Improved InGaP/GaAs HBTs AC Performance and Linearity with Collector Design

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Abstract **— The additional thin high-doping layer within the collector on InGaP/GaAs HBT has been designed and fabricated to improve threshold current of Kirk effect, cutoff frequency, and power distortion while keeping high breakdown voltage. The proposal structure effectively relieves Kirk effect and results in higher current drive and cut-off frequency. From the extracted C_{BC} with V_{CB}, HBT with non-uniform doping collectors demonstrate less base-collector capacitance variation than that in baseline HBT due to the depletion region limited by a thin high-doping layer. The experimental results on third-order intermodulation demonstrate the significant improvement on OIP3 by as large as 6 dB. This proposed InGaP/GaAs HBT with non-uniform collector doping is well suitable to replace current InGaP/GaAs HBT for power amplifier applications due to its significantly improved linearity and current/frequency capability with negligible impact on dc characteristics and fabrication.**

Index Terms **— InGaP, GaAs, HBT, linearity, collector, Kirk effect.**

I. INTRODUCTION

InGaP/GaAs HBTs have been applied to power amplifiers for wireless communication extensively. The advantages of HBTs include high current drive, operating frequency and power linearity [1]. High linearity in power devices is required especially in modern wireless communication. Therefore, the third-order intermodulation (IM3) and adjacent channel power ratio (ACPR) were specified for the device linearity performances [2]-[4].

Power amplifiers usually designed to deliver high output power at operating frequency with cost consideration. However, the current drive and operating frequency of the HBTs were limited by the maximum current from the Kirk effect. The limitation on operational current is well explained by the threshold current (J_{Kirk}) of Kirk effect [5] [6]. The following equation approximately describes the relationship between collector doping/thickness and threshold current,

$$J_{Kirk} = v_s \left\{ qN_C + \frac{2\varepsilon V_{cb} + V_{bi}}{W_C^{2}} \right\}$$

Where the N_c and W_c are the collector doping and thickness, V_{cb} and V_{bi} are the applied bias and built-in potential of the base-collector (BC) junction. The collector doping, thickness and the electron saturation velocity are main factors on the threshold current of Kirk effect. As the thickness of the collector decreases and doping increases, J_{kirk} increases with devices operating. This is the effective way to increase current drive and power capability. In addition, the high electric field at the BC junction results in electrons traveling with saturation velocity in collector region. Papers have been published on improvement of f_T by epi-layer design to adjust BC junction E-field. In this paper, an additional thin high-doping layer is inserted in collector, which is similar to n/n+ collector structure to improve both J_{kirk} and f_T. However, the breakdown voltage in the proposed structure remains without significant sacrifice and resulting improved Johnson figure of merit.

In addition, there are two major distortion components in HBTs: transconductance (gm) and base-collector capacitance (C_{BC}) [7]. The transconductance has strong nonlinearity when the devices just turn on. In the higher current density the transconductance becomes less nonlinear. The variation of C_{BC} is pronounced due to a large-signal swing at high frequency operation, which causes the third-order intermodulation (IM3) and low APCR. The proposed structure with non-uniform collector doping has been proved to reduce C_{BC} variation and results improvement on linearity.

Therefore, the non-uniform collector doping design proposed in this paper can relieve Kirk effect (thus increase the maximum collector current and cutoff frequency) and increase power linearity while keeping high breakdown voltage and no impact on process [8][9]. The non-uniform collector design is to employ a thin high-doping layer inside the collector. To our knowledge, these are the first InGaP/GaAs HBTs designed and fabricated with non-uniform collector doping profile to discuss on threshold current of Kirk effect, cutoff frequency, power distortion, and breakdown voltage.

