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Invited

Resonant-Tunneling Hot Electron Transistors (RHET): Potential and Applications

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Resonant-tunneling hot electron transistors using the transfer of a quasi-monoenergetic hot electron beam generated by a quantum well resonator are described. Results are reviewed and new functionalities are demonstrated, covering the potential and applications of these devices. It is predicted that, with a proper choice of parameters for the quantum-well resonator, RHETs can operate as functional switches and memory elements, with greatly improved performances.

1. Introduction

The resonant-tunneling barrier structure, proposed by Tsu and Esaki in 1973 [1], has been attracting much interest recently due to its intriguing characteristics, which include high-speed charge transport and a pronounced negative differential resistance. In fact, theoretical treatments to understand physics of resonant-tunneling effect were attempted [2]-[4], and experimental evidence [5]-[8] and device application of the resonant-tunneling effects were reported [9][10]. In 1985, the author and others succeeded in demonstrating the first three terminal resonant tunneling device, which was named a RHET, standing for resonant tunneling hot electron transistor [11]. The device uses a resonant tunneling barrier as a hot electron injector, enabling us to make a forward hot electron beam in a quasi-monoenergetic form.

This paper describes the operating principle of the RHET and demonstrates new functionalities covering the potential and application of this device.

2. Operating principle of the RHET

The device discussed in this paper is conceptually similar to the GaAs/AlGaAs hot electron transistor [12][13]. However, there is an important difference in that the emitter-base junction is formed with a quantum well structure and electrons are injected from the emitter to the base by resonant-tunneling. Figure 1 illustrates

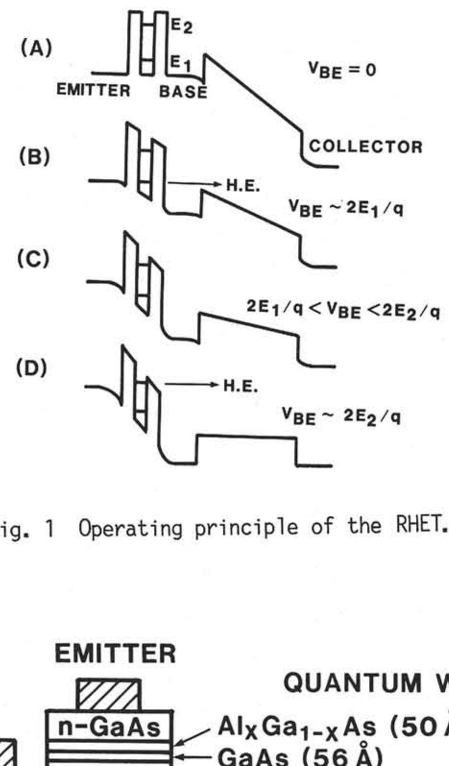

Fig. 1 Operating principle of the RHET.

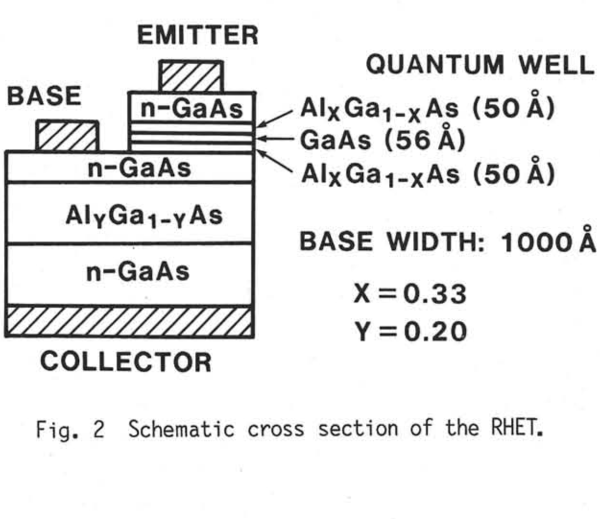

Fig. 2 Schematic cross section of the RHET.

the operating principle of the RHET. E_1 and E_2 indicate the energy of the resonant-states formed in the quantum well. (A) When the base-emitter voltage is zero, there is no electron injection and no collector current. (B) When base-emitter voltages of around $2E_1/q$ are applied, electrons are injected into the base by resonant tunneling through the first resonant state. Electrons injected into the base are ballistically or near-ballistically transferred to the collector through the base, and collector current flows. (C) When the base-emitter bias is further increased, the collector current is reduced, because the resonant tunneling current is reduced. (D) The collector current increases again with the base-emitter voltage at around $2E2/q$, due to resonant tunneling through the second resonant state. The high-speed nature of the HET device is naturally maintained because of the use of resonant-tunneling and hot electron transport.

