# InGaP/GaAs/AlGaAs Power DHBT with Enhanced Linearity near Saturation Region

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*Abstract* — **This paper describes InGaP/GaAs/AlGaAs power DHBTs with the enhanced linearity near saturation output regions. The DHBT, having compositionally graded AlGaAs collector layers with a δ-doped layer, effectively improved the nonlinearity of the base-collector capacitance near the knee voltage and, consequently, reduced the distortion at near saturated output power levels. The power DHBT achieved an improvement in linear output power and PAE of 0.7 dBm and 2.5%, respectively, compared to the conventional SHBT, and exhibited an output power of 21.1 dBm and a PAE of 33.5% at an EVM of 5%, measured with 54Mbps 64-QAM-OFDM signals of 5.25 GHz at a supply voltage of 3.3 V.**

## I. INTRODUCTION

Recent wireless communication systems, as typified by cellular phones and wireless LANs, impose strict requirements on power amplifiers (PAs). Multicarrier modulation schemes like OFDM require highly linear PAs because of the high peak-to-average power ratio of the signals. Furthermore, PAs for use in mobile terminals have to be as efficient as possible to conserve battery power. The linearity specifications can be satisfied by operating PAs at large back-off output power. However, the large back-off from the saturation power causes a drastic reduction in the efficiency. This trade-off relation makes it difficult to achieve both high linearity and high efficiency simultaneously.

GaAs heterojunction bipolar transistors (HBTs) are presently in widespread use for PAs in wireless communication systems due to their high power-handling capability per unit chip area and high efficiency operation at a low bias voltage with a single power supply. For the improvement in the linearity of power HBTs, several attempts have been made including source impedance matching techniques for reducing phase deviation [1]-[2], bias circuit techniques for compensating the distortion near saturation output power regions [3]-[4], and employment of punch-through collector structures for suppressing the nonlinearity behavior of the base-collector capacitance [5]-[6].

In this paper, we present GaAs-based power double heterojunction bipolar transistors (DHBTs) with enhanced linearity near the saturation region. The DHBT effectively improves the nonlinearity of the base-collector capacitance near the knee voltage and reduces the distortion at near saturated output power levels. The improvement allows us to reduce the back-off, namely, to enhance the linear output power and thus the efficiency.

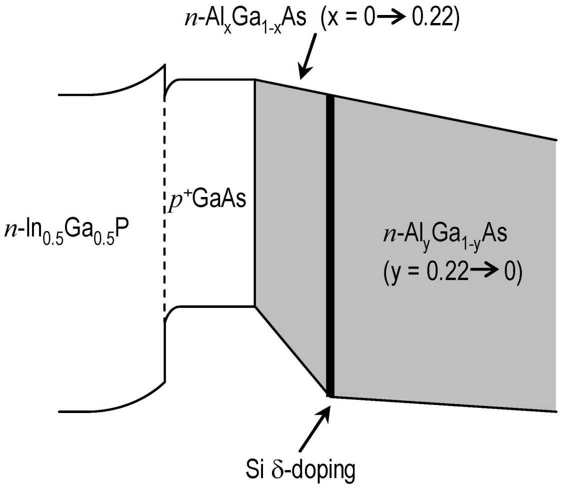


Fig. 1. Schematic band diagram of the developed InGaP/GaAs/AlGaAs DHBT.

## II. EXPERIMENTS

Figure 1 illustrates a schematic band diagram of the developed DHBT. We utilized InGaP/GaAs/AlGaAs systems in the DHBT. The main features of the DHBT structure are compositionally graded AlGaAs layers in the collector and a δ-doped layer inserted between the graded layers. The graded layers prevent the conduction band discontinuity at the base-collector (B-C) heterojunction. The sheet doping density of the δ-doped layer is designed to exactly compensate the conduction band electric field discontinuity. These layers provide a smooth and barrier-free conduction band even when biased in the saturation region, suppressing the collector current blocking at the B-C heterojunction. Furthermore, a large valence band barrier sufficiently blocks hole injections from the base, reducing the diffusion capacitance at the B-C junction.

