Single and Double Heterojunction Bipolar Transistors in Collector-up Topology

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ABSTRACT

For the first time, DC- and RF characteristics of single and double heterojunction bipolar transistors (S-HBT and D-HBT respectively) in collector-up topology are measured and compared. Both devices are realized in InGaP/GaAs technology and offer high common emitter breakdown voltage (BVceo > 16V) and high maximum oscillation frequency (f_{max} > 115GHz)

INTRODUCTION

The idea of introducing heterojunction into emitter-base junction of a bipolar transistor has existed since the beginnings of solid state electronics. Shockley already mentioned it in his patent in 1948 (1). However it took two decades to realize the first suitable devices. GaAs technology has been sufficiently developed during the last two decades making it possible to put the theoretical advantages into practice.

The S-HBT is a promising candidate for microwave power amplification (2) and for low phase noise sources (3-5). Their major advantages stem from their high power densities and the improved power added efficiency (6-7) obtained with a 2µm technology. Thanks to the vertical electronics transport leading to a limited influence of free surface, HBT's show a low 1/f noise pretty similar to RF silicon bipolar transistors. The breakdown voltage in common emitter mode (BV_{ceo}) depends on both the current gain of the devices and the base-collector breakdown voltage. Device optimized for X-Band power applications exhibit BV_{ceo} in the range of 18V with a current gain of 30. The typical unit cell so far realized for X-Band power applications is able to emit typically 1W with power-added efficiency (PAE) over 50% at 10 GHz in CW with an associated gain close to 10dB. The MMIC integration of those cells give rise to power amplifiers with output power in the 10W range and PAE higher than 45% in X-Band (8). The use of D-HBT's overcomes the limitation due to the material behavior of GaAs by introducing a wide bandgap collector such as InGaP. Since the maximum electrical field of InGaP is 80% higher than the GaAs one, a drastic improvement of breakdown behavior of D-HBT compared to S-HBT is achievable (9).

The collector-up topology is another way of RF performance improvement by decreasing the base-collector extrinsic capacitance C_{BC-ex}. The figure 1 shows the comparison between the classical emitter-up and collector-up topology. Usually the emitter is grown above the base layer and this topology is called "emitter-up". The area of the base-collector junction is at least three times larger than the base-emitter area. Consequently, the total base-collector capacitance C_{BC} does not only include the intrinsic capacitance, but also two extrinsic elements C_{BC-ex}. This parasitic capacitance has a large impact on the RF performance since f_{max} depends directly on C_{BC} and R_b. Inversion of the topology like in « collector-up » topology should be an appropriate solution to decrease the base-collector capacitance by a factor of three. However a major difficulty of the « collector-up » topology is that the injecting base-emitter diode covers a larger area than the collecting base-collector junction. Electrons injected from the emitter into the extrinsic base regions will recombine in the base precluding the use of such devices if no specific actions are taken. Simple calculations shows that the current gain would be below 0.5 in the case of the schematic shown figure 1. Two kinds of solutions can be explored :

- Lateral overetching of the emitter below the base layer down to the width of the collector
- Ion implantation of the extrinsic emitter to change this part of this device into high resistivity material.

The aim of this paper is to make an overview of the technology which has been used to overcome this parasitic injection and to give some results which have been obtained.

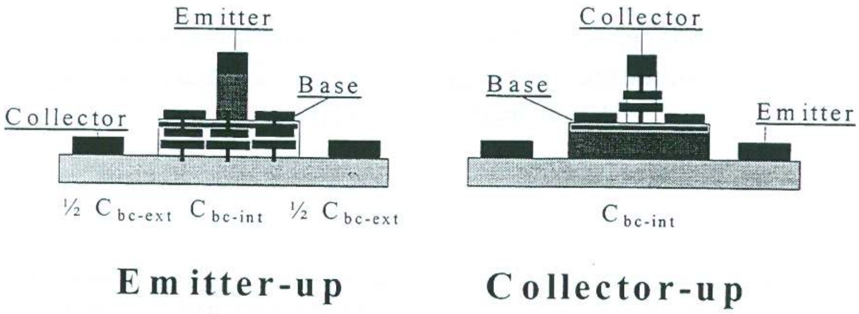

Figure 1 : Comparison of the emitter-up and the collector-up HBT topology.