3. Experiments and discussion

Figure 2 shows a schematic cross section and a band diagram of the RHET, that we fabricated. This device uses n-GaAs layers for emitter, base and collector with carrier concentration of $1 \times 10^{18} cm^{-3}$. The quantum well, consisting of 56-Å GaAs, sandwiched between 50-Å $Al_xGa_{1-x}As$ ($x = 0.33$) barriers, is inserted between the emitter and the base. The thicknesses are 1000 Å for the n^+-GaAs base and 3000 Å for the $Al_yGa_{1-y}As$ ($y = 0.20$) collector barrier. This sophisticated structure was grown by MBE at 580°C.

Figure 3 shows the collector current as a function of the base-emitter voltage in common-emitter configuration with a constant 2 volts applied to the collector. The collector current exhibits a peak with respect to the base voltage. Figure 4 shows the collector current as a function of the base current with a constant collector voltage of 2 V. As the base current increases, collector current increases monotonously, and then increases rapidly once the base current reaches 0.84 mA. The common-emitter current gain measured at this point reached 2000. On the other hand, as the base current decreases, the collector current decreases monotonously, rapidly dropping at a base current of 0.1 mA. Thus, there is a large hysteresis loop in the collector current with respect to the base current. This is due to the presence of a negative resistance region in the base current with respect to the base voltage.

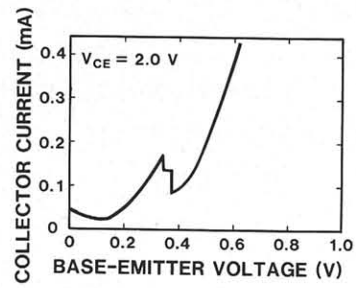

Fig. 3 Collector current versus base-emitter voltage with a constant 2 V on the collector.

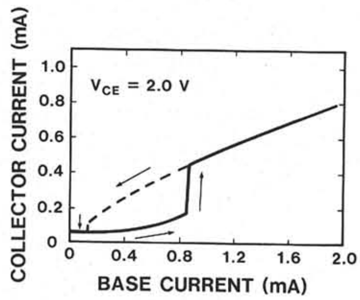

Fig. 4 Collector current versus base-emitter current with a constant 2 V on the collector.

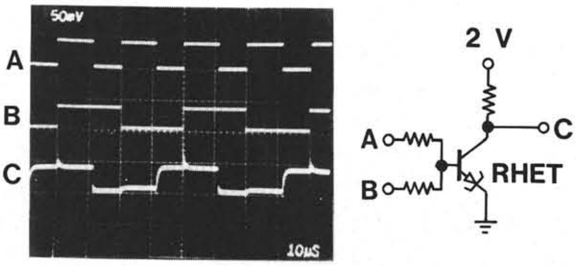

Fig. 5 Exclusive-NOR logic using the RHET and resistors.

4. RHET Applications [11][14]

4-1 Exclusive-NOR logic

Figure 5 shows an oscillograph of two inputs, A and B, and one output, C, observed using a circuit composed of one RHET and three resistors. The resistances are 1 k ohm for the load and 50 ohms for the wired-or resistor. DC offset voltages of 0.35 V are applied to the input A and B. Note that output C is high only for A=B, indicating that the circuit has an Exclusive-NOR logic function. The small logic swing of 50 mV is due to increased valley current and increased peak voltage. The Exclusive-NOR function is widely used to build adders and parity detectors/generators. Considering that several switching FETs or bipolar transistors are required to build Exclusive-OR logic, the RHET shows great promise for use in very high-speed, high-density integrated circuits.

4-2 Bistable multivibrator

Figure 6 shows a test circuit and the waveforms observed in the circuit. A 1.6 k-ohm resistor was connected to the base of the RHET, with a supply voltage of 1 V, to achieve bistable states in the base-emitter circuit loop. Then, positive and negative trigger pulses were input to the 1.6 kohm resistor to interchange the states. A 51 kohm load resistor was connected to the collector with a supply voltage of 4 V.

The upper trace is of the input pulses, and the lower trace of the output waveforms. As shown in the figure, the output voltage goes low with a positive trigger pulse, indicating that the RHET goes to a conductive state. With a negative trigger pulse, the output voltage goes high, indicating that the RHET goes to a poor conductive state. It should be noted here that these two states are maintained even after removal of these pulses. The minimum trigger pulse width to interchange the states was found to be less than our measurement-resolution limit of 1 ns.

Thus, this circuit acts as a bistable multivibrator. This attractive feature should be useful for memory and/or logic applications, since the flip-flop is a fundamental element used in these circuits.

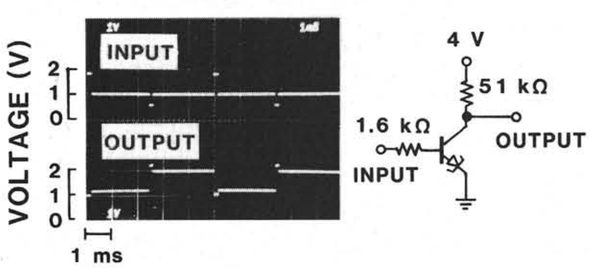

Fig. 6 Flip-flop function using the RHET and resistors.

