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Near-Ballistic Collection in an AlGaAs/GaAs HBT

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Electron transport in the collector of a new type of AlGaAs/GaAs HBT, "Ballistic Collection Transistor(BCT)" which has an i-p^+-n^+ collector doping profile, is described. Microwave characterization indicates that the velocity enhancement appears in a BCT associated with electron transport confined to the Γ-valley. It is also shown that a significant base-widening effect does not occur in BCT's. A modified BCT with electron launching from the base to further elevate the average velocity is presented. A propagation delay time of 3.8 ps/gate evaluated in fabricated ECL ring oscillators demonstrates the potential performance of the BCT structure.

I. Introduction

Since its proposal in the 1970's, utilization of electron velocity overshoot or ballistic transport in GaAs high-speed devices has attracted considerable interest[1),2)]. To date, the ballistic behavior has been intensively studied in the operation of hot electron transistors. In more popular three terminal devices, however, the behavior had not been observed very clearly. Recently, the overshoot effect has been confirmed in the collector of AlGaAs/GaAs HBT's[3),4)], which is more pronounced than that in GaAs FET's[5)].

A reduction in the collector transit time by use of near-ballistic transport is becoming increasingly important. This is because other delays have been shortened comparatively in current HBT's. It may be stated simply that shortening collector width gives less collector transit time. However, the tradeoff relation between collector transit time and collector capacitance is of greater concern in bipolar devices. In a new HBT structure, which has been termed as "Ballistic Collection Transistor (BCT)," collector transit time can be minimized by enhanced electron velocity without increasing the collector capacitance.

In this paper, device performance of BCT's and their application to integrated circuits are discussed.

II. Near-Ballistic Transport in the Collector

In conventional AlGaAs/GaAs HBT's, a relatively small Γ to L valley separation energy of 0.3 eV is a major source of difficulty in fully incorporating the near-ballistic transport. To take full advantage of the near-ballistic transport, electron energy should be controlled so that electrons remain in the Γ-valley. A BCT structure with an i-p^+-n^+ collector doping

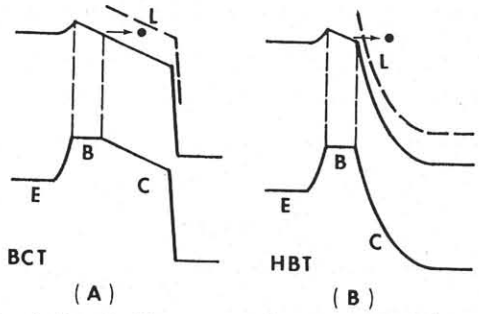

Fig.1 Band diagrams for a BCT (A) and for a conventional HBT (B).

profile shown in Fig.1(A) satisfies the above requirement[6]. A depleted planar doped p^+-layer lifts up the potential profile of the i-layer, leading to electron collection mostly confined to the Γ-valley in a certain collector voltage range. The potential cliff is formed steeply to minimize the collection within the upper valleys. When the potential profile for the conventional n-collector HBT shown in Fig.1(B) is compared to that of BCT, it is clearly found that the overshoot contribution in the n-collector is very little.

At an appropriate i-layer thickness, a near-ballistic state, where effective scattering occurs approximately once, is maintained. It has been shown that near-ballistic travelling distance is extended to about 1500 Å for an electric field of 20 kV/cm, when momentum relaxation time is 230 fs (μ_e = 6000 cm^2/Vs)[6]. Here, an average velocity as high as $5x10^7$ cm/s is expected. These characteristics are desirable for practical devices operated at room temperature. Because of the LO-phonon emission process, significant extension of the near-ballistic range at lower temperatures is limited.