COLLECTOR MATERIAL COMPARISON

Power and RF performances essentially depends on an optimized collector. Gao and Morkoç have proposed a « figure of merit » to compare different collector material (10) for power RF applications. This figure of merit C_{fm} considers the most important collector parameters such as the thickness Wc, the impurity concentration Nc, the maximum electrical field at breakdown ε_m, and the electron saturation velocity v_s. Wc and Nc are kept constant for better comparison (Wc = 1µm and Nc = 2×10^{16} cm^{-3}). This model does not take into account the transition effect between base and collector, which have a strong impact on the output characteristics.
The proposed figure of merit relates the four collector parameters (Wc, Nc, ε_m, v_s) and determines the collector performance C_{fm} by the following equation :

$$C_{fm} = Wc^{5/4}\, Nc\, \varepsilon_m\, v_s^{5/4} \qquad (1)$$

Table I compares several collector materials of widely used RF devices. The $In_{0.49}Ga_{0.51}P$ material parameters have been mostly determined through the present work (9). The last raw gives the figure of merit normalized to the GaAs collector.

Material	Eg (eV)	ε_m (10^5 V/cm)	$v_s(\varepsilon=10^5$V/cm) (10^7cm/s)	C_{fm} (10^{25} v $cm^{-3/2}$ $s^{-5/4}$)	C_{fm}/C_{GaAS}
Si	1.1 (11)	4.1 (11)	0.86 (10)	3.44	1.07
InP	1.35 (12)	4.4 (10)	1.1 (12)	5.02	1.56
GaAs	1.42 (11)	4.8 (13)	0.72 (13)	3.22	1.00
$Al_{0.3}Ga_{0.7}As$	1.78 (12)	6.5 (10)	0.86 (10)	5.45	1.69
$In_{0.49}Ga_{0.51}P$	1.89 (9)	7.6 (9)	0.71 (9)	5.01	1.56

Table I : Performance of different collector materials

The figure of merit shows that a 50% improvement is expected by using InGaP/GaAs D-HBT compared to S-HBT.

BORON IMPLANTED HETEROJUNCTIONS

Collector-up HBT's required to avoid the parasitic electron injection in the base. A study has been carried out to avoid such effect (14). The objective of this processing step is to transform the InGaP material into a high resistivity layer while preserving as much as possible the extrinsic base layer. The difficulty of this step stems from the fact that ions must cross the extrinsic base layer and stop into the InGaP emitter. Figure 2 shows the effect of 200keV boron implantation on 6×10^{19} cm^{-3} P+ GaAs base layer as a function of the ion doses and as a function of 416°C post-annealing duration. Below 5×10^{12} cm^{-2} doses, a 10% resistivity increase is observed with a good electrical stability even after a 1 hour long 400°C annealing.

In the case of 3×10^{17} cm^{-3} N-InGaP emitter the effect of boron implantation is quite sensitive. Figure 3 shows for the same condition of ion implantation and annealing a strong InGaP resistivity increase. This is obtained into an emitter layer covered by the P+ GaAs base layer. With this material the effect of temperature is no longer negligible and maximum InGaP resistivity is observed for doses of 5×10^{12} cm^{-2} and after 10mn and 1hour long annealing due to evolution of point defect concentration with annealing. Electrical characterizations of implanted InGaP layers have demonstrated that from room temperature to 200°C a deep level induced by ion implantation is present in the InGaP with an energy of 1.04 ±0.02eV below the conduction band, which explain the high resistivity of boron implanted InGaP material.

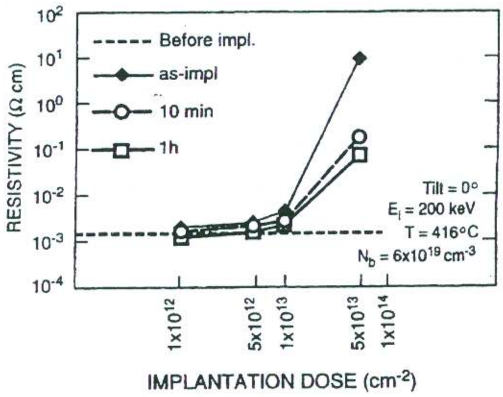

Figure 2 : Resistivity of P+ GaAs layer as a function of the boron implantation dose before implantation, as-implanted, after 10-min, and after 1-hr annealing at 416°C.

