A Possible Near-Ballistic Collection in an AlGaAs/GaAs HBT with a Modified Collector Structure

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***Abstract*—A new AlGaAs/GaAs HBT structure with an n-p_1^+-i-p_2^+-n^+ doping profile that enables electron collection in the Γ valley of GaAs is presented. In fabricated HBT's operating at low collector current density, f_T reaches its peak value when the potential variation in the i collector layer is around 0.4 V, which indicates that the electron transport here is dominated by the Γ valley feature in GaAs. A high f_T value of 105 GHz obtained at a collector current density of 5×10^4 A/cm^2 also demonstrates the significance of the proposed near-ballistic collection structure.**

I. Introduction

It is well known that the high electron velocity that appears in unsteady conditions, usually called velocity overshoot or ballistic transport, should permit improvement in the high-speed performance of electron devices fabricated with GaAs or other high-mobility III-V materials [1], [2]. Up to the present, much interest has been focused on the electron velocity overshoot effect on field-effect transistors.

Recently in the field of HBT research, velocity overshoot has also attracted attention in reducing collector transit time [3], [4]. A reduction in the base transit time is comparatively easy when either a thin base or a graded base with high quasi-field are utilized. Therefore, the design of the collector is thought to be more important in advanced HBT structures. Up to the present, very little experimental work concerning the overshoot in the collector has been reported. A recent study on AlGaAs/GaAs HBT's with a conventional collector has revealed that the overshoot phenomenon exists in the collector depletion layer on the base side and it reduces the collector transit time [4]. This characteristic was obtained in an analysis of current gain cutoff frequency, which changes drastically with collector bias voltage. Although the estimated overshoot range was somewhat larger than that predicted by Monte Carlo simulation results, it clearly had a restricted width.

In GaAs collectors, an energy separation between the Γ and L valley minima of 0.28 eV is basically too narrow compared to the potential difference between the base and neutral collector when transistors are biased in the active region. This is a major source of difficulty in exploiting the effectiveness of the overshoot. Transient electron velocity is definitely influenced by the electric field profile. Under the inverted collector field structure utilizing a depleted p-collector layer, a gradual acceleration makes the overshoot range wider compared to conventional ones, which has been theoretically shown by Mazier *et al.* [3]. However, there is still a high field region in the collector depletion layer, leading to the electron transition from the Γ valley to the upper valleys.

In this paper, a new HBT structure with a modified collector is proposed in which electrons remain in the Γ valley of GaAs over a wide area. A simple analysis of transient electron velocity shows how the velocity enhancement occurs. The dc and high-frequency performance of the fabricated HBT's are also discussed.

II. Ballistic Collection Transistors (BCT's)

Since the lower velocity part degrades the overall collector transit time significantly, it is more important to minimize the electron traveling distance at a low velocity rather than to raise the peak overshoot velocity. For this requirement, electrons should be confined to the Γ valley. Fig. 1 shows an HBT structure with an n-p_1^+-i-p_2^+-n^+ doping profile that we have termed the ballistic collection transistor (BCT). The BCT is characterized by a collector that consists of i and planar doped p_2^+ layers. Here, the electric field or potential drop in the i layer is controlled to produce an appropriate value for electron velocity enhancement by introducing a depleted p_2^+ layer. Since the p_2^+ layer is designed to be very thin resulting in a potential "cliff," the collector transit time is mainly determined by the electrons traveling in the i collector layer. Within a certain collector bias voltage range, the electron collection takes place only in the Γ valley. Even at room temperature, this structure enables a near-ballistic collection as shown below.

III. Transient Electron Velocity in the i Collector Layer

For simplicity, electron transport in the Γ valley is considered through phenomenological equations of motion. The motion of electron is described as

$$dv_d/dt = -qF/m^*(E) - v_d/\tau_m \qquad (1)$$

$$dE/dt = |qv_dF| - (E - E_0)/\tau_e \qquad (2)$$

where F, E, E_0, τ_m, and τ_e denote electric field intensity, average electron energy, average electron energy at equi-

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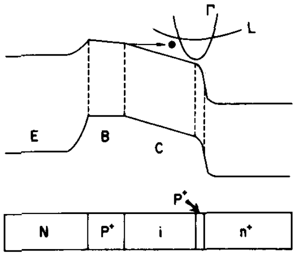

Fig. 1. A proposed HBT structure.

librium, momentum relaxation time, and energy relaxation time, respectively. Effective mass $m^*(E)$ is also expressed by

$$m^*(E) = 0.067m_0(1 - (6\alpha/E_g)E) \qquad (3)$$

where α is a nonparabolicity parameter in GaAs of -0.824 [5]. In the calculation, the effect of energy relaxation on the average energy was neglected, which is ensured since τ_e is much larger than τ_m or the typical traveling time in the collector. At room temperature, an electron mobility of 6000 $\text{cm}^2/\text{V} \cdot \text{s}$ used in the calculation gives τ_m of 230 fs. Fig. 2 shows the velocity profiles against transit distance for various electric fields from 5 to 80 kV/cm. Here, the calculations were performed numerically with an initial velocity of 10^7 cm/s using (1) and (2). Note the broken line on which the transit time is equal to the momentum relaxation time. This situation suggests that near-ballistic transport occurs in a reasonably wide collector thickness. When the electric field is taken to be 20 kV/cm, the velocity is found to be maintained substantially high over 5×10^7 cm/s for a transit distance of 1500 Å.

