Development of High Breakdown Voltage InGaP/GaAs DHBTs

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Abstract

In this paper, we report the development of a high breakdown voltage InGaP/GaAs HBT process for low-to-mid power and high-voltage power amplifier operation. To achieve the high-breakdown InGaP HBT, two different collector designs and collector-etch processes were investigated. The first device process approach uses a thick GaAs collector with low n^- doping. The process challenges and considerations of this long collector approach are briefly discussed. An alternative approach uses wide band gap InGaP material as part of the collector design. High breakdown voltage can be obtained from both material design approaches. However, to fully leverage the existing process modules of our high volume HBT production line and allow the re-use of our current HBT design rules and libraries, our high voltage HBT (HV-HBT) development efforts focus on HBTs with InGaP in the collector (either composite collector, CCHBT, or double heterojunctions, DHBTs). Using a slightly modified process, InGaP DHBT devices have been demonstrated with BV_{ceo} and BV_{cbo} values of 40 V and 56 V, respectively. A cut off frequency, f_t, of 40 GHz has also been obtained at a current density of Jc=0.3 mA/µm^2 by using this process. Preliminary circuit level performance results are also presented and discussed.

INTRODUCTION

In recent years InGaP/GaAs heterojunction bipolar transistors (HBTs) have been the dominant technology for wireless handset power amplifier (PA) applications due to their excellent performance, reproducibility, reliability and manufacturability. With their excellent power handling capability, good linearity and power added efficiency (PAE), InGaP/GaAs HBTs have also become a candidate for PA designs in low-to-mid power infrastructure applications currently dominated by the LDMOS or pHEMT [1-3]. To penetrate the low-to-mid power base station PA market, the key technical challenges for the InGaP HBTs are the high voltage operation and high breakdown voltage requirements.

In this paper, we discuss the development of a new InGaP/GaAs HBTs process targeted for high voltage applications. The fabrication processes of two groups of material structures are studied and evaluated. The first group achieves high voltage performance by increasing the collector thickness and reducing the collector doping [3, 4]. Typically, 2.8 µm or 3.0 µm collector thickness and collector doping as low as $8x10^{15}$ cm^{-3} are used. The second material group uses an InGaP double heterojunction collector (DHBT) or an InGaP/GaAs composite collector (CCHBT) [5]. High breakdown voltages are obtained from both groups. However, to take advantage of the existing InGaP related process modules in our high volume HBT production facility; this work emphasizes the development of a manufacturable InGaP DHBT (or CCHBT) process. Epi design considerations and process for InGaP DHBTs are addressed in this paper. Finally, S-parameter measurements and circuit application results are presented.

CONSIDERATION AND EXPERIMENT

To achieve higher breakdown voltages in InGaP HBTs, two approaches can be employed. The first one is brute force: increasing the collector thickness and reducing the collector doping. However, the penalty for using a longer collector structure is that the device topology can be more than 5 µm in depth, presenting severe process and photo lithography challenges and, potentially, introducing reliability problems. The use of a wide-band gap material, InGaP, to form a DHBT, to replace the thicker GaAs collector layer overcomes the above topology problems and improves offset voltage, and increases power handling capability. A drawback of DHBT is that a conduction band discontinuity can be introduced at the base-collector heterojunction. Such an offset can lead to current blocking degrading both the DC and RF performance. To minimize the impact of this conduction band offset, a GaAs spacer layer/doping spike combination is inserted between the p^+ GaAs base and InGaP collector layers [6]. This structure effectively minimizes the spiking and results in excellent I-V characteristics. To improve transistor knee voltage (reducing the on-resistance), a composite collector structure was also investigated, which consists of a short wide band gap InGaP layer in the high-field region of the collector and GaAs layer over the remaining collector. This improves the on-resistance by minimizing the use of the low-mobility InGaP layer. Both of these approaches present different device design and process challenges. Our results indicate that InGaP DHBT/CCHBT is more compatible with our high volume HBT process for handset PAs and gives performance that is equal or superior to the long-collector approach.