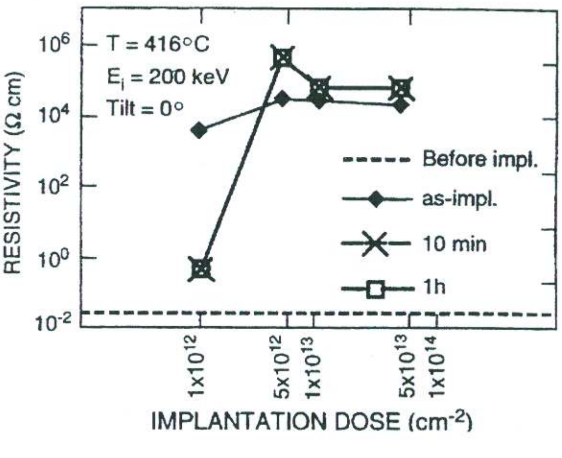

Figure 3 : Resistivity of an InGaP emitter as a function of the implantation dose before implantation, as-implanted, after 10-min, and after 1-hr annealing at 416°C.

DC CHARACTERISTICS OF COLLECTOR-UP DEVICES

The base-collector interface of D-HBT give rise to collector current variation as a function of V_{ce} at constant base current if one does not optimize the interface. This effect is mostly due to the reflection of electron flow at the exit of the base layer by the energy spike introduced by the conduction band discontinuity. To avoid the effect a 3 x 10^{17} cm^{-3} N -type GaAs spacer is introduced between the base and the 1µm thick 2 x 10^{16} cm^{-3} N-InGaP collector. Figure 4 shows the output characteristics of a collector-up D-HBT thanks to this N+ GaAs spacer. Near-ideal curves are observed.

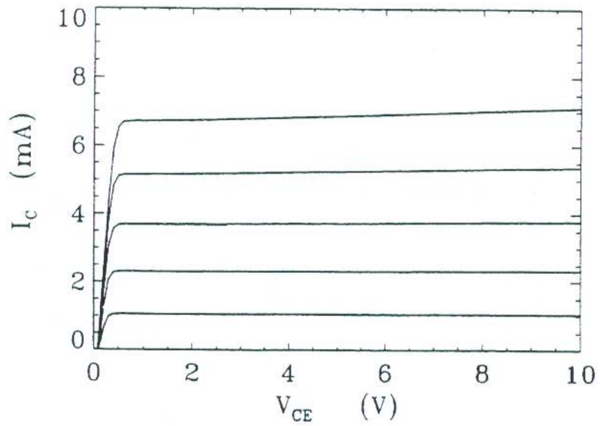

Figure 4 : DC output characteristics of Collector-up D-HBT

The breakdown voltage of devices is very important for power applications. The figure 5 shows the breakdown voltage BV_{ceo} of both S- and D-HBT's with 1µm thick 2 x 10^{16} cm^{-3} N-doped collector as a function of the current gain. An improvement of 80% is observed by using InGaP collector. Data points have been nicely fitted using the classical law (equation 2) (13) giving BV_{ceo} as a function of common base breakdown voltage BV_{cbo}, ε_m, the current gain β, and a constant n depending on the collector material.

$$BV_{ceo} = BV_{cbo}(1+\beta)^{-1/n} \qquad (2)$$

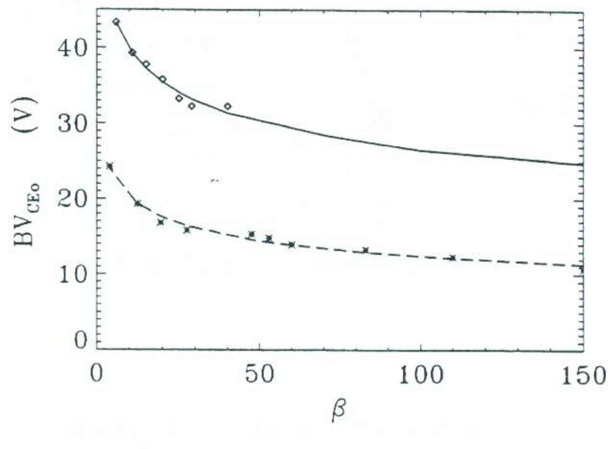

Figure 5 : BV_{ceo} depending on current gain for a D-HBT (diamond) and S-HBT (cross)