The devices were fabricated by using two self-alignment techniques with a front-side via-hole process [7]-[8]. The emitter size of each HBT was 4.2 × 60 μm$^2$, which was optimized on the condition that the maximum available gain at 5 GHz becomes the highest at a collector current density $J_C$ of 10 kA/cm$^2$ [8]. The cutoff frequency $f_T$ and the maximum oscillation frequency $f_{\max}$ were 30 GHz and 57 GHz, respectively, at $J_C$ of 10 kA/cm$^2$. Small via-holes with a size of 15 μm × 40 μm were arranged adjacent to each HBT finger in order to

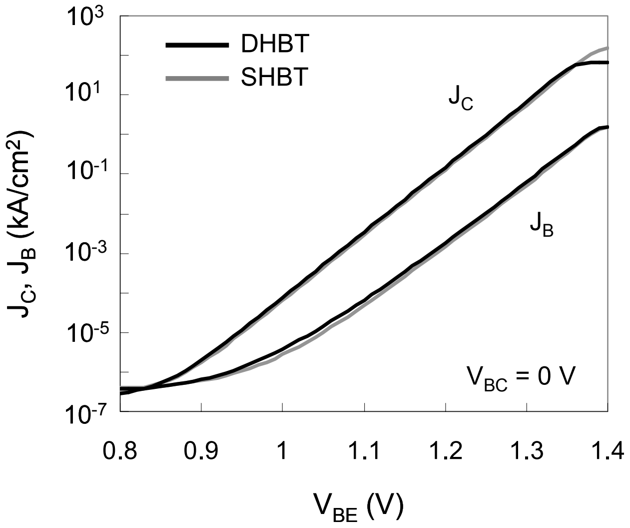


Fig. 2. Gummel Plots of DHBT and SHBT.

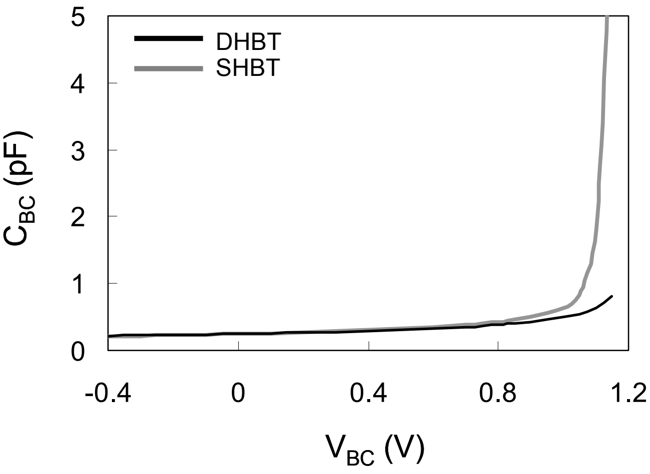


Fig. 4. Dependence of the base-collector capacitance $C_{BC}$ on the bias voltage $V_{BC}$.

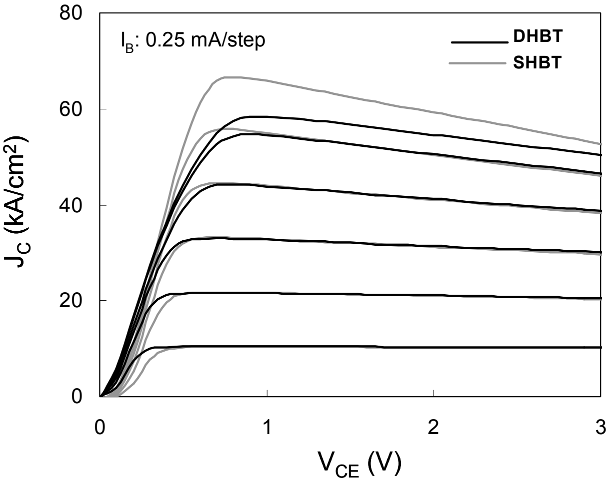


Fig. 3. Common-emitter I-V characteristics of DHBT and SHBT.

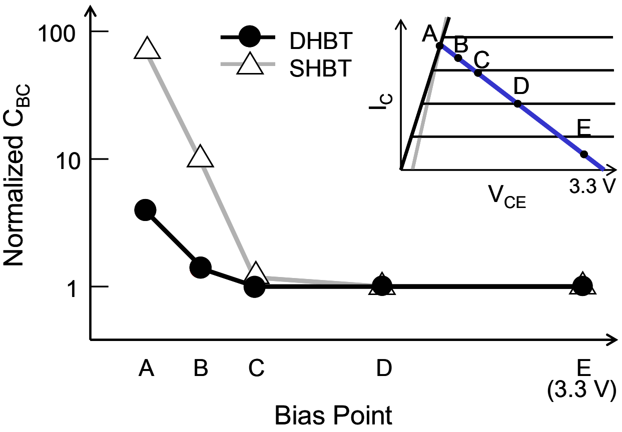


Fig. 5. Extracted base-collector capacitance $C_{BC}$ at several bias points along load line.

improve gain, current distribution, and thermal distribution in multi-finger transistors [8]. For comparison, we also fabricated InGaP/GaAs single heterojunction bipolar transistors (SHBTs) with *n*-GaAs collector.