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Tab. 1 The collector structures of baseline, B4 and B5.

	baseline		B4		B5	
	Thickness (Å)	Doping (cm^{-3})	Thickness (Å)	doping (cm^{-3})	Thickness (Å)	doping (cm^{-3})
Collector	7000	1×10^{16}	4000	1×10^{16}	5000	1×10^{16}
			200	$\mathbf{5 \times 10^{17}}$	**200**	$\mathbf{5 \times 10^{17}}$
			2800	1×10^{16}	1800	1×10^{16}

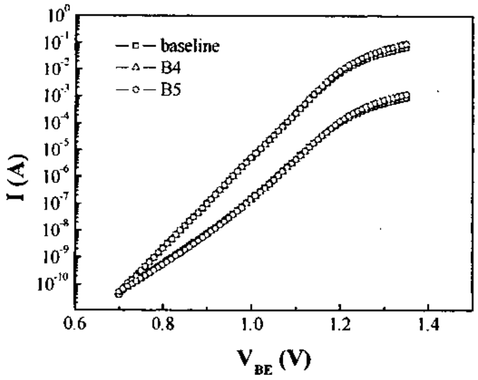

Fig. 1 Measured Gummel plots for structure baseline, B4, and B5, respectively. (emitter size of 120 x 120 μm^2)

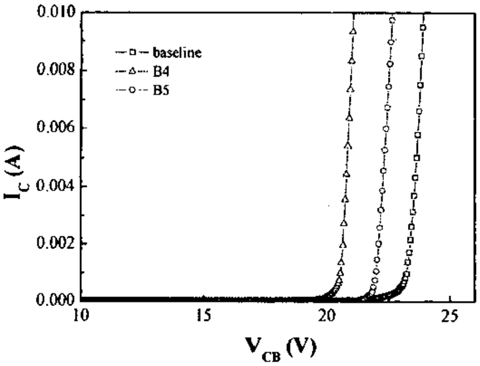

Fig. 2 Measured base collector junction breakdown voltage (BV_{CBO})

II. DEVICE PERFORMACE ANALYZE

The epitaxial structures were grown by metalorganic chemical vapor deposition (MOCVD) on a 6-inch semi-insulating GaAs substrate. Silicon and carbon were used as n- and p-type dopants, respectively. The collector epitaxial structures of InGaP/GaAs HBTs are shown in Table 1 while emitter and base being 600 Å of 4×10^{17} cm^{-3} and 800 Å of 4×10^{19} cm^{-3}, respectively. The baseline structure of collector was uniform doping of 1×10^{16} cm^{-3} and thickness of 7000 Å, which was dedicated to be reference (baseline). A thin high-doping layer inside the 7000 Å collector was employed at non-uniform collector design. Two different structures of B4 and B5 represent the modified InGaP/GaAs HBTs with the identical epi-layers to the baseline HBT except the additional thin high-doping layer within the collector. An additional thin high-doping layer of 5×10^{17} cm^{-3} /200 Å is inserted 4000 Å (5000 Å) from the base-collector junction for structure B4 (B5).

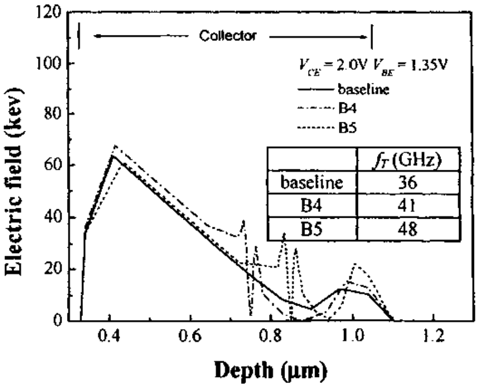

Fig. 3 (a) The simulated electric field versus depth for structure baseline, B4 and B5, respectively. (V_{CE}=2.0 V, V_{BE}=1.35 V)

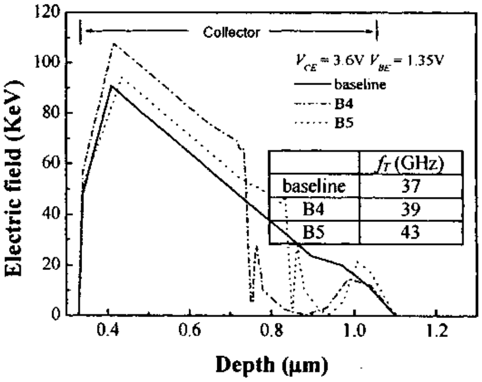

Fig. 3 (b) The simulated electric field versus depth for structure baseline, B4 and B5, respectively. (V_{CE}=3.6 V, V_{BE}=1.35 V)

