

# An InGaP/GaAs DHBT with an Integrated Wide-Tuning-Range Varactor for Broad Band Monolithic VCO Products

Yuefei Yang, Dave Wang, Wing Yau, Bryan Lee, Dave Rasbot, Hua Tan, and Daniel Hou

Global Communication Semiconductors, LLC  
23155 Kashiwa Court, Torrance, CA 90505  
Phone: (310) 530 7274, Email: [yfyang@gcsincorp.com](mailto:yfyang@gcsincorp.com)

**Keywords:** InGaP/GaAs DHBTs, Hyperabrupt Doping, Varactor, VCO.

## Abstract

This abstract reports an InGaP/GaAs DHBT with an integrated wide-tuning-range varactor for broad band monolithic voltage controlled oscillator (VCO) products. The DHBT base-collector junction with InGaP collector using a hyperabrupt doping profile serves as a wide tuning range varactor with high breakdown voltage. A varactor tuning range of 7:1 was obtained while the DHBT has good performance for VCO applications.

## INTRODUCTION

InGaP/GaAs heterojunction bipolar transistor (HBT) is an ideal candidate for low phase noise voltage controlled oscillator (VCO) applications mainly because of its low  $1/f$  noise due to its low surface recombination and its free of DX centers in the InGaP ledge layer. Low phase noise monolithic VCOs using InGaP/GaAs HBT and its base-collector junction as varactor have been demonstrated in the mid-1990's [1]. GCS has been mass producing low phase noise monolithic VCOs using InGaP/GaAs HBTs for over 10 years. However, the base-collector junction varactor's tuning range is narrow due to the conventional uniform collector doping.

Recently an InGaP/GaAs HBT with a wider tuning range varactor in a VCO circuit has been reported [2]. However, its 27% frequency tuning range is still relatively narrow. In order to make a wide tuning range varactor, a hyperabrupt doping profile is required [3]. Wide tuning range Si and GaAs varactors with hyperabrupt doping profiles have been reported and are available as catalog items [4, 5, 6]. However, InGaP/GaAs HBT with hyperabrupt collector doping profiles for broad band monolithic VCO application has yet to be reported.

There are two problems in using hyperabrupt doping profile in the GaAs HBT collector. One problem is that the high doping density required near the base-collector junction reduces the HBT breakdown voltage. The second problem is that the collector thickness has to be increased

in order to get a wider varactor tuning range, which unfortunately degrades the HBT's RF performance.

The current solution for wide tuning range VCOs employs a hybrid approach by using separate HBTs or BJTs along with wide-tuning-range varactor devices. This approach requires two chips that increases the VCO's size and cost compared to a monolithic VCO. In this paper we will report a novel InGaP/GaAs double heterojunction bipolar transistor (DHBT), which includes an integrated wide-tuning-range varactor and a good performance DHBT. This approach can solve the aforementioned problems simultaneously.

## DEVICE DESIGN AND FABRICATION

The InGaP/GaAs DHBT wafers were grown by MOCVD. The DHBT structure consists of an  $n^+$ -InGaAs/GaAs emitter cap layer, an n-InGaP emitter layer, a C-doped  $p^+$ -GaAs base layer, a thin n-GaAs setback layer, an n-InGaP collector with hyperabrupt doping, and an  $n^+$ -GaAs sub-collector layer. A conventional InGaP/GaAs single heterojunction bipolar transistor (SHBT) with uniform collector doping was also grown and fabricated for comparison. Fig. 1 shows the DHBT schematic layer structure.

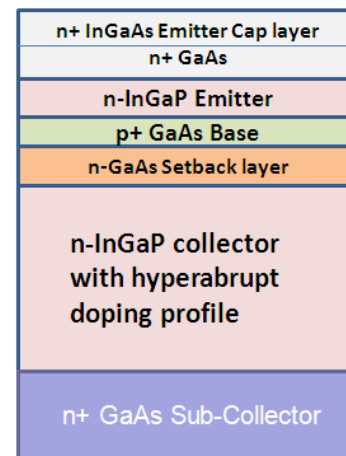


Fig. 1. InGaP/GaAs DHBT layer structure

The n-InGaP collector doping profile was carefully designed to have a wide tuning range and a linear frequency tuning response, while keeping a high breakdown voltage. A varactor tuning range is defined as the ratio of its maximum capacitance to its minimum capacitance, which is related to the depletion widths in the n-layer of a p<sup>+</sup>-n junction as follows:

$$\frac{C_{j0}}{C_{jVmax}} = \frac{T_{max}}{T_0} \quad (1)$$

where  $C_{j0}/T_0$  are the p<sup>+</sup>-n junction depletion capacitance/width at 0V bias, and  $C_{jVmax}/T_{max}$  are depletion capacitance/width at punch through voltage. In this case,  $T_{max}$  is the HBT collector thickness. We selected the collector thickness of the DHBT to be the same as that of the SHBT. With a fixed  $T_{max}$ , we need to reduce  $T_0$  in order to widen the tuning range. By properly designing a hyperabrupt doping profile, with a high doping density near the p<sup>+</sup>-n junction,  $T_0$  can be reduced. However, there is a trade-off between the tuning range and  $C_{j0}$ . The higher the  $C_{j0}$ , the lower the  $f_{max}$  becomes. For a conventional GaAs collector HBT, reducing  $T_0$  will significantly reduce the p<sup>+</sup>-n junction breakdown voltage, which makes the HBT unusable. Because InGaP is a wide band gap material with high breakdown field, it can tolerate reduced  $T_0$  without substantially affecting its breakdown voltage.

For a p<sup>+</sup>-n junction varactor diode, the typical C-V formula is:

$$C(V) = \frac{C_{j0}}{\left(1+k\frac{V_{tune}}{V_{bi}}\right)^\gamma} \quad (2)$$

where  $V_{bi}$  is the built-in potential of the p<sup>+</sup>-n junction, and  $\gamma$  is the varactor gamma number determined by its doping profile [3],  $k$  is a correction factor based on measured data. In this work, we target the gamma number of 2 to obtain a linear frequency tuning feature.

The devices were fabricated using a two-mesa structure by wet etching process. Ion implantation was used for sub-collector isolation. The typical Ti/Pt/Au metal systems were used for the emitter and base contacts, as well as the metal interconnects. An alloyed metal stack was used for the collector Ohmic contact. The varactor was fabricated using the base-collector junction diode of the DHBT. Silicon nitride was used for device passivation and for the MIM capacitor. Two-level metals were used for interconnect, and polyimide was used as the inter-layer dielectric.

#### VARACTOR and HBT PERFORMANCES

Fig 2 shows the C-V curves of the base-collector junctions of the DHBT and SHBT, in which the capacitance values were normalized by  $C_{jVmax}$ . Note that  $V_{max}$ 's for DHBT and SHBT are different although they have the same collector thickness due to different doping levels. The  $V_{max}$

of SHBT is 14V and DHBT is 18V. The DHBT shows significantly higher  $C_{j0}$  with a capacitance tuning range  $C_{j0}/C_{jVmax}$  of 7:1. For comparison, the maximum tuning range of the SHBT varactor is only 2.7:1. By curve fitting using equation 2, the extrapolated average gamma number is close to 2 for DHBT and 0.5 for SHBT, matching the expected values from the design.

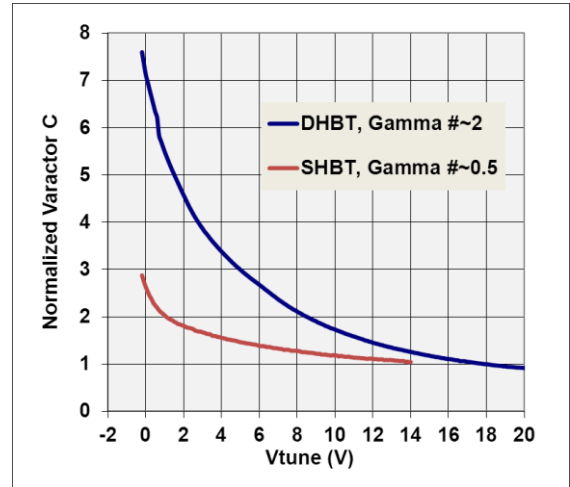


Fig. 2. Base-collector junction varactor C-V.

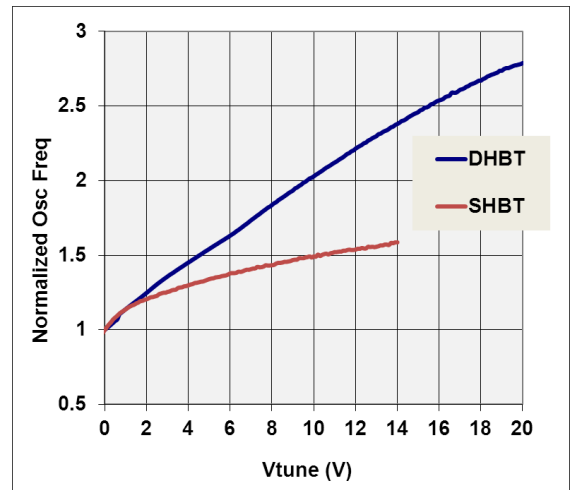


Fig. 3. Normalized oscillation frequency versus varactor tuning voltage.

