PO_4:H_2O_2:H_2O solution. The evaporated contacts were provided by Ge/Au/Ag/Au for the emitter and the collector and by Ni/Au/Ge/Au for the gate.

The emitter-collector current-voltage (I-V) characteristics of the device are expected to peak at biases which maximize the RT of the emitter electrons into the two-dimensional (2-D) collector subbands. The expected NDR is similar to that in double-barrier RT structures, and results solely from the tunneling from a 3-D into a 2-D system. The presence of two tunnel barriers is not essential (Ref. 8, pp. 544–548). Transistor action in our structure is obtained via the influence of the gate field on the alignment of the 2-D electron gas (2DEG) energy levels relative to the emitter Fermi level. This occurs for two distinct reasons. One, which in accordance with Ref. 3 can be called a generalized Stark effect, is associated with the field penetration into the quantum well.[9] The other effect is the quantum capacitance of a 2DEG,[10] as a result of which the gate field partially penetrates beyond the 2-D metal in the quantum well and induces charges on the emitter electrode.

In Fig. 2 the band diagram of our device is shown in the common-collector configuration with applied biases $V_G>0$ and $V_E<0$ such that the bottom of the conduction band in the emitter is in resonance with the second collector subband; this corresponds to a peak in the current. The RT current can be subsequently quenched by increasing V_G; this leads to negative transconductance. As will become clear later, we can be certain that the observed peaks correspond to the RT into the second subband rather than the first, because at the experimental bias conditions corresponding to the peaks, the ground subband bottom is below the conduction-band edge in the emitter. Moreover, the ground subband wave function in the triangular part of the well is displaced away from the emitter barrier, which further suppresses tunneling into it.

Figure 3 shows our experimental data at 7 K. The expected features present in the I-V were observed up to liquid-nitrogen temperature, not as pronounced because of the in-

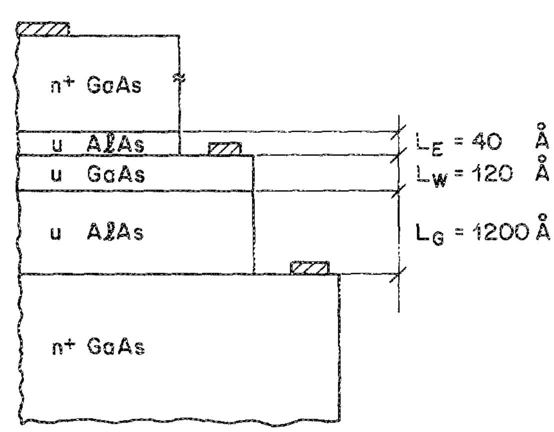

FIG. 1. Schematic cross section of the resonant tunneling transistor.

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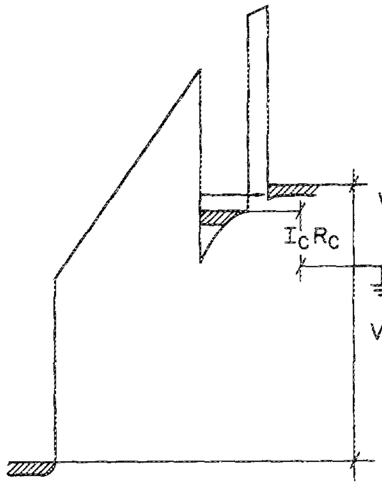

FIG. 2. Band diagram with the collector at reference and the biases $V_G > 0$ and $V_E < 0$ corresponding to peak resonant tunneling of emitter electrons into the second subband of the well.

creased influence of competing transport channels. We see both the NDR in the emitter current and the control of the emitter current by the gate. In particular, if we examine I_E at a fixed V_E we see that we can bring the device into and out of resonance by varying V_G. This control is electrostatic in nature as evidenced by the fact that the gate current is always several orders of magnitude smaller than the emitter current. At the resonance, for instance, I_G varies from ~ 1 pA with $V_G = -3$ V up to ~ 10 nA with $V_G = 2$ V.

In order to understand quantitatively the operation of our device in the range $V_G > 0$, let us first analyze the shift of the I-V peaks with varying positive V_G. As discussed above, to estimate these shifts $(\Delta V_E)_p$ we need to calculate the shift of the second subband relative to $E_{F,E}$. We shall perform this in two steps, first by calculating with first-order perturbation theory the "Stark" shift due to the penetration of the gate field into the well, and then by taking into account the quantum capacitance effect and the corresponding additional shift due to the gate field penetration into the emitter barrier.

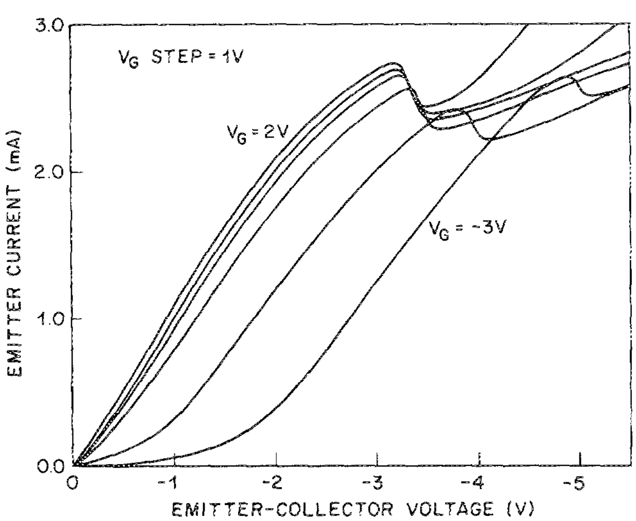

FIG. 3. Common-collector characteristics of the resonant tunneling transistor at various V_G (2,1,0, − 1, − 2, − 3 V). The measurements were performed at 7 K.