5. Projected performance of the RHET

Figure 7(a) superposes hot electron energy spectra for various supply voltages, V_{BE}, calculated for a resonant tunneling barrier optimized for logic applications. These were obtained by solving Schrodinger and Poisson equations with a self-consistent method [15]. Figure 7(b) plots the collector current and base current as functions of the base-emitter voltage of the RHET, assuming 200 Å base and 0.15 eV collector barrier. The transfer efficiencies of hot electrons were estimated using the hot electron energy spectra and a Monte Carlo simulation, with taking into account of a quantum mechanical reflection from the collector barrier.

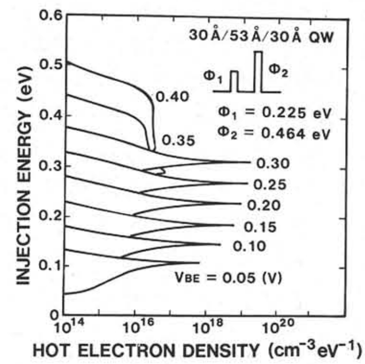

Fig. 7(a) Hot electron spectra simulated for a resonant-tunneling barrier, optimized for logic applications.

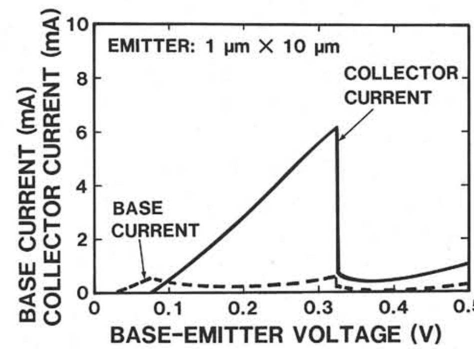

Fig. 7(b) Collector current and base current as functions of base voltage of the RHET, projected for logic applications.

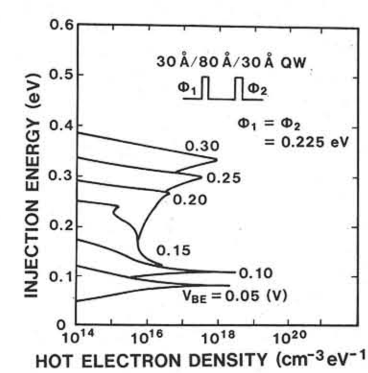

Fig. 8(a) Hot electron spectra simulated for a resonant-tunneling barrier, optimized for flip-flop applications.

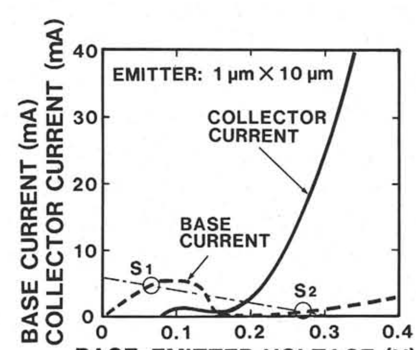

Fig. 8(b) Collector current and base current as functions of base voltage of the RHET, projected for flip-flop applications.

For logic applications, hot electrons, injected through the first resonant-state, surmount the collector barrier, contributing to a collector current peak with respect to the base voltage. The peak to valley ratio should be more than 10. The injection energy is designed to be small to avoid intervally scattering in the base. The RHET exhibits the conduction state when the base voltage is between 0.1 and 0.3 V. Using this device, Exclusive-NOR gate with a logic swing of about 0.4 V, and NOR gate with a logic swing of about 0.2 V are possible.

Figures 8(a) and 8(b) show the theoretical results of a RHET optimized for flip-flop applications. For this device, hot electrons through the first resonant-state bounce back from the collector barrier due to their small injection energy. This results in the base current peak with respect to the base voltage. Hot electrons through the second resonant-state have enough energy to surmount the collector barrier and small enough energy to be ballistically transferred through the base. With a 50 ohm load resistor connected to the base, and a supply voltage of 0.3 V, a RHET can have bistable states, S1 and S2. The collector current in the poor conduction state, S1, is zero in principle, and that in the conductive state, S2, reaches 15 mA. Positive or negative pulses with a pulse height of 0.2 V can change the states. With a 30-ohm load resistor in series with the collector, output voltage swing of about 0.4 V should be obtained with a supply voltage as low as 1 V.

6. Summary

The device structure and operating principle of the RHET were described. The RHET has a variety of applications, including logic and memory circuits. It was emphasized that the RHET has both the switching and memory functions, while conventional transistors have only the switching function. It should be mentioned that the present performance of the RHET, in particular current gain and collector current ratio between conduction state and poor conduction state, is not yet sufficient to allow practical use in these circuits. However, as was shown in this paper, these performances should be improved by optimizing the resonant tunneling barrier structure, and by reducing the base width. Research on the dynamic properties of resonant-tunneling devices should be extensively studied in the next step.

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