DESIGN STUDY OF LINEARIZED AlGaAs/GaAs HBTs USING VOLTERRA SERIES

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ABSTRACT

The intermodulation (IM) mechanism of HBT has been studied theoretically and experimentally. Volterra Series analysis with an analytical nonlinear HBT model shows that IP3 can be greatly enhanced by using a punch-through collector structure. It is also found that the high linearity of HBT stems mainly from the almost exact cancellation between base-emitter and base-collector nonlinear current components. The fabricated HBT with a punch through collector has the IP3 of 31 dBm at a dc power consumption of 150 mW, which is 3 dB higher than those of HBTs with normal collector.

INTRODUCTION

The power amplifier of digital communication systems must be very linear, producing low harmonic distortions as well as high output power and high efficiency. AlGaAs/ GaAs HBTs are known to exhibit low distortions. An ultra-low dc power HBT LNA was reported to have the third order intermodulation intercept point (IP3) level of 22 dBm at 2 GHz with 20 mW dc power consumption[1]. In spite of the good experimental results, the mechanism responsible for the good linear behavior of AlGaAs/GaAs HBTs has not been clearly understood yet [2-4]. Furthermore, all the reported works used the experimentally determined HBT models and one cannot get a design guide-line for the optimized linear HBT structure.

To understand the IM characteristics of HBT and find the optimized linear HBT structure, we have developed an analytical nonlinear HBT equivalent circuit model and a computer program calculating IP3 based on Volterra Series analysis.

NONLINEAR HBT EQUIVALENT CIRCUIT MODEL

Fig. 1 shows the nonlinear equivalent circuit used for the analysis. In the figure, R_E, R_B, R_C, and r_0 are linear components calculated from HBTs structure while I_e, I_c, C_{BE}, and C_{BC} are nonlinear sources changing with applied bias. The four nonlinear parameters are modeled as functions of device structure. The input and output networks are simultaneously conjugate-matched. The IP3 of HBT with 3 μm × 20 μm size emitter was simulated at 10 GHz as a function of epi-layer doping levels and thicknesses for various bias conditions.

DESIGN OF THE LINEARIZED HBTs

Fig. 2 shows IP3 variation depending on the collector doping and thickness at I_c =24 mA and

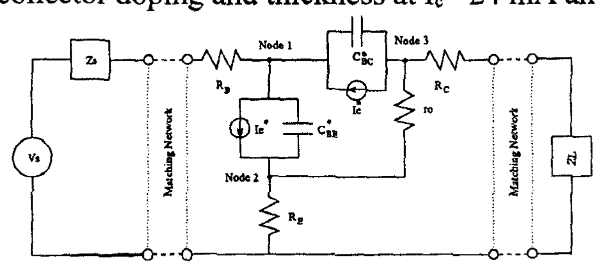

Fig. 1. Nonlinear HBT equivalent circuit model with matching networks (Nonlinear components are marked by *)

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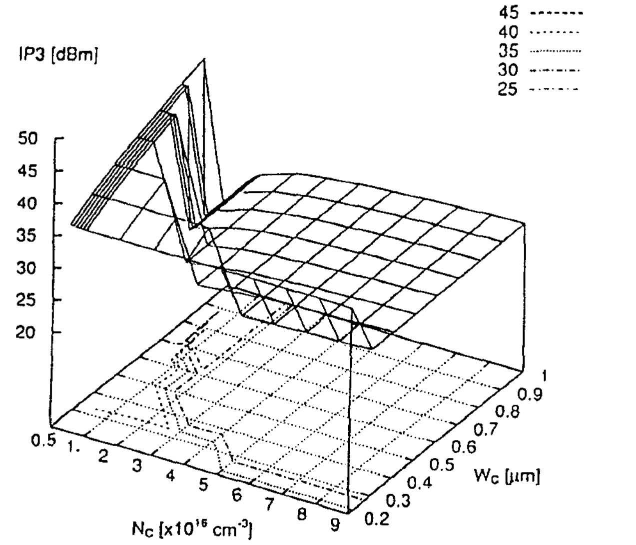

Fig. 2. IP3 variation as a function of collector parameters (N_E = 2 × 10^{17} cm^{-3}, P_B = 2 × 10^{19} cm^{-3}, W_E = 0.2 µm, W_B = 0.1 µm, I_C = 24 mA, and V_{CE} = 3 V.)

V_{CE} = 3 V. IP3 is very high for an HBT with the depleted collector (C_{BC} = constant) but is suddenly decreased by about 15 dBm crossing the punch-through line. Fig. 3 shows IP3 dependency on the base thickness and doping at the same bias condition. IP3 depends weakly on the base thickness, but increases a little as the base doping decreases. IP3 is not dependent on emitter structure. In usual base doping and thickness range, IP3 of the device is about 25 dBm.