The front-side process of the InGaP DHBT is compatible with Skyworks' existing InGaP/GaAs HBT processes, allowing the libraries and design rules to be shared between this process and our baseline process. ICP dry etch process is used for both the InGaP emitter layer and the collector layer. The three device contacts (emitter, base and collector) are formed using the same individual metal systems as in the baseline HBT process which has demonstrated high integration levels and high reliability.

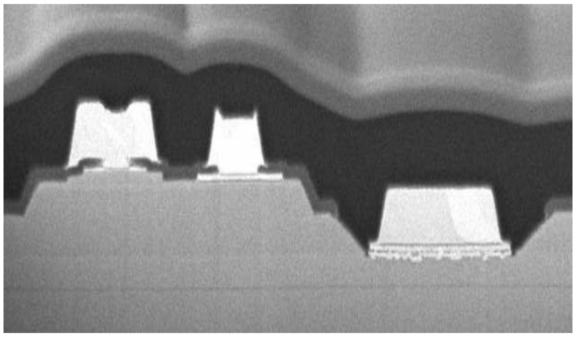

Fig.1. FIB cross section of fabricated InGaP DHBT

He-ion implantation is used to electrically isolate the devices. One of the benefits of the DHBT/CCHBT approach is that the total collector thickness is the same as our baseline process, so there is no additional requirement for the isolation implant step. The back-end processing, including precision TaN resistors, MIM capacitors, spiral inductors and interconnect metals, also re-use the exact modules from our high volume, high yield processes. A Focused-Ion Beam (FIB) cross section of fabricated InGaP DHBT is shown in Fig. 1.

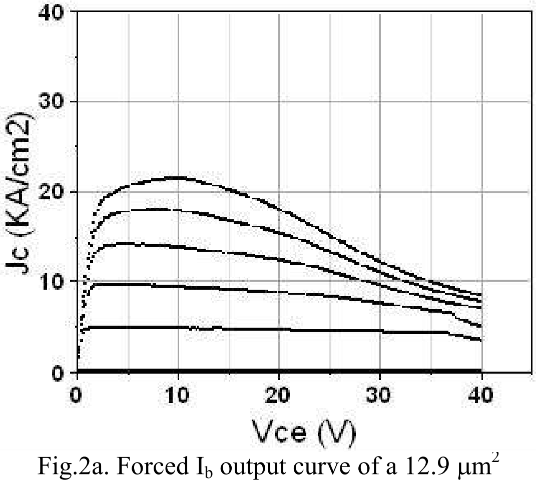

Fig.2a. Forced I_b output curve of a 12.9 μm^2 InGaP DHBT

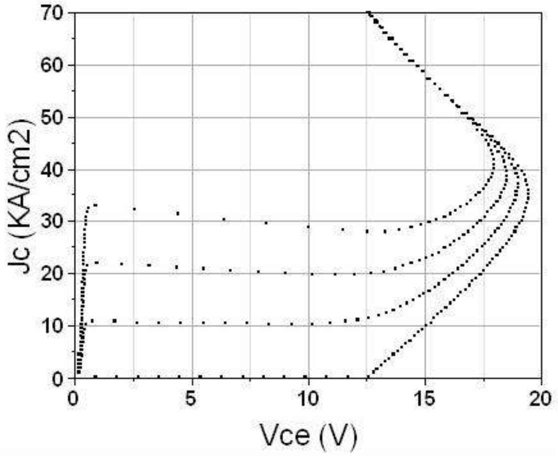

Fig.2b. Forced I_b output curve of 12.9 μm^2 InGaP/GaAs baseline HBT

Since this DHBT/CCHBT material is a direct drop-in to our HBT PA process (all the etch-depths are the same as the baseline process), manufacturability and excellent process yield for this is expected.