Table II give the value obtained from measurements shown in figure 5.

	unit	**GaAs**	**InGaP**
BV_{cbo}	V	34.25	61.75
n		4.54	5.49
ε_m	V/cm	4.9×10^5	7.6×10^5

Table II : Breakdown behavior of GaAs and InGaP collector

SMALL SIGNAL RF PERFORMANCES

S- and D-HBT have been processed for microwave analysis. In both case .6µm thick collectors with doping level of 3×10^{16} cm^{-3} have been used. In the case of D-HBT a N+ GaAs spacer of 25nm doped at 5×10^{17} cm^{-3} has been introduced between the base and collector to avoid electron flux reflection.

Figure 6 shows the typical RF performances of a 2x30µm^2 monofinger HBT bias at V_{ce} = 4V and I_c = 9.3mA. f_t is found close to 22GHz and f_{max}, obtained by an extrapolation using -20dB/dec of Ug, is equal to 115GHz. Classical S-HBT in emitter-up configuration would exhibit a f_{max} of 80GHz. These high gains are obtained with BV_{ceo} over 28V simultaneously instead of 18V for a S-HBT. The base-collector capacitance of this « collector-up » D-HBT extracted using a classical equivalent model gives a value of 13fF instead of 30fF for a classical « emitter-up » S-HBT. Dispersion of C_{bc} for the collector-up device is below 15% over a 3-inch wafer.

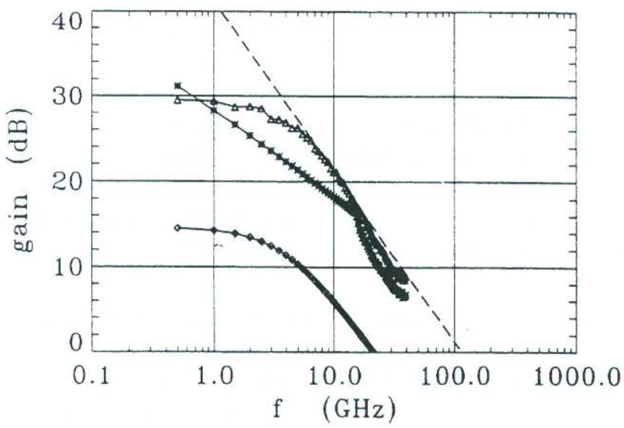

Figure 6 : RF gain of Collector-up D-HBT as a function of frequency (2x30µm^2, V_{ce} = 4V, I_c = 9.mA)

The collector-up S-HBT shows f_t of 28GHz and f_{max} equal to 121GHz at similar bias conditions. However BV_{ceo} is lower than the D-HBT one with a value of 16V.

The figure 7 shows a comparison of best published results in term of BV_{ceo} as a function of fmax. The collector-up InGaP/GaAs, both S-HBT and D-HBT. Our present results seem to be close to the theoretical limits of III-V material.

CONCLUSION

Collector-up InGaP/GaAs D-HBT seem very promising devices for microwave applications. The boron implantation into InGaP leads to selective sensitivity with P+ GaAs. This allows the development of industrial process favorable to industrial developments of collector-up devices. D-HBT's allow to reach high breakdown voltages while keeping high RF gains. Devices with performances close to limit of III-V material have been realized in term of breakdown voltage versus RF gain.