CANCELLATION MECHANISM OF HBT NONLINEAR COMPONENTS

To see the cancellation effects of nonlinear components, we have chosen a typical power HBT structure with $N_E = 2 \times 10^{17}$ cm^{-3}, $P_B = 2 \times 10^{19}$ cm^{-3}, $N_C = 2 \times 10^{16}$ cm^{-3}, W_E = 0.2 µm, W_B = 0.1 µm, and W_C = 1.0 µm. Fig. 4 shows the IP3 performance of the HBT at various bias points. If one of the third order nonlinear currents generated by I_e or I_c source is eliminated, IP3 level decreases appreciably (See Figs. 5 and 6).

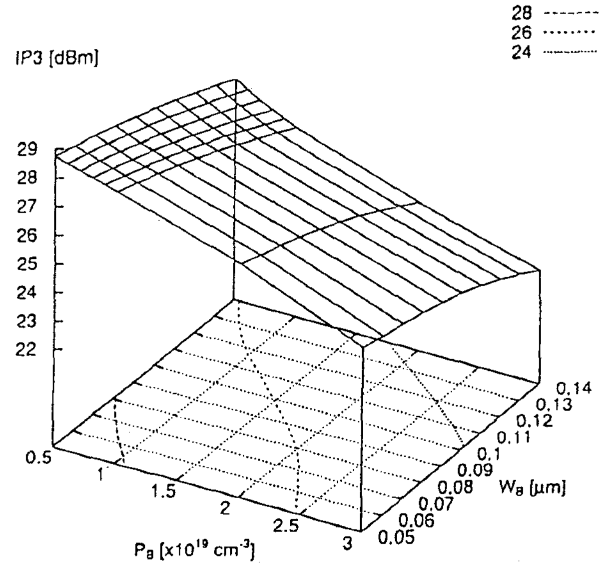

Fig. 3. IP3 variation as a function of base parameters (N_E = 2 × 10^{17} cm^{-3}, N_C = 2 × 10^{16} cm^{-3}, W_E = 0.2 µm, W_C = 1.0 µm, I_c = 24 mA, and V_{CE} = 3 V.)

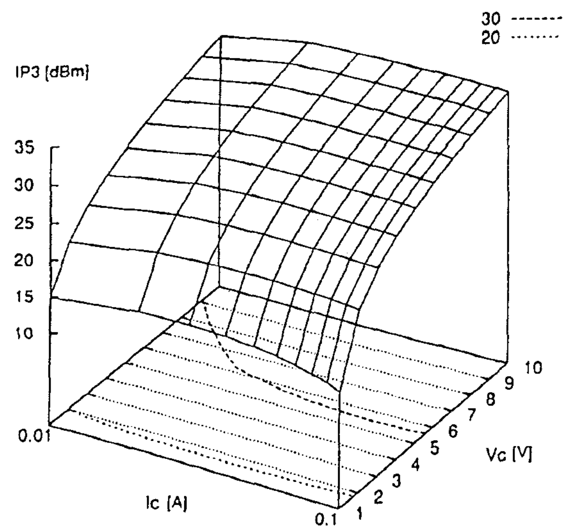

Fig. 4. IP3 level of HBT with all nonlinear elements included. (N_E = 2 × 10^{17} cm^{-3}, P_B = 2 × 10^{19} cm^{-3}, N_C = 2 × 10^{16} cm^{-3} W_E = 0.2 µm, W_B = 0.1 µm, W_C = 1.0 µm)

Fig. 7 shows IP3 performance when both I_e and I_c are linearized. Note that IP3 performance is quite similar to the result of HBT with all nonlinear sources(See Fig. 4). These facts clearly indicate that output IM current components generated by I_e and I_c.

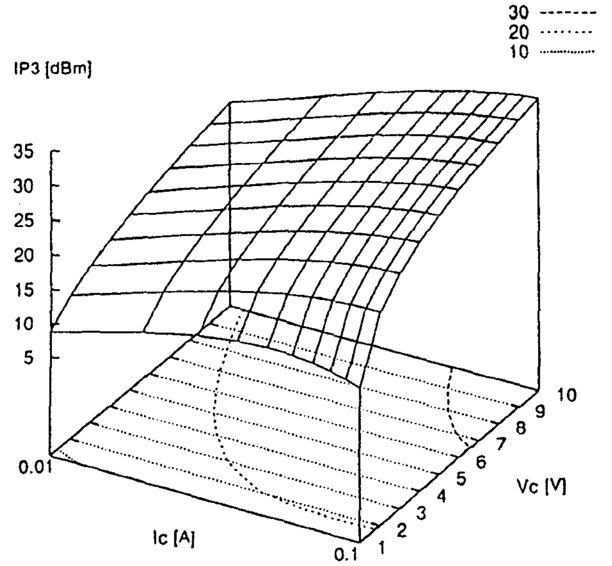

Fig. 5. IP3 level of HBT with linearized I_e.($N_E = 2 \times 10^{17}$ cm^{-3}, $P_B = 2 \times 10^{19}$ cm^{-3}, $N_C = 2 \times 10^{16}$ cm^{-3} $W_E = 0.2$ µm, $W_B = 0.1$ µm, $W_C = 1.0$ µm)