RESULTS

The common emitter characteristics comparisons of InGaP DHBT and InGaP/GaAs baseline HBT with same emitter areas of 12.9 μm^2 are shown in Fig.2a and Fig.2b, respectively. It can be seen that for InGaP DHBT, BV_{ceo} up to 40 V and BV_{cbo} of 56 V are readily achieved, while comparing InGaP/GaAs baseline HBT, typical BV_{ceo} and BV_{cbo} are 12 V and 27 V, respectively. Fig.3 shows the Gummel plot comparisons of InGaP DHBT, CCHBT, long

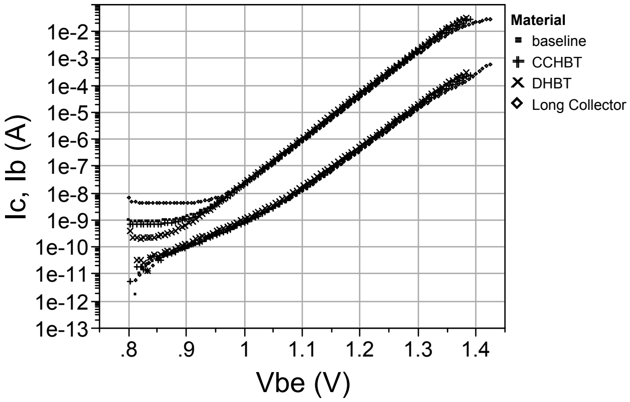

Fig.3. Gummel Plot Comarisons

collector InGaP/GaAs HBT and baseline HBT. We can note that no significant difference is found among these epi structures.

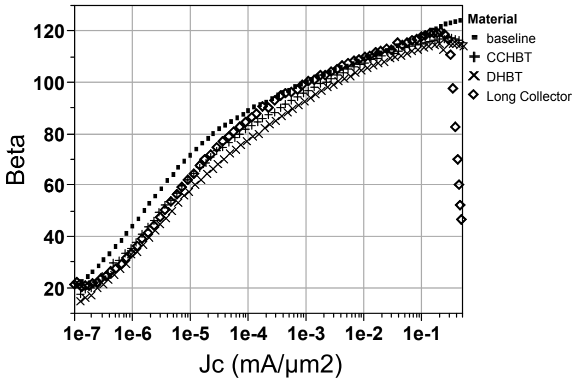

Fig.4. Beta (I_c/I_b) vs. collector current density J_c

Fig. 4 shows the DC current gain vs. collector current density for the above devices. We observed that there is no current blocking even up to collector current densities of 0.3 mA/µm^2. AC performance was characterized by S-parameter measurement. f_t's of 40 GHz at Jc=0.3 mA/µm^2 was obtained as shown in Fig. 5.

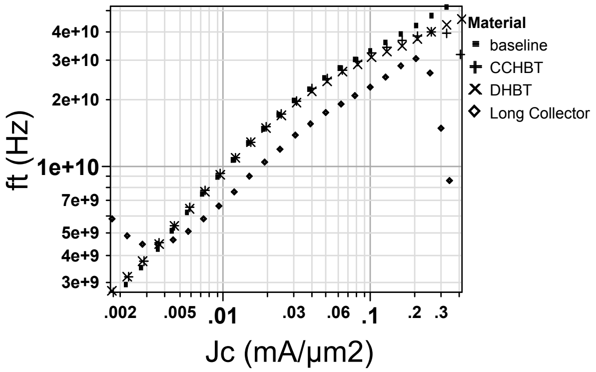

Fig.5. DHBT f_t vs. collector current density Jc

APPLICATION

Due to current and emerging high data rate modulations, there has been an increasing need for higher linear output power PA's. Some of the main drivers for this are WiFi and WiMax which are not only being deployed through households and businesses, but city wide. This can be seen in the recent installation of free WiFi networks in the San Francisco area. Many other large metropolitan cities are following suit.

For WiFi and WiMax applications, Orthogonal Frequency Division Multiplexing (OFDM) with 64-QAM is often used. Because of the inherently large Peak-to-Average-Ratio (PR) of the OFDM signal, a PA with higher P_{1dB} is required to operate in a linear mode. The Error Vector Magnitude (EVM) is an important figure of merit for the linearity of the amplifier at high output power. Fig.6 and Fig.7 show test data using the high breakdown HBT process with a Skyworks WLAN PA at 2.437GHz. The PA was originally designed for our baseline process and was retuned using off-chip components.