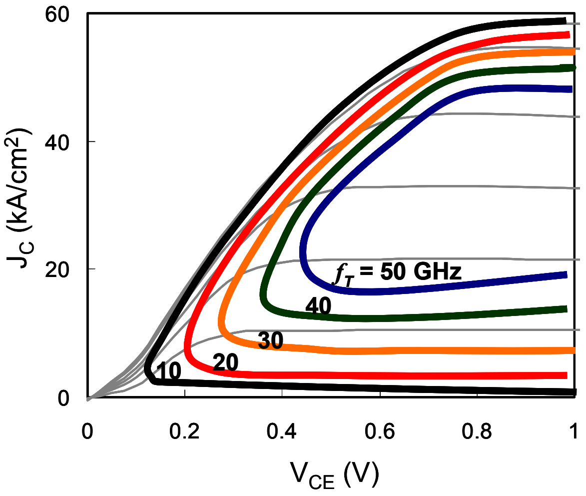
Device characteristics were evaluated by DC and small-signal *s*-parameter measurements. The linearity characteristics of power HBTs were investigated by measuring large signal operations with CW signals and 54Mbps 64QAM-OFDM modulation signals of 5.25 GHz at a supply voltage of 3.3 V.

## III. MEASURED RESULTS AND DISCUSSIONS

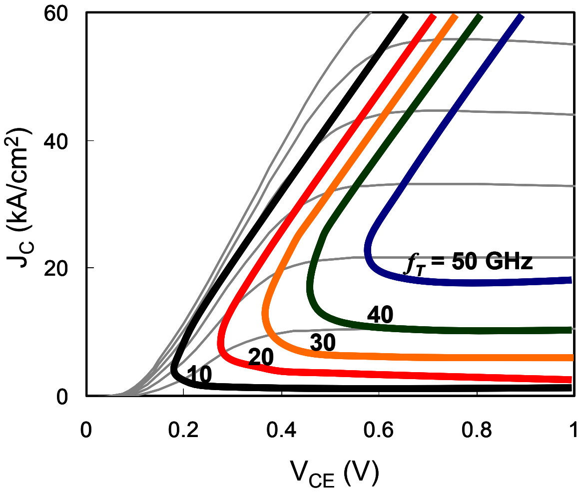
### *A. DC and Small-Signal Characteristics*

Figure 2 shows Gummel plots of the DHBT and the SHBT. The current gain $h_{FE}$ of the DHBT is not degraded up to a collector current density $J_C$ as high as 60 kA/cm$^2$, and at low $J_C$, the $h_{FE}$ is almost the same as that of the SHBT. Figure 3 shows the common-emitter I-V characteristics. The current saturation is seen in the DHBT, causing the increase in the knee voltage $V_k$ at high $J_C$. However, the $V_k$ of the DHBT is lower than that of the SHBT at $J_C$ of lower than 35 kA/cm$^2$, which is a sufficient $J_C$ for practical PA applications. That is, the collector current blocking of the developed DHBT is satisfactorily suppressed.

Figure 4 shows the dependence of the B-C capacitance $C_{BC}$ on the B-C bias voltage $V_{BC}$. A significant difference is observed at $V_{BC}$ higher than 1.0 V: i.e., the increase in the $C_{BC}$ of the SHBT is sharp, whereas the $C_{BC}$ of the DHBT increases gradually. This result signifies the effectiveness of the large valence-band barrier in the DHBT, which suppresses the hole injections at the forward B-C bias voltage and, thus, reduces the diffusion capacitance. Figure 5 shows the $C_{BC}$ of the DHBT and the SHBT extracted from the *s*-parameters measured at several bias points along a typical resistive load line. The increase in the $C_{BC}$ near the $V_k$ region for the DHBT is



(a) DHBT



(b) SHBT

Fig. 6. Constant contours of the cutoff frequency $f_T$ near saturation region for (a) DHBT and (b) SHBT plotted with the common-emitter I-V characteristics.

less than 1/10 of that for the SHBT. This improvement in the nonlinearity of the $C_{BC}$ is attributed to the reduction of the diffusion capacitance, suggesting that the distortion caused by the nonlinearity of device parameters can be reduced in the DHBT [2], [9].

Figure 6 shows the constant contours of the cutoff frequency ($f_T$) near saturation region plotted with the common-emitter I-V characteristics. It should be emphasized that, despite the higher $V_k$ of the DHBT than that of the SHBT at $J_C$ of higher than 35 kA/cm$^2$, the DHBT has higher $f_T$ than the SHBT near $V_k$ at $J_C$ as high as 45 kA/cm$^2$. This result is ascribed to the smaller $C_{BC}$ near the $V_k$ region of the DHBT, implying that the reduction in the gain of PAs caused by the degradation in the high frequency characteristics of transistors can be suppressed in the DHBT.

