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Characterization of Ballistic Transport in a Resonant-Tunneling Hot-Electron Transistor Using Pulsed High Magnetic Fields up to 42 T

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The collector current of an InAlAs/InGaAs resonant-tunneling hot electron transistor studied at 4.2 K in pulsed transverse magnetic fields up to 42.5 T decreases strongly with increasing field. The high field part of the current was found to be due to single barrier tunneling. The energy of hot electrons in the base was determined from the magnetic field dependence. A ratio for ballistic transport through the base was derived by extrapolating the high field dependence of the collector current to zero field.

I. Introduction

Ballistic transport - first directly observed by Heiblum et al.[1)] and Levi et al.[2)] - is essential for the high speed operation of resonant-tunneling hot electron transistors (RHET)[3)]. In RHETs, electrons are injected as hot and monoenergetic electrons from the emitter into the base by resonant tunneling through a quantum well structure between the emitter and base. RHET-integrated circuits, such as a full adder[4)], have already been demonstrated.

II. Experiment

A schematic cross section of the InAlAs/InGaAs RHET and its energy band diagram are shown in Fig. 1. All layers have been grown on an InP substrate using molecular beam epitaxy (MBE) at 480° C. The doping material was Si. The layered structure was then processed into a three-terminal device with self-aligned emitter and base electrodes.[4)]

The base current I_B and the collector current I_C were measured at constant voltages V_{EB} and V_{EC} at common emitter configuration, whilst sweeping the magnetic field. The field direction was oriented perpendicular to the current. The sample was immersed in a liquid helium bath. The pulsed magnetic field up to 42.5 T was provided by discharging a 200 kJ condenser bank into a solenoid coil wound with Cu wire that has been reinforced by Nb-Ti filaments[5)]. The field pulse had a duration of about 10 ms.

III. Results

The I_C-V characteristics show a typical resonant tunneling behavior with negative differential resistance. Its field dependence has been discussed in Ref. 6. Fig. 2 shows the currents measured at

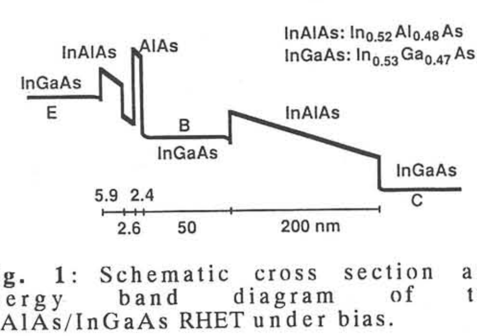

Fig. 1: Schematic cross section and energy band diagram of the InAlAs/InGaAs RHET under bias.

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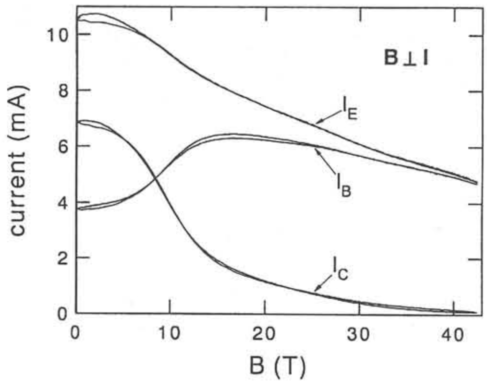

Fig. 2: Emitter (I_E), base (I_B) and collector (I_C) current at 4.2 K as a function of the magnetic field perpendicular to the current direction.

$V_{EB} = 0.9V$. The collector current exhibits a rather Gaussian shape field dependence; at 40 T it has dropped to 2% of its zero field value. The base current exhibits a more complicated field dependence, going through a local maximum at about 15 T.

IV. Discussion

Electrons ballistically injected into the base are forced into cyclotron motion under a perpendicular magnetic field. As electrons are scattered and thermalized in the base, they can not reach the collector. If the magnetic field is increased, the curvature of the trajectory increases until the electrons are forced into skipping orbits. Then, ballistic transport is in principle not any longer possible and the collector current is given entirely by a current I_c^{tunn} due to electrons that lose energy by scattering in the base and that tunnel through the collector barrier. However, at fields lower than about 10 T the collector current is given by I_c^{tunn} and a pure ballistic current I_c^{ball}. Fig. 3 illustrates this model.

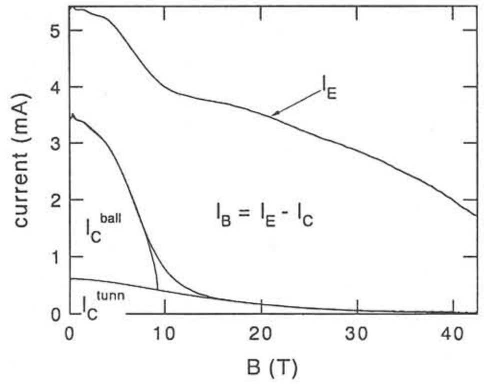

Fig. 3: Illustration of model for collector current (see text) by showing data for (I_E) emitter, (I_B) base, and (I_C) collector current at $V_{EB} = 0.7$ V.

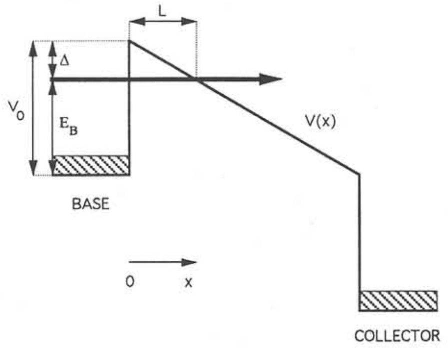

Fig. 4: Tunneling of scattered base electrons through the collector barrier under bias.

