Millimeter-Wave AlGaAs–GaAs HBT Power Operation

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Abstract— **The AlGaAs–GaAs HBT has demonstrated good power performance up to 18 GHz. Although f_{max} is typically above 100 GHz, the power performance limitation and large signal operation at millimeter wave have not yet been studied. Power results at 35GHz of two HBT structures, with an analysis based on numerical simulation are summarized. The HBT demonstrated 8.5-dB linear power gain, 30% PAE with 7.8-dB gain and 7.5-V V_{ce} bias. The power density reaches 1.25 mW/μm^2. A shorter collector (0.4 μm) is shown to be better suited for 35-GHz operation as a result of shorter collector transit time and smaller "residual collector voltage." Improvement can be achieved by reducing the base and collector resistance, and the collector capacitance.**

I. Introduction

The AlGaAs–GaAs HBT has demonstrated high power performance in the microwave frequency range [1], [2]. Typical value of f_T is 50 GHz and f_{max} is over 100 GHz with the best result of 350 GHz f_{max} [3], allowing HBT for millimeter-wave operation. The attraction of millimeter-wave HBT is the easy fabrication (2-μm minimum feature size) and good reproducibility. High HBT f_{max} can be achieved by the reduction of base resistance and collector capacitance, which can be reduced by a smaller base/collector junction area or a longer collector. Since the base resistance is limited by material growth, the study reported here has concentrated on the collector structure.

The CB (common base) mode was chosen for its better unilateral property and higher gain in the millimeter-wave range. The power test was done at 35 GHz on 40-μm^2 emitter-junction-area HBT's with two collector lengths −0.4 μm and 0.7 μm. At 35 GHz, the HBT with 0.4-μm collector length demonstrated 8.5-dB linear power gain. 30% PAE was achieved at 7.8-dB gain, and 1.25-mW/μm^2 power density. A numerical simulation utilizing the drift-diffusion equation shows a "residual collector voltage" that raises the minimum value of the dynamic collector voltage. The shorter collector HBT has a smaller residual collector voltage which allows larger collector voltage swing thereby yielding better power performance.

II. HBT Structures, Fabrication, and Power Result

The CB (common base) HBT is more a unilateral device than the CE (common emitter) HBT. The CB HBT, therefore, has a higher small signal gain in millimeter-wave band as shown in Fig. 1. At 18 GHz, the CB HBT already showed better power performance than the CE HBT [4]. Therefore, the 35-GHz power experiment was done with CB HBT's. The HBT's were fabricated by the "self-aligned dual lift-off" process. The unique features are the self-alignment of the emitter/base ohmic contacts to reduce the base resistance and the implantation under the base ohmic contact to reduce the base-collector capacitance. The experiment was carried out on single cell HBT's to study the intrinsic limitation of transistor structure; each cell has two 2 μm by 10 μm emitter fingers spaced 2 μm apart [1]. The 2-μm finger width has a 0.9 utilization factor at 35 GHz and is easy for processing [5]. Specification of base layer is 80-nm thick; and doped to 5×10^{19}cm^{-3} with C as dopant, which provides 200 to 250 Ω base sheet resistance. Current gain is around 15.

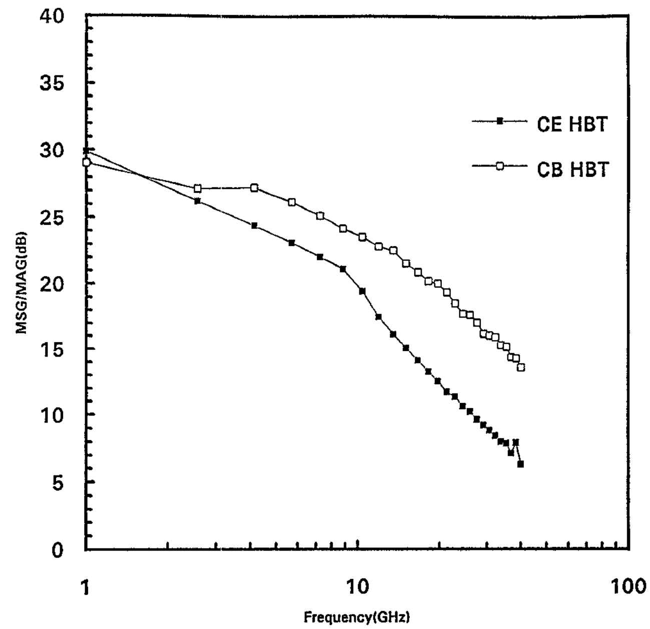

Fig. 1. Measured MSG/MAG versus frequency for both CE (common emitter) and CB (common base) HBT's. CB HBT has higher small signal gain at higher frequency range.