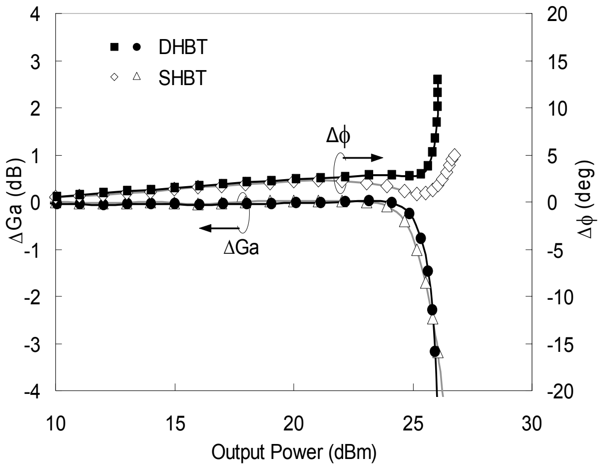


Fig. 7. Gain deviation ΔGa and phase deviation Δϕ as a function of output power of 8-finger power HBTs under a CW signal of 5.25 GHz and a supply voltage $V_{CC}$ of 3.3 V.

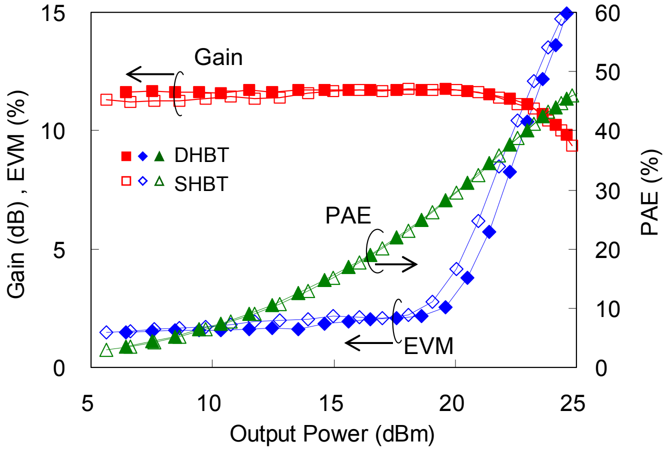


Fig. 8. Input-output characteristics of 8-finger power HBTs measured with 54Mbps 64-QAM-OFDM signals of 5.25 GHz at $V_{CC}$ of 3.3 V.

### *B. Power Characteristics*

Figure 7 shows the dependence of the gain and phase deviations on the output power of 8-finger power HBTs under a CW signal of 5.25 GHz and a supply voltage $V_{CC}$ of 3.3 V. The DHBT has lower saturation output power than the SHBT, implying that the $V_k$ of the DHBT at the measured load impedance is higher than that of the SHBT. However, the compression power of the DHBT is higher than that of the SHBT. These results verify that the improvement in the nonlinearity of the device parameters near the $V_k$ region effectively suppresses the distortion at near saturated output power levels.

Figure 8 shows input-output characteristics of the 8-finger power HBTs measured with 54Mbps 64-QAM-OFDM signals of 5.25 GHz at $V_{CC}$ of 3.3 V. Both power HBTs exhibit excellent linearity in the low and medium output power regions, with an error vector magnitude (EVM) of less than 3%. It should be noted that the

DHBT maintains the low EVM at higher output power than the SHBT. At an EVM of 5%, where the EVM is determined by the distortion near the saturation output power region, the DHBT achieved an improvement in linear output power and power added efficiency PAE of 0.7 dBm and 2.5%, respectively, compared to the SHBT, and exhibited an output power of 21.1 dBm and a PAE of 33.5%. This result is attributed to the enhancement in the linearity of the DHBT, as shown in Fig. 7, indicating the great potential of the developed DHBTs for power amplifier MMICs achieving both high linear output power and high efficiency simultaneously.

## IV. CONCLUSION

We have demonstrated InGaP/GaAs/AlGaAs power DHBTs with enhanced linearity near the saturation region. The developed DHBT improved the nonlinearity of the base-collector capacitance and, as a result, improved the high frequency performance near the knee voltage, resulting in the reduction of the distortion near the saturated output power. The power DHBT achieved an improvement in linear output power of 0.7 dBm and an improvement in PAE of 2.5% in comparison to the SHBT, and exhibited an output power of 21.1 dBm and a PAE of 33.5% at an EVM of 5%, measured with 54Mbps 64-QAM-OFDM signals of 5.25 GHz at a supply voltage of 3.3 V. These results indicate the great potential of our DHBTs for power amplifier MMICs requiring both high linearity and high efficiency.

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