The resonant frequency ( $f$ ) of an LC network is  $(2\pi)^{-1}(LC)^{-1/2}$ . To estimate the oscillation frequency tuning property for VCO applications, we define the normalized oscillation frequency versus tuning voltage as  $f(V)/f_0$ :

$$\frac{f(V)}{f_0} = \sqrt{\frac{C_{j0}}{C(V)}} \quad (3),$$

where  $f_0$  is the resonant frequency at 0V. Fig. 3 shows the normalized oscillation frequency versus  $V_{tune}$ .  $f(V)/f_0$  represents the maximum available oscillation frequency

tuning ratio for a VCO. For example, the maximum frequency tuning ratio  $f(V_{max})/f_0$  is 1.5:1 for a SHBT varactor and  $> 2.7:1$  for a DHBT varactor, respectively. The oscillation frequency tuning ratio of an actual VCO is normally less than that shown in Fig. 3 due to the addition of external fixed capacitors in the LC resonator. However, with a proper circuit design, it is easy to obtain one octave frequency tuning bandwidth for a VCO. Fig. 3 also shows good linearity of the resonant frequency versus tuning voltage for the DHBT varactor in the entire tuning range as the result of a gamma number close to 2.

Because of its wide tuning range, the DHBT varactor's frequency tuning sensitivity could become high. To evaluate the tuning sensitivity, we use the  $\Delta(f(V)/f_0)/\Delta V$  slope in Fig. 3 as the relative tuning sensitivity. Fig. 4 shows the relative tuning sensitivity versus varactor tuning voltage as derived from Fig. 3. The average sensitivity for DHBT is about 3 times higher than that of SHBT. With wideband tuning, the sensitivity will become worse. Some trade-off needs to be made. However, with proper VCO design, reasonable tuning sensitivities can be obtained for actual VCOs using this DHBT.

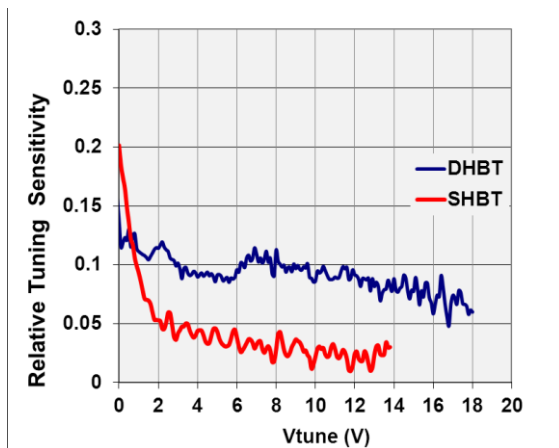


Fig. 4 Relative tuning sensitivity versus varactor tuning voltage.

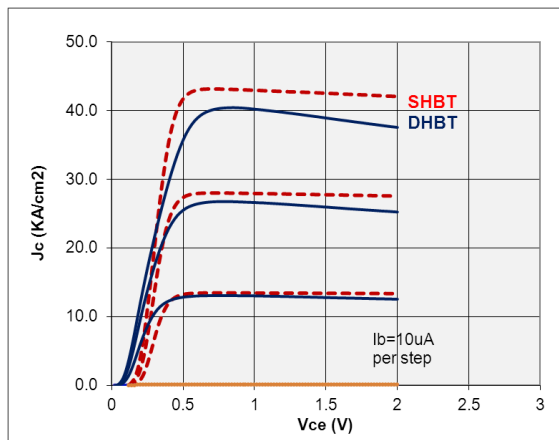


Fig. 5. IV curves for DHBT and SHBT with emitter size of  $2 \times 6 \mu\text{m}^2$

Fig. 5 shows the IV curves of the DHBT and SHBT. The electron blocking effect in the DHBT was effectively eliminated due to the high doping in InGaP near the GaAs setback layer. The DHBT has low Vce-offset voltage as expected. It shows slightly higher on-resistance and knee voltage due to lower electron mobility of InGaP collector. Fig. 6 shows the Gummel plots of the DHBT and SHBT. The current gain of the DHBT is the same as that of the SHBT in the whole Gummel plot region.

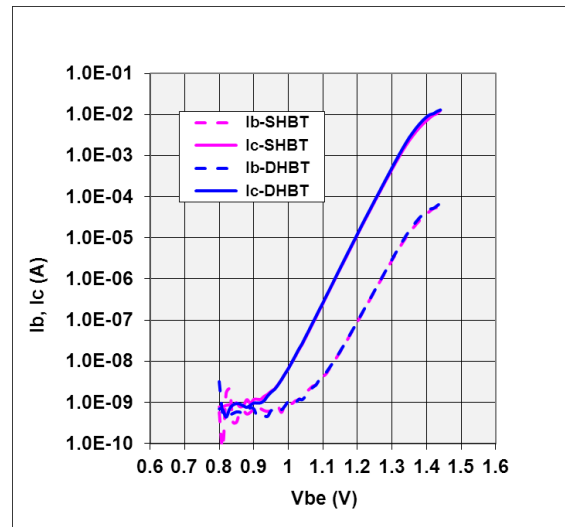


Fig. 6 Gummel plots of DHBT and SHBT with emitter size of  $2 \times 6 \mu\text{m}^2$