As show in Fig. 1, the measured Gummel plots (V_{BC} = 0V) for all three devices (baseline, B4, and B5) demonstrate the similar dc performance. The measured current gains at

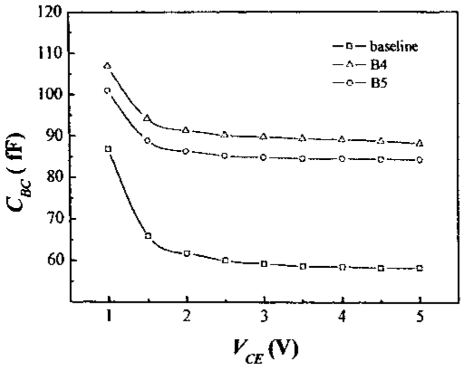

Fig. 4 Extracted C_{BC} with difference collector voltage at collector current of 10mA. (Emitter size is 4x 12x 2 μm^2)

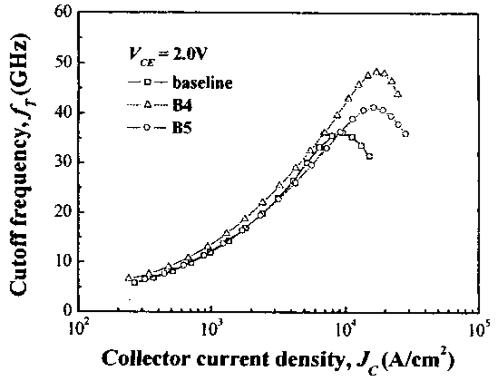

Fig. 5 (a) Dependence of cutoff frequency on collector current density (V_{CE} = 2.0V)

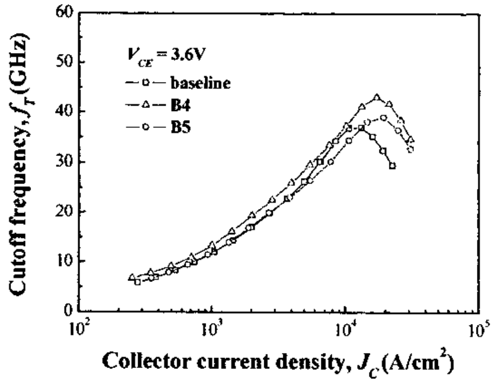

Fig. 5 (b) Dependence of cutoff frequency on collector current density (V_{CE} = 3.6V)

V_{BE} = 1.37 V (J_C of 0.7 kA/cm2) for all three devices (baseline, B4, and B5) are 82, 80, and 81, respectively. The similarity between baseline and B4/B5 structures is expected due to the identical emitter and base structures. However, the breakdown voltage (as measured in Fig. 2) is slightly degraded due to the additional thin high-doping layer within the collector. Measured BV_{CBO} (defined at I_C of 1 mA) for structure baseline, B4, and B5 are 23.5 V, 21 V, and 22.5 V, respectively. The electric filed at the base-collector junction will increase (as simulated in Fig. 3) if an additional thin high-doping layer had added in the collector due to the limited depletion thickness. Since the addition layer is close to the sub-collector and the maximum electric field being located at base-collector junction, the measured breakdown voltages demonstrated the negligible degradation in BV_{CBO}. If the additional layer moved closer to the base-collector junction, the lower breakdown voltage is expected and the less variation of C_{BC} with V_{CB} is observed (Fig. 4). Fig. 4 shows the base-collector junction capacitance extracted from measured *S*-parameters using T-model under different bias (V_{CE}) at the same I_C of 10 mA. From the extracted C_{BC} with V_{CE}, structure B4 and B5 demonstrate the less base-collector capacitance variation than that in baseline HBT due to the depletion region limited by a thin high-doping layer. The depletion region will first reach the thin high-doping layer in structure B4 and B5 with increasing V_{CB}, and result less C_{BC} variation. This observation is limited at observed V_{BC} range (< 5 V). Moreover, the C_{BC} of structure B4 and B5 will begin to drop at V_{CB} larger than 11 and 15 V due to the punch through the thin high-doping layer and reach subcollector. This C_{BC} drop corresponds to the position of the thin high-doping layer in the collector. Eventually, both structure B4 and B5 demonstrate the same C_{BC} as baseline under high reverse base-collector bias. However, the observation in Fig. 4 for structure B4 and B5 are good for bias of 3.6 V power amplifier applications.