III. Characterization of BCT's

The epitaxial structure of a BCT has been grown by MBE[6]. In a test device, the p^+ planar doped layer, 200 Å thick, is heavily doped with Be at $2x10^{18}$ $/cm^3$. The p^+-layer parameters are very important since the collector bias voltage range for near-ballistic collection is determined by them. The i-layer thickness is 2000 Å and the base layer graded linearly from 0 to 12 % AlAs fraction has an 800 Å thickness doped at $4x10^{19}$ $/cm^3$. Other parameters are similar to those reported previously[7]. A variation in collector depletion width with base/collector voltage is shown in Fig.2. A step-like shape

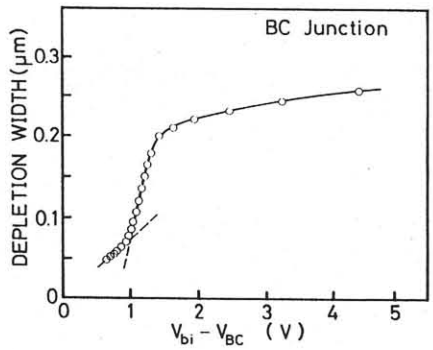

Fig.2 Variation of collector depletion width against the band bending obtained from C-V measurements.

results from a high-low-high doping profile in the base/collector junction. In this case, the potential cliff height is found to be about 1 V.

Behavior in f_T for the BCT with collector voltage V_{CE} is shown in Fig.3(A) and compared to that for a conventional n-collector HBT in Fig.3(B). Emitter and collector dimensions are 2x10 μm^2 and 4x12 μm^2, respectively, for both devices fabricated by the self-aligned process. At a lower collector current density J_C of 1.25 x 10^4 A/cm^2, f_T of the BCT gives its peak at V_{CE} = 1.5 V. At this bias, the potential difference in the i-collector is found to be 0.4 V, which is reasonable since Γ - L separation energy is 0.3 eV. From the peak f_T value the maximum average velocity in the collector is estimated to be 3 to $5x10^7$ cm/s,

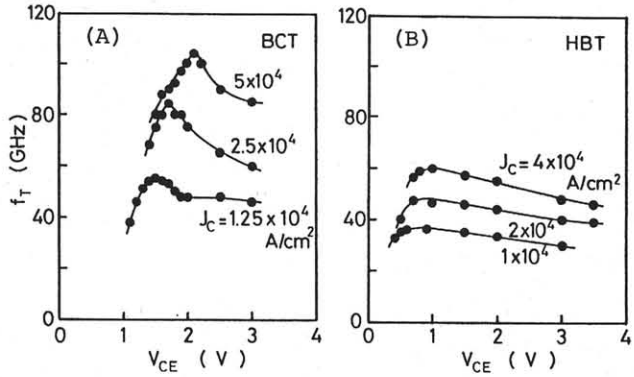

Fig.3 f_T versus V_{CE} characteristics for a BCT (A) and for an HBT (B).

which is several times higher than that in a conventional structure.

A shift in V_{CE}, which produces the f_T peak for higher J_C, is considered to be due to the space charge effect associated with high electron injection. A negative charge accumulation around the potential cliff is expected to cause an increase in cliff height, leading to a positive shift in V_{CE} to obtain the f_T peak. The highest f_T value obtained here is 105 GHz at $J_C = 5\times10^4$ A/cm^2.

IV. On the Base-Widening Effect

Since an i-type collector layer is used in BCT's instead of the n-type, resulting in lower electric field, the space charge effect associated with carrier injection is quite interesting. Base-widening or collector depletion layer shrinking can be evaluated by the following measurement. Power gain cutoff frequency f_{max} is approximated to be

$$f_{max} = (f_T/8\pi R_B C_{BC})^{1/2},$$

where R_B is the base resistance and C_{BC} the base collector capacitance. Measured (f_T/f_{max}^2) is proportional to C_{BC} assuming R_B unchanged. Thus, we can investigate the variation in collector depletion width through (f_T/f_{max}^2). Variations of (f_T/f_{max}^2) for the BCT and the HBT against J_C are illustrated in Fig.4. A rapid increase in C_{BC} is observed for both devices. The increase appears in the lower J_C for the BCT with a critical J_C value of 6×10^4 A/cm^2. In spite of the collector structure mainly being composed of an i-layer, the current handling capability shown here is substantially high. This is due to the lower electron concentration provided by the higher electron velocity. Modification with an n^+-planar doped layer in the collector on the base side, which will be shown in the next section, is expected to suppress base-widening.