Two collector structures were tested (with all other layers being identical): 0.7-μm and 0.4-μm collector lengths. The 0.7-μm collector length structure is the standard one for X- and Ku-bands (6–18 GHz) operation. Both structures were processed using the same mask set and the identical processing sequence. All the key parameters are listed in Table I. As expected, the 0.7-μm collector HBT has higher breakdown

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TABLE I
KEY PARAMETERS OF HBT'S WITH TWO DIFFERENT COLLECTOR LENGTHS (0.4 μm AND 0.7 μm)

Parameters	l_c= 0.4 μm	l_c= 0.7 μm
Collector Doping Concentration	3×10^{16}cm^{-3}	3×10^{16}cm^{-3}
BV_{cbo}	16 V	20 V
$V_{cb\ bias}$	5–6 V	5–6 V
C_{bc}	40 fF	32 fF
MSG/MAG at 35 GHz	13–14 dB	15.5 dB
Linear Power Gain	8.5 dB	8.9 dB
Gain at Maximum PAE	7.83 dB	7.85 dB
Maximum PAE	30%	23%
Collector Transit Time $l_c/(2v_d)$	2.5 pS	4.4 pS
35-GHz $\times$ Collector Transit Time	8.75%	15%

The 0.4-μm collector offers better efficiency at 35 GHz although its small signal gain is slightly lower.

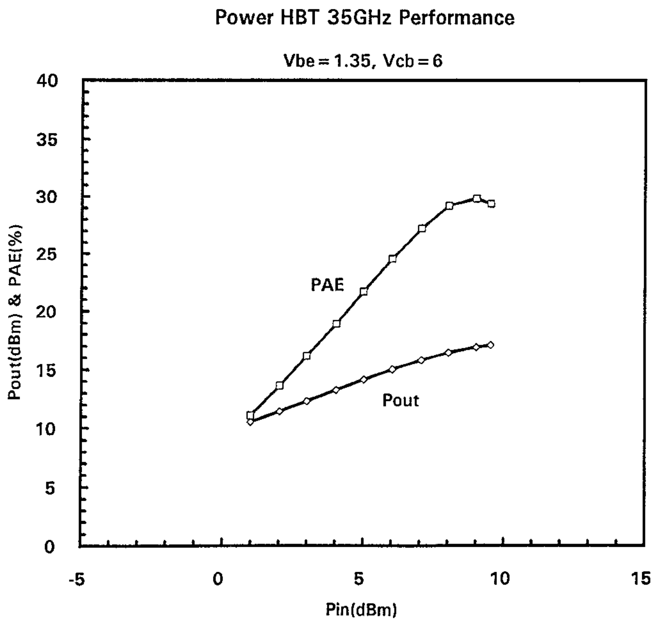

Fig. 2. Power saturation curve of HBT with 0.4-μm collector length at 35 GHz. V_{cb} was biased at 6 V and V_{be} at 1.35 V. Power density reaches 1.25 mW/μm2.

voltage, lower collector capacitance, and higher MSG/MAG at 35GHz; but the power gain is almost identical and it has lower power added efficiency (PAE). The power gain is lower than MSG/MAG because load impedance for maximum output power is different from the impedance for maximum small signal gain. 5–6V V_{cb} was used to avoid excessive heating. The 0.4-μm collector HBT has almost identical power gain, and the efficiency is better. Its performance is shown in Fig. 2, with 30% PAE and 7.8-dB gain. The power density reaches 1.25 mW/μm^2, as compared to 1.6 to 2.0 mW/μm^2 for 6–18-GHz operation. The lower V_{cb} bias results in the lower power density.

III. ANALYSIS

The HBT structure of 0.7-μm collector length does not offer satisfactory performance at 35 GHz even though the collector transit time (around 4.4 pS) is only 15% of the cycle at 35 GHz. A numerical simulation using the drift-diffusion equation was carried out to compare the two collector structures. The avalanche breakdown effect is included, and the base pushout condition is avoided in the simulation. The electron carrier concentration in the collector was found to be spatially nonuniform, contrary to the "quasi-static" condition usually assumed in transistor circuit modeling.

