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A Monte Carlo Analysis of AlGaAs/GaAs Ballistic Collection Transistors (BCT's) under High Current Injection

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AlGaAs/GaAs Ballistic Collection Transistors (BCT's) have been investigated using self-consistent Monte Carlo simulation. It has been shown that the Kirk effect in BCT's is effectively suppressed by adopting an n$^-$-p$^+$-n$^+$ collector structure instead of i-p$^+$-n$^+$ or p$^-$-p$^+$-n$^+$. For a new BCT with an n$^-$-p$^+$-n$^+$ collector, a successful reduction in collector capacitance charging time $r_E C_{BC}$ leads to improvement in f_T at high collector current densities.

1. Introduction

It is generally recognized that electron transport in non-equilibrium can yield high velocity, referred to as velocity overshoot or ballistic transport. Recently, in the field of HBT, the velocity overshoot effect has attracted attention as the key to a reduction in collector transit time.[1-4]

A significant reduction in collector transit time by taking advantage of the near-ballistic electron transport has been achieved with AlGaAs/GaAs Ballistic Collection Transistors (BCT's).[5] The BCT is characterized by its collector structure which has an i-p$^+$-n$^+$ doping profile (Fig. 1). The depleted planar doped p$^+$ layer makes it possible to relax the electric field in the i-layer, leading to electron collection in the Γ-valley. Electrons can travel at high velocity in a wide area of the i-layer where there is little intervalley scattering.

Electric field intensity is designed to be considerably low in the i-collectors of BCT's. Because of this, the Kirk effect (the base-widening effect) tends to appear even with near-ballistic electron injection. It has been demonstrated that the base-widening is insignificant up to collector current densities of the mid-10^4 A/cm^2 range.[6] In order to achieve further reduction in the total delay time, however, suppression of the Kirk effect is necessary at higher collector current densities (which provide shorter emitter charging time).

In this paper, we investigate the space charge effect in the BCT structures using self-consistent Monte Carlo simulation. It has been shown that the new BCT structure

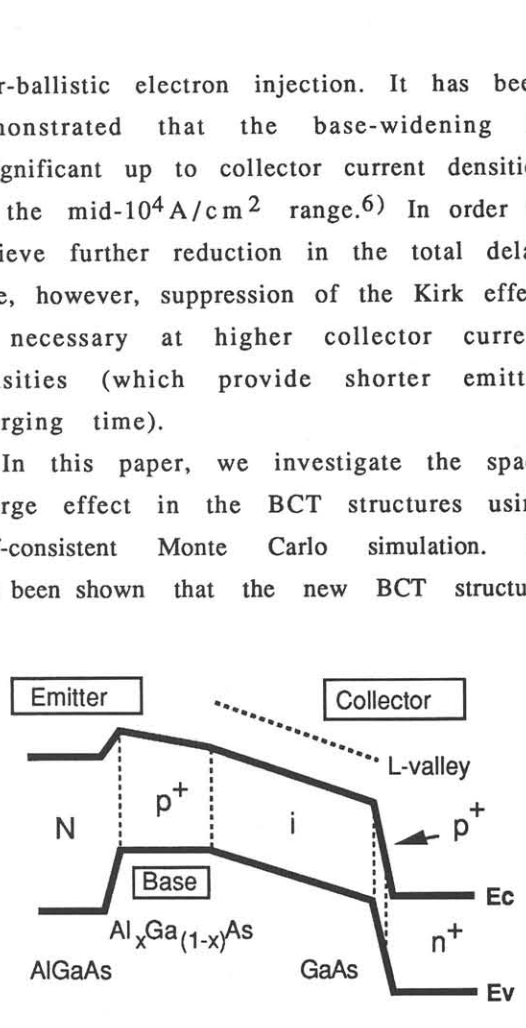

Fig. 1 Band diagram of conventional BCT

with an n^--p^+-n^+ collector effectively suppresses the Kirk effect in high collector current density operations.

2. Device Structures and Model

The new BCT has an n^--p^+-n^+ collector structure instead of i-p^+-n^+. The n^--layer is adopted to compensate for electron space charges with ionized donors. The layer parameters of simulated devices are listed in Table I. The donor concentration in the n^--layer was predetermined to be 1.5×10^{16} cm^{-3} to compensate the charge of near-ballistic electrons around a collector current density of $1 \times 10^5 A/cm^2$. The n-layer in the collector is adopted for convenience in simulation. Another BCT with a p^--p^+-n^+ collector structure has also been analyzed for comparison.