Lets assume that the energy distribution of the electrons that reach the left side of the collector barrier and are not thermalized in the base, can be described by an average electron energy $E_B = V_0 - \Delta$. (Fig. 4). The potential of the collector barrier under bias is $V(x) = V_0 - bx$, with $b = V_{BC}/d_{BC}$, where V_{BC} is the bias voltage between base and collector and d_{BC} the collector barrier thickness. The transmission probability can be written as

$$\log T = -2 \int K dx, \qquad (1)$$

where K in the presence of a magnetic field B is given by[7]:

$$K = \sqrt{\frac{2m^*}{\hbar^2} \left(V(x) - E_B + \frac{e^2B^2x^2}{2m^*} \right)}. \qquad (2)$$

where m^* is the effective mass. After insertion in Eq. 1, the collector current at high fields is $I_c^{tunn} =$

$$= I_0 \exp\left\{ -2\sqrt{\frac{2m^*}{\hbar^2}} \int_0^L \sqrt{(aB^2x^2 - bx + \Delta)}\, dx \right\} \qquad (3)$$

with $a = e^2/(2m^*)$. Eq. 3 contains a standard integral which can be solved analytically. Functions of the form Eq. 3 were fit to the part of the collector current measured at fields larger than 15 T, using I_0 and Δ as fitting parameters (Fig. 5). The agreement is very good. Δ is about 15% of V_0 for all bias voltages. The energy

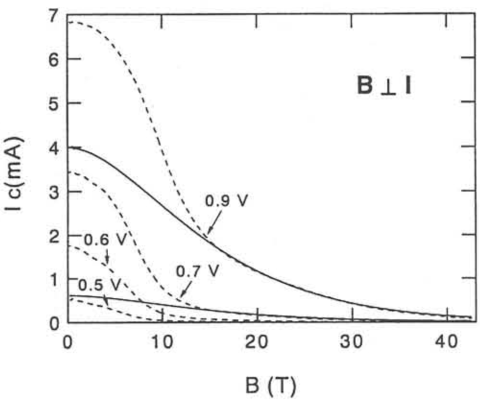

Fig. 5: Collector current I_C as a function of magnetic field perpendicular to the current direction. Data (dashed lines) were averaged over up and down sweep raw data. Functions of the form of Eq. 3 were fitted to the data for B>15T and extrapolated to zero field (plain lines, only shown for V_{EB} =0.7 V and 0.9 V).

$E_B = V_0 - \Delta$, plotted in Fig. 6, is about 0.45 eV (5200 K). E_B is almost independent of the emitter base bias, suggesting that at high fields electrons are scattered in the same way regardless of the emitter base voltage.

Assuming that E_B does not depend on the field (certainly a crude assumption), the magnetic field dependence of I_c^{tunn} can be extrapolated to zero field. This is shown in Fig. 5 for two bias voltages. By comparing the zero field values of I_c^{tunn} and I_C one can define a base transfer ratio r_{ball} for ballistic transport through the base as $r_{ball} = (I_E - I_B - I_c^{tunn})/I_E$. Fig. 6 shows this ratio as a function of emitter-base voltage V_{EB}. At small V_{EB} the transfer ratio is about 0.5, but is smaller for V_{EB} = 0.9 V. This bias dependence can be due to scattering into higher valleys at higher electron energy. Also, part of this is due to the dependence of r_{ball} on the effective collector barrier height. In the common emitter configuration, V_{BC} decreases as V_{EB} increases, increasing the effective barrier height due to a smaller voltage drop in the accumulation region at the base-collector barrier interface. A similar effect has been predicted in the overall transfer ratio of the collector current by Ohnishi et al.[8] Note, that the ratio defined in this paper is different from the ratio for ballistic transport across the collector barrier which exhibits an opposite dependence on the base collector bias due to scattering into the upper valleys[9].

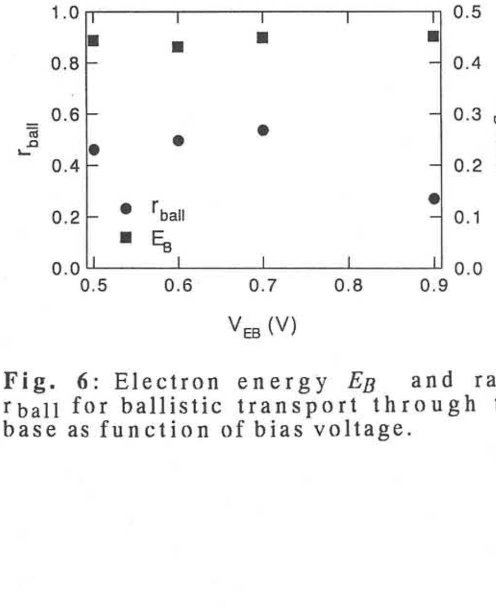

Fig. 6: Electron energy E_B and ratio r_{ball} for ballistic transport through the base as function of bias voltage.

In conclusion, the magnetic field dependence of the collector current at high fields can be solely explained by single barrier tunneling of hot electrons with an average energy of 0.45 eV. An extrapolation to zero field enables us to define a transfer ratio for ballistic transport through the base.

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