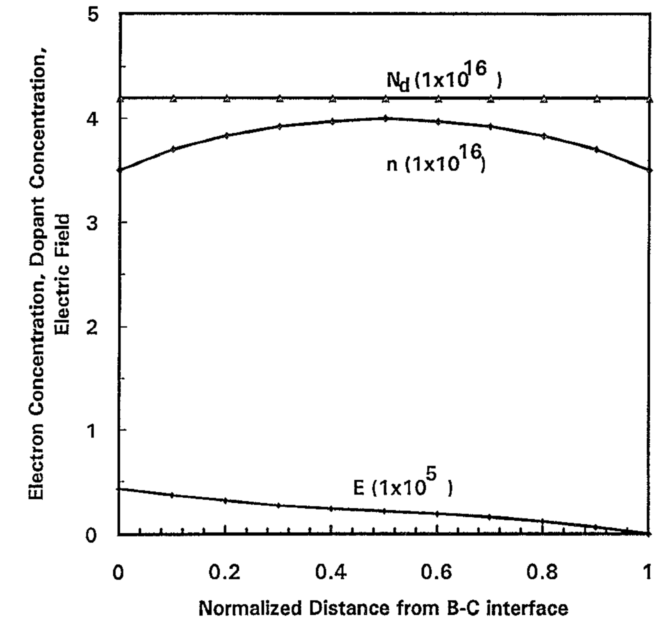

Fig. 3. A "snapshot" of the electric field, electron concentration, and background dopant concentration at the instance of the maximum current/minimum voltage within the 0.7-μm long collector. Nonuniform electron concentration and the total net charge within collector result in a "residual voltage" in collector that raises the "knee voltage."

A "snapshot" at the maximum-current/minimum voltage instance for the 0.7-μm collector for a certain operation condition is shown in Fig. 3. Carrier concentration, background dopant concentration, and the electric field were displayed against distance from the base-collector interface to the N^+ subcollector. The nonuniform electron concentration implies a nonzero slope of the electric field. Therefore, the electric field is nonzero within the collector. The integration of the electric field is the residual voltage and is about 1.5 V in Fig. 3, which is quite significant as compared to the $V_{cb,bias}$ of 5–6 V. [Note: 1) V_{be} bias is around 1.4 V. 2) The residual voltage minus the bandgap voltage is the knee voltage in V_{cb}.] Certainly the carrier concentration at the maximum current point may be very different from the background dopant concentration, which results in even greater residual voltage. The residual voltage effectively raises the knee-voltage of the transistor and reduces the efficiency. In contrast, the shorter collector HBT has a much more spatially uniform electron concentration, and the residual voltage can be minimized with appropriate collector doping concentration.

The HBT was modeled with the measured S parameters. Because of unexpectedly high-contact resistance, the base resistance is 15 ohms, and the collector resistance is 7 ohms for the 0.4-μm collector HBT; both are higher than the typical resistance values obtained on the 0.7-μm collector HBT (8 and 3 ohms, respectively). The resistance values agree with the process control monitors' result. The collector capacitor introduces a large reactive current, $\omega C_{cb} V_{cb(RF)} \tilde{} 40mA$, which is much greater than the bias current of 18 mA. This reactive current causes substantial power loss on the base and collector resistors. Using the T model of the HBT, the power lost on the base resistor is estimated to be 5.6 mW, and the power lost on the collector resistor is 7.5 mW. The power loss in those resistors is substantial (13.1 mW) compared to the net output power of 50 mW. For the nominal resistance values, the power loss could be cut down by 6.5 mW. Therefore, the reduction of both base and collector resistors results in higher gain and higher output power.

IV. Conclusion

HBT of 2-μm finger width demonstrated good power performance at 35 GHz. 30% PAE was achieved with 7.8-dB gain, 1.25-mW/μm^2 power density, and a high-bias voltage (V_{ce} up to 7.5 V) as compared to 0.25-μm gate MESFET/HEMT. The HBT has a shorter (0.4 μm) collector length than the X/Ku-band device but was processed with the identical sequence and the mask sets. A numerical simulation explained the concept of the "residual voltage" and the better performance of the shorter collector HBT. Improvement can be achieved by the reduction of the base and collector resistance, as well as the collector capacitance. With the advantage of high yield and high uniformity, HBT technology can offer a low-cost, high-performance power transistor into the millimeter-wave frequency range.

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