Layer	Material	Doping (cm^{-3})	Thickness (nm)	AlAs Fraction
Emitter	N-AlGaAs	2×10^{17}	125	0.3
	N-AlGaAs	2×10^{17}	25	0.3-0.12
Base	p^+-AlGaAs	1×10^{19}	40	0.12-0
Collector	n^--GaAs or p^--GaAs	1.5×10^{16}	150	
	p^+-GaAs	2×10^{18}	20	
	n^+-GaAs	2×10^{18}	20	
	n-GaAs	3×10^{17}	70	

Table. I Layer parameters of simulated BCT's

A Monte Carlo method (or particle model) is applied to electrons and a drift-diffusion model to holes with Poisson's equation being solved self-consistently. In addition to the usual scattering mechanisms, two scattering processes for electrons are particularly taken into account to accurately simulate the electron transport in the heavily doped p-type base. One is electron scattering with the coupled modes of LO phonon and hole plasmon,[7] and the other is electron-hole scattering taking into account the effect of degeneracy of holes assumed to be distributed by drifted-Maxwellian law.[8-10] The simulation is performed using a three-valley model where Γ to L valley scattering rates are calculated with a coupling constant recently reported.[11] The lattice temperature is assumed to be 300 K.

3. Results and Discussion

It is possible to investigate the Kirk effect by evaluating the collector delay time τ_c defined as

$$\tau_c = \Delta Q_c / \Delta J_c,$$

where ΔQ_c is the variation in the total electron charge per unit area in the collector region and ΔJ_c is the variation in the collector current density, for the slight change of emitter-base bias voltage (ΔV_{BE}) at a fixed V_{CE}.

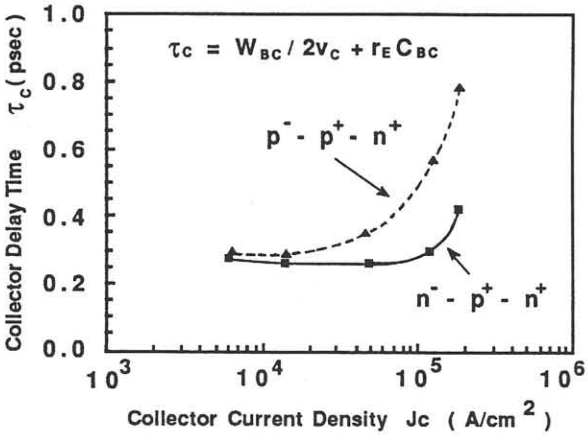

Fig. 2 J_c dependencies of collector delay time τ_c

Calculated J_c dependencies of τ_c for the two collector structures are shown in Fig. 2. The calculations are performed under fixed V_{BC} ($V_{BC} = 0$ which is the nearly optimum condition for the near-ballistic electron transport in the collector) over the whole range of J_c in order to investigate the influence of injected carriers only. (In the delay time calculations, ΔV_{BC}, corresponding to ΔV_{BE}, is taken into account.)

A rapid increase in τ_c appears at J_c in the middle of the $10^4 A/cm^2$ range for the p^--p^+-n^+ collector, while for the n^--p^+-n^+, τ_c is nearly constant at 0.25 ps up to around $J_c = 1 \times 10^5 A/cm^2$. The τ_c for the p^--p^+-n^+ collector is about two times larger compared to the n^--p^+-n^+ at J_c of the above. The velocity profiles, however, are almost the same in the collector depletion region for the two BCT's as shown in Fig. 3.

When V_{BE} is slightly changed at a fixed V_{CE} (this is the regular condition for the small-signal operation of bipolar devices), τ_c in the analytical form can be expressed by

$$\tau_c = W_{BC} / 2\, v_c + r_E\, C_{BC},$$

where W_{BC} is the width of the collector depletion region, v_c the effective electron velocity in the depletion region, r_E the emitter resistance, and C_{BC} the collector capacitance. The first term on the right side of the expression is the so-called collector transit time,$^{12)}$ and the second the collector capacitance charging time which is usually considered a part of the emitter charging time. The second term arises from the variation in the base-collector bias voltage (ΔV_{BC}). By assuming a transit time component only, τ_c of 0.25 ps for the n^--p^+-n^+ collector gives v_c of 4×10^7 cm/s for W_{BC} = 200 nm. This value of effective electron velocity is consistent with the velocity profile. Therefore, the difference in τ_c between the two collector structures is not due to the increase in the transit time $W_{BC}/2v_c$ but to the charging time $r_E C_{BC}$.