IV. Device Fabrication

A BCT structure has been grown by MBE on a (100) oriented semi-insulating GaAs substrate. Layer parameters are listed in Table I. An i GaAs collector layer was made relatively thick to be 2000 Å. A planar doped p_2^+ layer, 200 Å thick, was heavily doped to form a steep potential cliff. Both microwave transistors and large-area diodes for characterizing base-collector junctions were fabricated on the same HBT wafer. In order to reduce the emitter resistance, an $In_{0.5}Ga_{0.5}As$ cap layer for nonalloyed ohmic contacts was used [6]. Fabricated microwave devices have emitter and collector dimensions of 2×10 μm^2 and 4×12 μm^2, respectively.

Capacitance-voltage measurements on base-collector junctions were carried out. As shown in Fig. 3, the depletion width W_C as a function of band bending $(V_{bi} - V_{BC})$ has a step-like shape, indicating a high-low-high doping profile. For a $(V_{bi} - V_{BC})$ higher than 1.4 V, W_C is nearly constant. When $(V_{bi} - V_{BC})$ is below 1 V (indicated by the intersection of broken lines), the p-n junction is formed by a planar doped p_2^+ layer and an n^+ collector buffer layer. Here, the potential cliff height produced is found to be about 1 V.

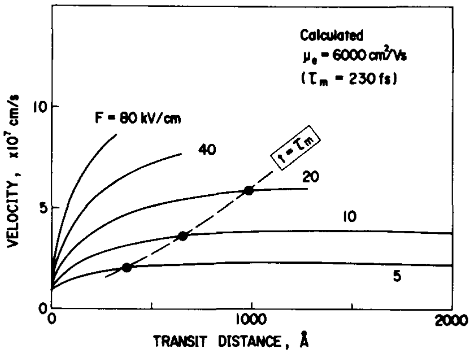

Fig. 2. Calculated electron velocity versus transit distance at various electric field F. On the broken line, a transit time is equal to the momentum relaxation time τ_m of 230 fs.

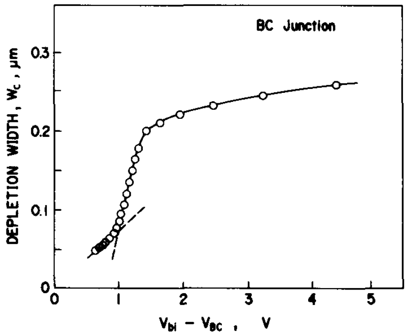

Fig. 3. Variation of the base/collector depletion layer width W_C against band bending $V_{bi} - V_{BC}$, obtained from C–V measurements.

TABLE I
Layer Parameters of Fabricated BCT

Layer		Thickness (Å)	Doping (/cm3)	AlAs or InAs fraction (%)
	n^+-InGaAs	500	$2\text{x}10^{19}$	50
Cap	n^+-InGaAs	500	$2\text{x}10^{19}$	50 - 0
	n^+-GaAs	500	$2\text{x}10^{19}$	0
Emitter	n-AlGaAs	1500	$5\text{x}10^{17}$	30
Base	p^+-AlGaAs	800	$4\text{x}10^{19}$	12 - 0
Collector	i-GaAs	2000		
	p^+-GaAs	200	$2\text{x}10^{18}$	
Buffer	n^+-GaAs	500	$2\text{x}10^{18}$	
	n^+-GaAs	7300	$3\text{x}10^{18}$	
S.I. Substrate				

V. Results and Discussion

Typical collector I–V characteristics are shown in Fig. 4. It can be seen that the I–V curve has two "knees" at collector voltages of $V_{CE} = 0.4$ and 1.2 V. Since the emitter-base voltage at these operations is $V_{BE} = 1.5$ V, a pseudo-base layer spreads over the i collector and a part of the p_2^+ planar doped layers for V_{CE} of up to 1.1 (V_{BC} of over +0.4 V). The larger base transit distance, therefore, decreases current gain. A change in the p_2^+ neutral layer thickness with V_{CE} results in low early voltage in the V_{CE} range from 0.4 to 1.2 V. Carrier recombination in the ex-

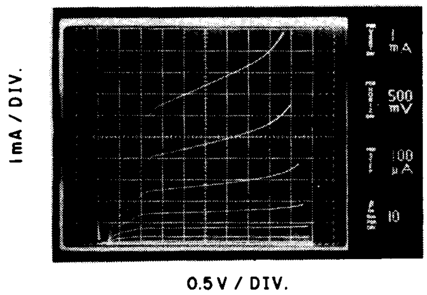

Fig. 4. Common emitter collector I-V characteristics of a BCT. The emitter dimensions are $2 \times 10\ \mu m^2$ and the collector dimensions are $4 \times 12\ \mu m^2$.

ternal pseudo-base is also responsible for the current gain variation. These explain the appearance of the second knee at $V_{CE} = 1.2$ V.