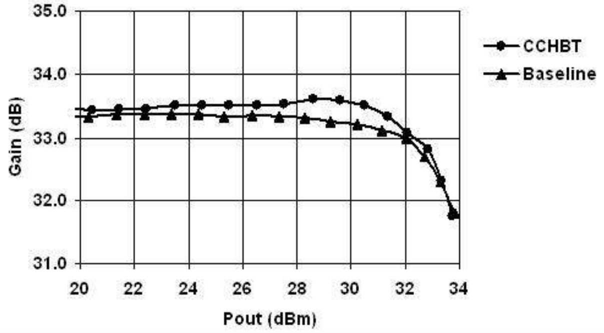

Fig.6. Gain vs. P_{out} taken at 2.437GHz with Skyworks WLAN PA using high breakdown HBT process.

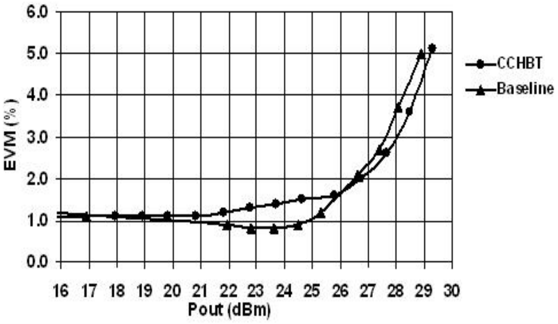

Fig.7. OFDM 64-QAM signal EVM vs. P_{out} taken at 2.437GHz with Skyworks WLAN PA using high breakdown HBT process.

CONCLUSIONS

We have demonstrated high breakdown voltage InGaP/GaAs HBTs using two different technology approaches. Both approaches (long collector and DHBT/CCHBT) can achieve adequately high breakdown for low-to-mid power infrastructure applications. However, we have shown that using DHBT/CCHBT approach results in a process that is more in-line with our high volume handset PA process and allows the re-use of our design libraries and design rules.

The DC test data show that, for DHBT, BV_{ceo} and BV_{cbo} as high as 40 V, and 56 V are obtained, respectively. Proper design of the base-collector transition was important for eliminating the current blocking effect. This effect is not observed on our DHBT/CCHBT until the collector current density of exceeds 0.3 mA/μm^2, well past the anticipated operating point in the target application. A cut off frequency, *ft*, of 40 GHz has also been obtained. We also demonstrated a PA with reasonable performance using this process.

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REFERENCES

[1] D. Hill, T.S. Kim, IEEE Trans. On Microwave Theory and Techniques, vol. 45, no. 12, pp. 2224-2228, 1997

[2] P. Kurpas, A. Maaβdorf, W. Doser, P. Heymann, B. Janke, F. Schnieder, H. Blank, P. Auxemery, D. Pons, W. Heinrich, J. Wurfl, Digest of the 2002 IEDM Conference, pp. 681-684, 2002

[3]. N. L. Wang, C. Dunnrowicz, X. Chen, W. Ma, H. F. Chau, X. Sun, Y. Chen, B. Lin, I. L. Lo, C. H. Huang and M.H. T. Yang, 2003 IEEE MTT-S International Microwave Symposium Digest, vol 2, June 2003, pp. 707-710.

[4]. P. Kurpas, F. Brunner, R. Doerner, B. Janke, P. Heymann, A. Maasdorf, W. Doser, P. Auxemery, H. Blanck, D. Pons, J. Wurfl, and W. Heinrich, 2001 IEEE MTT-S International Microwave Symposium Digest, vol. 2, 2001, pp. 633-636

[5] P.J. Zampardi, C.E. Chang, S. Fitzsimmons, R.L. Pierson, B.T. McDermott, P.F. Chen, and Peter Asbeck, Transactions on Electron Devices, Vol. 49, No. 4, April 2002, pp. 540-542, 2002

[6] W. Liu and D.S. Pan, IEEE Transaction on Electron Devices, Vol. 16, No. 7, July 1995, pp. 309-311, 1995.

ACRONYMS

PA: Power Amplifier

HBT: Heterojunction Bipolar Transistor

HVHBT: High breakdown Voltage HBT

DHBT: Double heterojunction HBT

CCHBT: Composite Collector HBT

ICP: Inductively Coupled Plasma