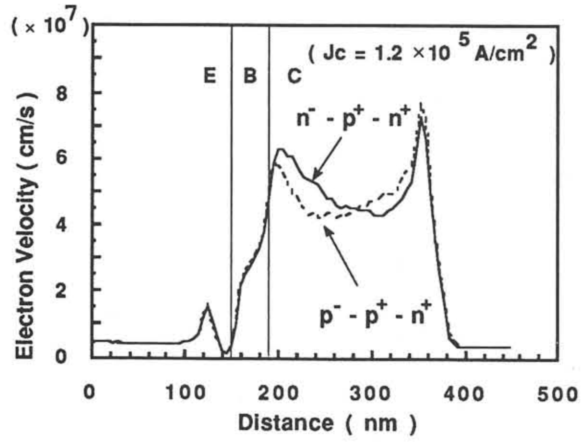

Fig. 3 Electron velocity profiles in the two types of BCT's

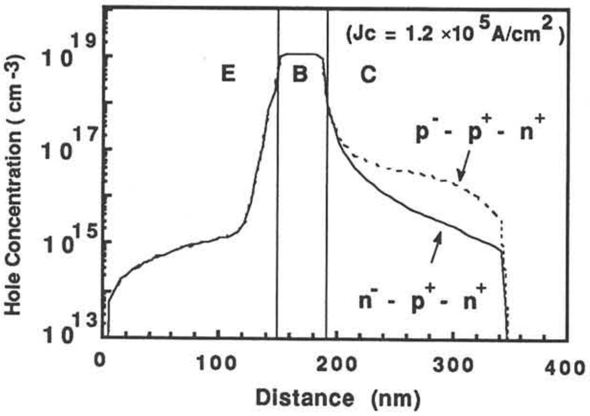

Fig. 4 Hole concentration profiles in the two types of BCT's

The increase in the charging time component for the p^--p^+-n^+ collector is ascribed to the large number of holes injected from the base into the collector (Fig. 4). The hole concentration reaching the 10^{16} cm^{-3} range in the p^--p^+-n^+ collector is responsible for the substantial shrinkage of the collector depletion region. The injection of holes results from a band-bending induced

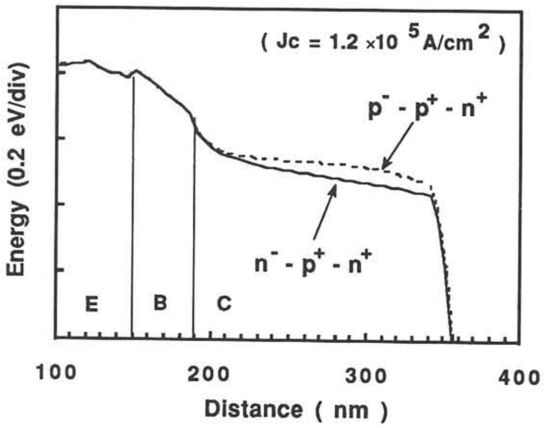

Fig. 5 Conduction band edge profiles for the two types of BCT's

by the negative space charge which is produced by near-ballistic electrons and ionized acceptors (Fig. 5). On the contrary, the band-bending is effectively compensated by ionized donors for the n^{-}-p^{+}-n^{+} structure.

Consequently, by adopting the n^{-}-p^{+}-n^{+} doping profile instead of i-p^{+}-n^{+} or p^{-}-p^{+}-n^{+} profiles, the Kirk effect is successfully suppressed at high collector current densities.

Dependencies of current gain cutoff frequencies f_T on J_c are shown in Fig. 6. Improvement in f_T up to as high as 180 GHz is predicted with the n^{-}-p^{+}-n^{+} collector structure. The suppression of the Kirk effect leads to an improvement in f_T at high collector densities. The delay times in each layer are $\tau_E = 0.32$ ps, $\tau_B = 0.26$ ps and $\tau_C = 0.29$ ps at the f_T peak for the BCT with the n^{-}-p^{+}-n^{+} collector.

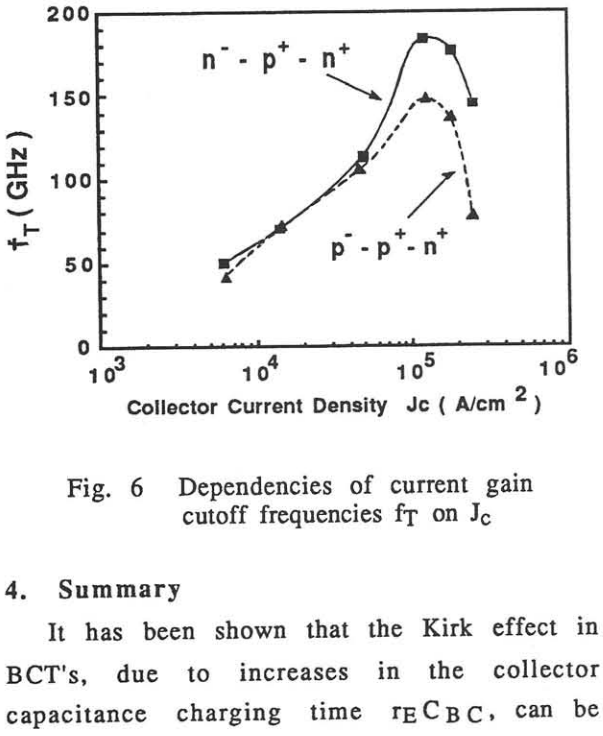

Fig. 6 Dependencies of current gain cutoff frequencies f_T on J_c

4. Summary

It has been shown that the Kirk effect in BCT's, due to increases in the collector capacitance charging time $r_E C_{BC}$, can be effectively suppressed by adopting an n^{-}-p^{+}-n^{+} collector structure instead of i-p^{+}-n^{+} or p^{-}-p^{+}-n^{+}. The n^{-}-layer is adopted to compensate for negative space charges of near-ballistic electrons which cause band-bending in high collector current density operations. The successful suppression of the Kirk effect leads to improvement in f_T under high current injection.

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