The electric fields at the base-collector junction as simulated in Fig. 3 demonstrate additional thin high-doping layers limit the high electric field within the 4000 Å (5000 Å) from the base-collector junction for structure B4 (B5), where electrons travel with saturation velocity. However, electron gains speed after leaving 4000 Å (5000 Å) from the base-collector junction for structure B4 (B5). For the same V_{CE} and I_C bias condition, structure B4 has best maximum f_T (Fig. 5) due to its collector design, which has thin high-doping layer close to BC junction. The measured f_T biased at 2V for structure baseline, B4 and B5 are 36, 41 and 48 GHz, respectively. In contrast, although B5 has similar collector design, but due to its

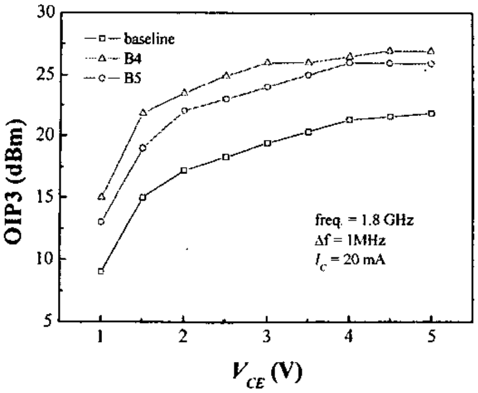

Fig. 6 Measured OIP3 for structure baseline, B4 and B5.

thin high-doping layer located close to C-Sub junction, which results less effect on improvement of f_T from the less region for lower E-field. However, both B4 and B5 show higher f_T at higher I_C due to the similar reason observed in n/n+ collector design. The higher current drive capability and ft can be explained by Kirk effect with factors of doping and the electron velocity for structure B4 and B5 compared to the baseline HBT.

Finally, the two-tone measurements (1 MHz offset) were performed on all HBTs (emitter size of 4 x 12 x 10 μm^2) at 1.8 GHz with different V_{CE} at I_C of 20 mA, showed as Fig. 6. The structures B4 demonstrated the best linearity (OIP3) than structure baseline and B5 due to the location of thin high-doping layer. The extracted output intermoduction intercept point (OIP3) biased at 2V for structure baseline, B4 and B5 are 17 dBm, 23 dBm, and 22 dBm, respectively. For structure B4, the experimental result on third-order intermodulation demonstrates the significant improvement on OIP3 of 6 dB. This improvement is believed to owing to the reduction the dependence of base-collector capacitor (C_{BC}) on base-collector junction voltage (V_{BC}).

III. CONCLUSION

The additional thin high-doping layer within the collector on HBT B4 and B5 show no obvious effects in dc characteristics except the negligible reduction in breakdown voltage. This collector design can improve current drive capability; cut-off frequency and inetrmodulation distortion while HBT is being used for power amplifier. The experimental results on third-order intermodulation demonstrate the significant improvement on OIP3 by as large as 6 dB. This proposed InGaP/GaAs HBT with non-uniform collector doping is well suitable to replace current InGaP/GaAs HBT for power amplifier applications due to its significantly improved linearity and current/frequency capability with negligible impact on dc characteristics and fabrication.

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