A collector breakdown voltage with a sufficiently high value of 4.5 V is achieved. This suggests that the tunneling current in the high-field cliff region is maintained at a negligibly low level because the cliff height energy is smaller than the bandgap energy.

Fig. 5 shows the current gain cutoff frequency f_T dependencies on V_{CE} for various collector current densities J_C of 1.25 to 5×10^4 A/cm^2. For each curve, f_T has a peak. First, the f_T variation for the lowest J_C of 1.25×10^4 A/cm^2 with the smallest space-charge effect (to be described shortly) is discussed. In this curve, f_T displays a clear "hump" and has a peak value of 55 GHz at V_{CE} of 1.5 V, which corresponds to a V_{BC} of 0 V. Since the potential cliff height is 1 V, as shown in Fig. 3, the amount of potential variation in the i collector layer at this V_{CE} is deduced to be about 0.4 V. This value compares with that expected from the energy separation between Γ- and L-valley minima. At a slightly higher V_{CE}, f_T decreases to 48 GHz ($V_{CE} = 1.9$ V). This f_T variation indicates that the electron collection concentrated in the Γ valley significantly enhances the average velocity as shown below.

The overall delay times, $\tau_{EC} = 1/(2\pi f_T)$, are 2.9 and 3.3 ps for f_T values of 55 and 48 GHz, respectively. Since only the collector voltage is changed here under a negligible variation in the collector depletion layer thickness, the difference in τ_{EC} of 0.4 ps above results from an electron velocity change. When we assume an electron velocity of 1.5×10^7 cm/s for $f_T = 48$ GHz operation (as a nonballistic case), which is typical in conventional collector structures [3], the collector transit time, here, is calculated to be $\tau_C = 0.72$ ps for $W_C = 2150$ A. This leads to a τ_C value of 0.32 ps for $f_T = 55$ GHz operation. Thus, the average electron velocity at the f_T peak is higher by about two times compared to the nonballistic case. Since this value is an averaged one over the collector depletion layer, the maximum velocity in the i collector region is expected to be much higher than this.

When raising the collector current density, f_T increases due to the emitter charging time reduction. The highest f_T value of 105 GH was obtained with a maximum oscillation frequency $f_{\max}$ of 55 GHz at $J_C = 5 \times 10^4$ A/cm^2.

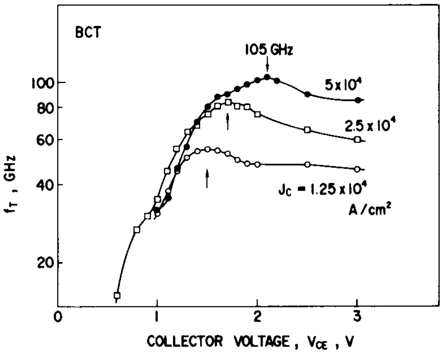

Fig. 5. Dependence of f_T on collector voltage V_{CE}. The arrows indicate positions of f_T peaks. The emitter dimensions are $2 \times 10\ \mu m^2$.

As seen in Fig. 5, the V_{CE} position that produces the f_T peak moves higher with increasing J_C. This behavior is thought to be due to the space-charge effect in the collector associated with electron injection. Since the negative charge accumulation around the i-p_2^+ interface increases the potential cliff height, a higher collector bias is necessary to produce an f_T peak at a higher collector current density.

VI. Summary

In summary, a new AlGaAs/GaAs HBT structure, in which a near-ballistic collection is possible, has been proposed. In this device, which we have termed ballistic collection transistor (BCT), a doping profile with an n-p_1^+-i-p_2^+-n^+ structure is utilized instead of a conventional n-p-n one. To enhance electron velocity, electrons are confined mostly to the Γ valley of the GaAs in the collector region. A p_2^+ planar doped layer is employed to produce a potential cliff at the collector–collector buffer interface and control the potential variation in the i-GaAs collector layer. In an MBE-grown BCT structure, C-V measurement confirmed that a potential cliff was formed, as expected. Measured f_T dependence on collector voltage has shown that the electron collection in the Γ valley contributes to velocity enhancement. The average velocity in the collector estimated at the f_T peak was higher by about two times compared to that for nonballistic transport, indicating direct evidence of near-ballistic electron transport. In high-frequency performance, an f_T value of 105 GHz, which is the highest ever reported in three-terminal devices, has been obtained at a collector current density of 5×10^4 A/cm^2, demonstrating a significant improvement by the proposed HBT structure.

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