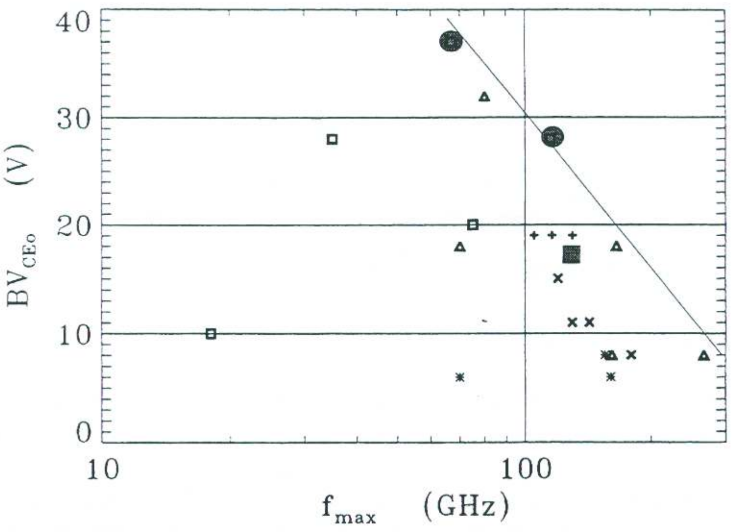

Figure 7 : Breakdown voltage versus fmax of different III-V devices
(gray circle : TH-LCR InGaP/GaAs D-HBT, open square : other GaAs D-HBT, triangle : InP/InGaAs D-HBT
+ : InGaP/GaAs HBT, x : AlGaAs/GaAs S-HBT)

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References :

1. W. Shockley, 1948, Claim 2 of US patent 2 569 347, filed 26 June.
2. W. Liu, T. Kim, P. Ikalainen, and A. Khatibzadeh, « High linearity power X-band InGaP/GaAs heterojunction bipolar transistor », 1994, IEEE Electron Dev. Lett., 15(6) 191-192.
3. H. Blanck, S.L. Delage, S. Cassette, E. Chartier, D. Floriot, M.-A. Poisson, C. Brylinski, D. Pons, P. Roux, P. Bourne, and P. Quentin, « Fully monolithic Ku and Ka-Band GaInP/GaAs HBT wideband VCOs », 1994, IEEE MTT-S Digest, 127-130.
4. I. Aoki, K. Tezuka, H. Matsuura, S. Kobayashi, T. Fujita, T. Yakihara, S. Oka and A. Miura, 1996, « 64GHz AlGaAs-HBT oscillator », Electr. Lett., 32(5) 463-464.
5. S. Pérez, D. Floriot, P. Maurin, P. Bouquet, P.M. Gutiérrez, J. Obregon and S.L. Delage, « Extremely low noise InGaP/GaAs HBT oscillator at C-Band », 1998, Electr. Lett., 34(8) 813-814.
6. A. Mallet, D. Floriot, J.-P. Viaud, F. Blache, J.M. Nebus, and S.L. Delage, « A 90% power-added-efficiency InGaP/GaAs HBT for L-band radar and mobile communication systems », 1996, IEEE Microwave and Guided Wave Lett., 6(3) 132-134.
7. F. Ali, A. Gupta, M. Salib, W. Veasel, and D.E. Dawson, « A 2-Watt and 8-14GHz HBT power MMIC with 20dB gain and >40% power-added efficiency », 1994, IEEE Trans. on Microwave Theory and Techniques, 42(12) 2635-2641.
8. A. Khatibzadeh, W. Liu, T. Henderson, J. Sweder, and S. Pierce, « High efficiency X-Band power amplifier », 1994, IEEE MM-W C Symp., 117-120.
9. A. Henkel, « Study and Realization of InGaP/GaAs "Collector-up" Double Heterojunction Bipolar Transistors of high performance RF applications », Fortschritt-Berichte VDI, Reihe 9 : Elektronik, Nr 275.
10. G.B. Gao and H. Morkoç, « Material based comparison for power heterojunction bipolar transistor », 1991, IEEE trans. on Electr. Dev., 38(11) 2410-2416.
11. S. Tiwari, « Compound semiconductor device physics, 1992, Academic press
12. N. Matine, « Réalisation et caractérisation de transistors bipolaires à hétérojonction InP/InGaAs/Métal (structure MHBT) », PhD Thesis, 1996, Université Paris XI, U.F.R. scientifique d'Orsay, France.
13. M. Sze, « Physics of semiconductor devices », 1981, John Wiley & Sons, 2nd edition.
14. A. Henkel, S.L. Delage, M.-A. diForte-Poisson, H. Blanck, and H.L. Hartnagel, « Boron implantation into GaAs/ $In_{0.49}Ga_{0.51}P$ heterostructures », 1997, Jpn. J. Appl. Phys., (36)175-180.