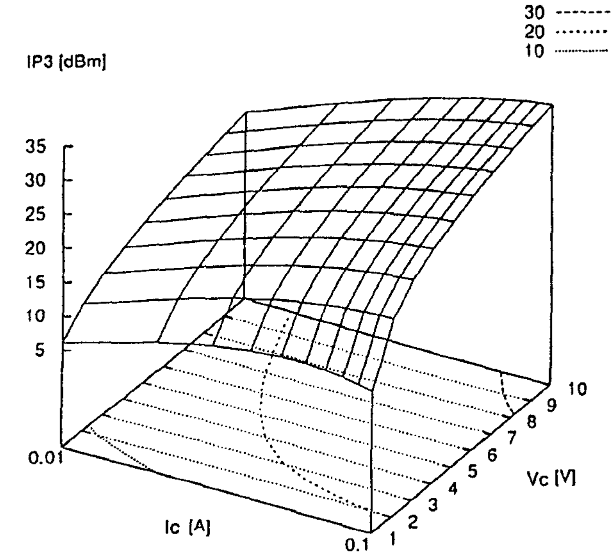

Fig. 6. IP3 level of HBT with linearized I_c.($N_E = 2 \times 10^{17}$ cm^{-3}, $P_B = 2 \times 10^{19}$ cm^{-3}, $N_C = 2 \times 10^{16}$ cm^{-3} $W_E = 0.2$ µm, $W_B = 0.1$ µm, $W_C = 1.0$ µm)

EXPERIMENTAL STUDY

We have fabricated HBTs using three different epi-structures and have performed two-tone test to verify our simulation results. The #19394 structure is the typical HBT structure used in the simulation. Base thickness is changed to 0.14 µm in #19894 structure and the #19294 HBT has the punch-through collector structure with $W_C = 0.4$ µm. We applied small signal gain matching condition to the numerical simulation using Volterra Series because power matching cannot be implemented for the analysis. Because of a low power level of that matching, our Spectrum Analyzer cannot detect the third order product output due to the system noise. To increase the power level, the devices were measured at the power matching condition. The two tone test results of the devices are summarized in table 1. The measured IP3 value of punch-through collector HBT is 31 dBm while that of normal collector HBTs is 28 dBm, indicating the superior IP3 performance of HBT with punch-through collector. The #19394 and #19894 HBTs have almost identical distortion characteristics.

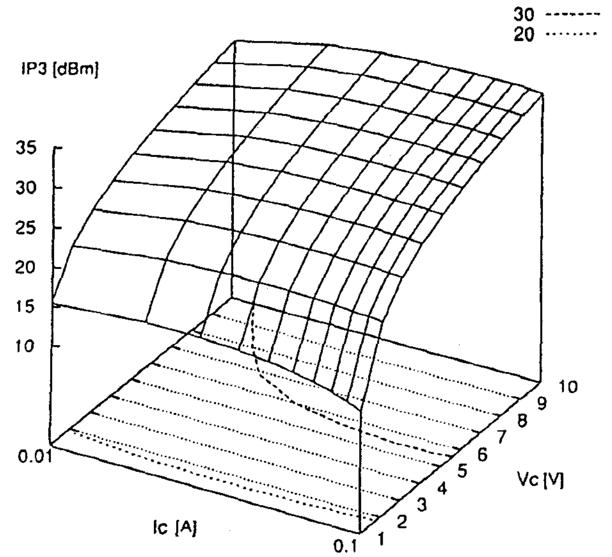

Fig. 7. IP3 level of HBT with linearized I_c and I_e. ($N_E = 2 \times 10^{17}$ cm^{-3}, $P_B = 2 \times 10^{19}$ cm^{-3}, $N_C = 2 \times 10^{16}$ cm^{-3} $W_E = 0.2$ µm, $W_B = 0.1$ µm, $W_C = 1.0$ µm)

	#19294 HBT	#19394 HBT	#19894 HBT
P_{1dBc} [dBm]	10.3	9.5	10.1
Power Gain [dB]	7.2	7.3	7.6
$Efficiency_{1dB}$ [%]	18	14	17
$IMD3_{1dB}$ [dBc]	-36	-33	-32
IP3 [dBm]	31	28	28
LFOM	28	14	14
I_b [mA]	0.44	0.47	1.15
Γ_S	0.199 $\angle$-17.5	0.031 $\angle$-77.2	0.203 $\angle$-45.0
Γ_L	0.292 $\angle$-89.0	0.423 $\angle$-124.6	0.426 $\angle$-109.7
$IP3_{SIM}$ [dBm]	35	25	25

Table 1. Two tone power test results of the HBTs (I_C = 15 mA, V_{CE} = 3 V f = 10 GHz).

SUMMARY

In summary, the simulation results have shown that IP3 does not depend on the emitter structure while it is appreciably affected by base and collector structures. Punch-through collector is the best structure for linearized HBT. The nonlinear distortion mechanism of HBT has also been studied by investigating the cancellation effects of IM components generated by nonlinear sources. The harmonic components generated by emitter-base current source and base-collector current source cancel each other almost exactly, resulting in high linearity.

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