Neglecting the quantum capacitance effect, the first-order variation in E_2 in response to a variation in the gate field is given by $\delta E_2 = \langle \psi_2 | e\delta\phi | \psi_2 \rangle$, where $\delta\phi(z)$ is the variation in the electrostatic potential in the well, which can be calculated from the Poisson equation

$$\frac{d^2\delta\phi}{dz^2} = \frac{e\,\delta n}{\epsilon} |\psi_1|^2. \tag{1}$$

Here δn is the variation in surface electron concentration and ϵ is the dielectric constant of the well layer. If we take for the ground subband the variational function of Stern and Howard[11] $|\psi_1|^2 = (b^3/2)z^2 e^{-bz}$, where $b = 3/\langle z \rangle_1$ and

$$\langle z_1 \rangle = (72\epsilon\hbar^2/11 m e^2 n)^{1/3} = 81\ \text{Å} \times (10^{12}/n)^{1/3}, \tag{2}$$

then (1) can be integrated analytically. For the second state, which is in the rectangular part of the energy diagram, we use the second sine solution of the corresponding square well, i.e., $\psi_2 = (2/L_W)^{1/2} \sin(2\pi z/L_W)$. We obtain then

$$\delta E_2 = \frac{6e^2\,\delta n}{\epsilon b^2 L_W}\left(1 - \frac{\alpha^4 + 3\alpha^2 + 6}{6(1+\alpha^2)^3}\right), \tag{3}$$

where $\alpha \equiv 4\pi/bL_W$. In our case of a rather thin well, the second term in the brackets in (3) is small. Defining the gate leverage factor λ as the variation in E_2 per unit variation in the gate voltage, $\lambda \equiv \delta E_2/e\delta V_G$, we obtain the Stark effect contribution to this factor in the form

$$\lambda_S = \frac{2\langle z \rangle_1^2}{3 L_G L_W} \approx \frac{1}{51}, \tag{4}$$

where $\langle z \rangle_1$ was evaluated from (2) with $n \approx 2 \times 10^{12}$ cm^{-2}.

The second contribution to λ results from the gate field penetration into the emitter barrier. We can easily estimate the additional shift from the expression[10] for the quantum-capacitance ideality factor ($\equiv \lambda^{-1}$), which gives

$$\lambda_Q = \frac{C_1}{C_1 + C_2 + C_Q} \approx \frac{1}{58}, \tag{5}$$

where $C_1 \approx \epsilon/L_G$ and $C_2 \approx \epsilon/(L_E + L_W)$ are the gate-collector and emitter-collector geometric capacitances, and C_Q is the quantum capacitance of a GaAs 2DEG, $C_Q = me^2/\pi\hbar^2 \approx 4.5\ \mu$F/cm^2. The total leverage factor $\lambda = \lambda_S + \lambda_Q = 1/27$ is directly measured in the I-V as a shift $(\Delta V_E/\Delta V_G)_p$. The predicted value of λ (≈ 37 mV per 1 V variation in V_G) is in good agreement with the experimentally measured ~ 40 mV per 1 V variation in V_G.

The second question to be considered is why the peaks in the I-V occur at such a high applied bias V_E. We believe this is associated with the series resistance introduced by the exposed part of the collector layer between the ring contact and the emitter mesa (in our devices this separation is $\approx 10\,\mu$m). The Fermi level pinning at the surface depletes the exposed collector channel much like the gate of a field-effect transistor.[12] It is easily shown that, for the whole range of V_G examined, the portion of the collector layer between the mesa and the ring contact is always pinched off by the surface potential (≈ 0.8 V). It will then present a constant resistance R_C characteristic of a space-charge-limited conduction with a constant saturation velocity. The potential drop across this resistance is in series with the internal emitter to collector bias. Referring to Fig. 2, we can write (at resonance)

$$eI_E R_C + (E_2 - E_1) - E_{F,W} = eV_E - E_{F,E}, \quad (6)$$

where $E_{F,E}$ and $E_{F,W} = \pi\hbar^2 n/m$ are the quasi-Fermi levels in the emitter and collector, respectively, and E_1 and E_2 are the bottoms of the first and the second subbands in the quantum well. Taking variation of Eq. (6), using (3) and a similar relation easily derived for δE_1, and substituting the experimental variations of V_E and I_E at resonance, we obtain a constant $R_C \cong 1$ kΩ in a wide range of V_G. This constancy of R_C for the different characteristics indicates that the operation of our structure cannot be understood as resulting from the series combination of the RT emitter-to-collector diode and a parasitic field-effect transistor.[13]

The operation of the device for negative V_G, at least for large magnitudes, is very different because in that limit no charge is induced in the collector layer. The field is then constant across the structure and can be calculated simply as $(V_G - V_E)/(L_G + L_E + L_W)$. In order to re-establish the resonant condition after a variation of V_G, one has to vary V_E by the same amount. This is observed experimentally for V_G varying from -2 to -3 V. For small negative V_G it is difficult to estimate the amount of charge induced in the well, but, qualitatively, a smooth transition to the "dry-collector" regime can be expected. This is experimentally observed for V_G ranging from 0 to -2 V, where steps of 1 V in V_G determine (at resonance) increasing steps in V_E from the 40 mV to the 1 V limits modeled above.

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