Small signal RF performance of the DHBT has also been evaluated. Table I summarizes the key performance parameters of the HBTs and varactors. It is noted that the BVcbo of DHBT is much higher than that of SHBT, but BVceo of both devices are the same due to the high collector doping near the base-collector junction in the DHBT. The  $f_t$  and  $f_{max}$  of DHBT are lower than those of SHBT due to the DHBT's lower electron saturation velocity and higher base-collector junction capacitance. Nevertheless, the DHBT performance should still be good enough for VCO products with oscillation frequency of up to  $\sim 15\text{GHz}$ .

TABLE I  
Key parameters of HBTs and Varactors

HBT Parameter	Unit	SHBT	DHBT
Current Gain at 1KA/cm <sup>2</sup>		150.0	150.0
Vce Offset Voltage	V	0.14	0.07
BVebo	V	6.5	6.5
BVceo	V	7.5	7.5
BVcbo	V	18.0	28.0
Ft at Jc of 50KA/cm <sup>2</sup>	GHz	55.0	48.0
Fmax at Jc of 50KA/cm <sup>2</sup>	GHz	65.0	35.0
<b>Varactor Parameters</b>			
Max Tuning Range		2.7:1	7:1
Max Tuning Voltage	V	14	18
Varactor Breakdown Voltage	V	18	28

Since the DHBT of this work is for VCO applications, the device's low frequency noise is an important parameter that will affect the phase noise of the VCO. The DHBT's  $1/f$  noise has been characterized and compared with SHBT as shown in Fig. 7. Almost identical  $1/f$  noise spectra for the DHBT and SHBT are obtained. This result indicates that the InGaP collector layer has good material quality and the DHBT of this work is suitable for VCO applications.

#### ACRONYMS

HBT: Heterojunction Bipolar Transistor  
 DHBT: Double Heterojunction Bipolar Transistor  
 SHBT: Single Heterojunction Bipolar Transistor  
 VCO: Voltage Controlled Oscillator

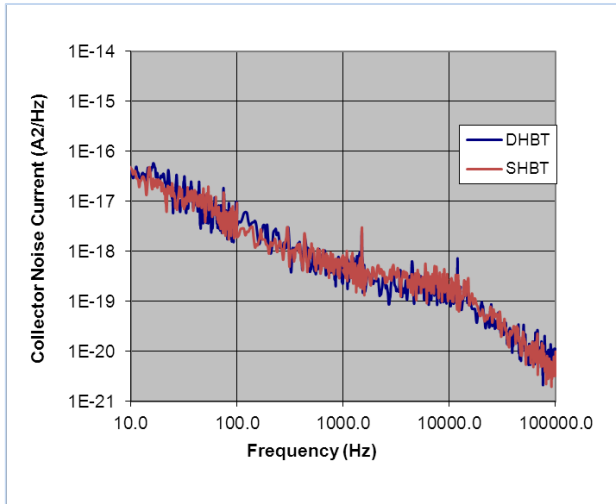


Fig. 7. Collector current  $1/f$  noise spectra for DHBT and SHBT at  $I_c$  of 2mA from devices with emitter size of  $2 \times 6 \mu\text{m}^2$ .

#### CONCLUSION

In summary, we have demonstrated an InGaP/GaAs DHBT with a hyperabrupt doping profile in the InGaP collector. A wide capacitance tuning range of 7:1 with high breakdown voltage of 28V has been obtained. The varactor shows good frequency tuning linearity, and the DHBT shows good DC, RF, and  $1/f$  noise performance, which make this device ideal for broad band monolithic VCO products.

#### ACKNOWLEDGEMENTS

The authors would like to thank GCS Fab personnel for their wafer processing support.

#### REFERENCES

- [1] U. Guttich et al, 1994 IEEE MTT-S Digest, p.131.
- [2] H. Zirath, Proc. IEEE Asia Pacific Microwave Conference (APMC), pp. 1861-1864, 2007
- [3] S. M. Sze, Physics of Semiconductor Devices, JOHN WILEY & SON, Chapter 2, Varactor.
- [4] C. Huang, et al, IEEE EDL 2010 Vol.30 (2), p.108
- [5] S.G. Choi et al, Microwave Conference, pp.1691-1694, Dec. 2009. APMC 2009. Asia Pacific
- [6] [http://www.aeroflex.com/AMS/Metelics/pdffiles/MGV\\_Series\\_Hyperabrupt\\_A17041.pdf](http://www.aeroflex.com/AMS/Metelics/pdffiles/MGV_Series_Hyperabrupt_A17041.pdf)