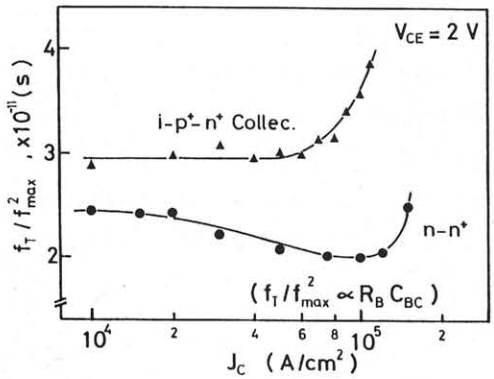

Fig.4 Measured variation of (f_T/f_{max}^2) with collector current density.

V. A Modified BCT Structure with Electron Launching

Launching the electrons from the base is also expected to provide a higher velocity averaged over the collector. High initial velocity is realized in a structure with a planar doped n^+-layer just inside the collector depletion layer(Fig.5(A)). Because of a hole barrier formed at the base collector junction, this structure also allows suppression of the base-widening under high electron injection conditions.

Drift velocity profiles calculated for various initial launching energy E_i under

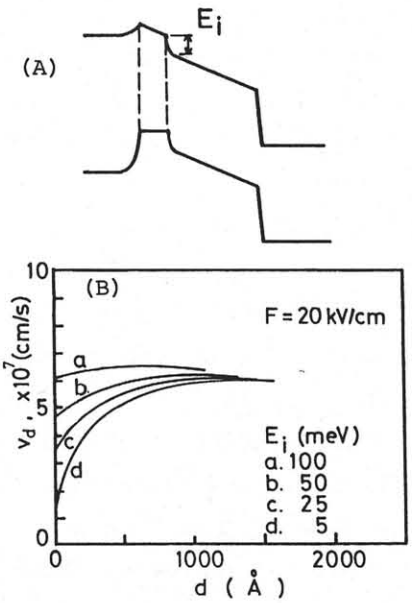

Fig.5 (A) A modified BCT with electron launching and (B) drift velocity profile for launching energy E_i.

electric field intensity of F = 20 kV/cm are illustrated in Fig.5(B), where the momentum relaxation time is taken to be 230 fs. Calculations performed here are based on equations of motion for momentum and energy, taking the band nonparabolicity into account. Drift velocity is found to be considerably elevated by the launching as shown in Fig.5(B). For example, the velocity averaged over the transit distance is enhanced by about 30 % for E_i = 100 meV compared to that without launching.

VI. Integrated Circuit Performance of BCT's

BCT's play significant roles when applied to integrated circuits. In conventional HBT's as shown in Fig.3(B), f_T peaks at a relatively low collector voltage around 1 V. On the other hand, in BCT's, a V_{CE} range producing high f_T can be designed. In addition to the higher f_T value, this flexibility is very important when emitter coupled logic(ECL) gates are constructed. If emitter/base on-voltage is 1.5 V, the highest speed obtained should be around a V_{CE} of 2.5 V for a logic swing level of 0.5 V. Good bias matching capability also has advantages in amplifier circuit use.

ECL ring oscillators(RO's) implemented with BCT's were fabricated to evaluate the propagation delay time t_{pd}. Emitter and collector dimensions used in 31-stage RO's are 2x5 μm^2 and 4x7 μm^2, respectively. A t_{pd} value of 3.8 ps/gate for logic swing of 400 mV has been achieved with power consumption of 62 mW/gate. Collector current density of the device in the circuit is 4.5×10^4 A/cm^2 and f_T for this condition is about 70 GHz. This value is 20 to 30 % higher than that for conventional HBT's. When logic swing was lowered to 250 mV, t_{pd} was as short as 2.6 ps/gate. To our knowledge, these are the fastest switching operations reported to date for semiconductor electron devices.

VII. Summary

A new HBT structure "Ballistic Collection Transistor," in which near-ballistic transport in the collector is achieved, has been discussed. In a fabricated BCT, a velocity enhancement is observed, indicating near-ballistic behavior. The flexibility of designing the f_T versus collector voltage characteristics is of great advantage when BCT's are used as an element in ECL gates. The obtained propagation delay time of 3.8 ps/gate demonstrates the potential performance of the BCT structure.

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