Advances in GaAs HBT Power Amplifiers for Cellular Phones and Military Applications

(Invited Paper)

Fazal Ali, Aditya Gupta and Aiden Higgins*
Westinghouse Electric Corporation, Advanced Technology Center
P.O. Box 1521, MS 3K13, Baltimore, MD 21203

*Rockwell International Science Center
1049 Camino dos Rios
Thousand Oaks, CA 91360

Abstract

This paper provides a synopsis of the research and development efforts in the USA in power amplifiers designed with GaAs Heterojunction Bipolar Transistor (HBT) technology. Design issues, performance and reliability of power amplifiers using AlGaAs/GaAs HBTs for RF, microwave and millimeter-wave applications are discussed. Key device parameters influencing different frequency applications are highlighted.

Introduction

Power amplifiers (PAs) are one of the key components for communication transmitter systems. This critical component governs much of the transmitter's size, cost, performance and manufacturability. Differentiating factors such as frequency, bandwidth, supply voltage, output power, efficiency and mode of operation drive the requirements for power amplifiers for commercial and military systems. Cellular phones and base stations operating in the 800MHz to 1.9GHz band, satellite communication services at 1.5 GHz, and wireless local area network (WLAN) manufacturers are the main customers for RF power amplifier ICs. In the microwave and millimeter-wave frequency range, power amplifiers are mainly used for military radars and secured communications, point to point radios and automotive radar applications. Table 1 outlines some significant differences between commercial and military power application requirements.

GaAs HBT For PAs: The RIGHT CHOICE

GaAs HBTs designed for microwave power applications have shown marked improvements in output power, power-added efficiency (PAE) and bandwidth in recent years. Amplifiers, with 1-5 W output power, exhibiting PAE in excess of 38% over 6-18 GHz band [1], 44% over 8-14 GHz band [2], 58% over 5-10 GHz band [3], 45% over 7-11 GHz band [4], and output power over 12 Watts in the X-Band [5] have been recently reported. As a consequence of these impressive results, HBTs are currently being considered as replacements for MESFETs in the next generation solid state power amplifiers requiring increased efficiency, linearity, power output and single positive voltage operation.

AlGaAs/GaAs HBTs are attractive for power amplifier applications compared to other microwave devices for several reasons. The power performance of HBTs are limited by thermal rather than electrical constraints. Thus, careful thermal design to control the maximum junction temperature is key to realizing the full microwave potential of GaAs HBTs; namely [6,7,8]:

- High power density operation originating from higher current handling capability. This provides much smaller device size with higher input impedance and higher output power compared to MESFET amplifiers. The output matching network becomes simpler due to the higher output impedance.
- High pulse-up capability - 3-4 dB higher output power than CW mode for short (few µs) pulses.
- Well controlled breakdown voltage with collector epitaxial design (thickness and doping). Unlike MESFETs and PHEMTs, the breakdown voltage is independent of input voltage and is insensitive to device processing steps.
- The transconductance increases with current and is typically much higher than a MESFET at comparable bias.
- High efficiency Class B and C operation without sacrificing output power performance and needing reduced power supply voltage [9,10,11].
- Extremely low leakage current requiring no extra DC switch (unlike MESFET) to turn off the power supply in standby mode.

- Single positive supply voltage operation. This performance eliminates one of the primary disadvantages of MESFETs/PHEMTs which require additional negative voltage usually obtained by a switching regulator or a charge pump.
- Good combining efficiency due to high uniformity of device parameters across large devices. This excellent uniformity of device parameters stems from the maturity of the materials and fabrication technology.
- High yield (>95% RF yield on 0.5W /X-Band HBTs obtained routinely), low cost, optical lithography process - 1-5 µm minimum geometry depending on frequency of application.

Research and development efforts in HBT power amplifiers in the USA have mainly focused in two areas: *non-linear and linear applications*. In non-linear applications, PAs are usually biased in Class AB mode to achieve the maximum PAE under few dBs of gain compression. Radar transmitters and analog cellular phones operate in this saturated mode. Digital phones and communication transmitters utilize linear PAs for low intermodulation distortion (IMD). Although the exponential I-V characteristic in HBTs is thought to make this device very non-linear, both analysis and experimental results indicate otherwise [12,13]. The low output conductance of the HBTs associated with the high Early voltage, high transconductance and slow variation of current gain (β) with collector current density can be used to achieve highly linear devices and circuits. The base resistance and the series feedback effect of the emitter ballast resistance also help in linearizing the HBT. The major contribution to non-linearities in an HBT originate from the modulation of the base-collector feedback capacitance (C_{bc}). This gives rise to phase distortion (AM-PM) in a common-emitter (CE) HBT which in turn affects spectral regrowth, a manifestation of IMD in digital cellular phones. The influence of this capacitance can be reduced or even suppressed by reducing the thickness of the collector layer and properly tailoring its doping profile.

The biggest design challenge for linear PAs is to maintain high efficiency and still achieve very good carrier to intermodulation ratio (C/I) or adjacent channel power rejection (ACPR) for digital cellular phones; some recent HBT results have demonstrated this. Researchers from SHARP used different device bias conditions and load-lines to minimize phase distortion and simultaneously achieve excellent linearity and good PAE [14,15]. Another possible method of achieving high efficiency with high ACPR is by <u>using a cascode HBT with different CE and CB device sizes</u>. This configuration, with proper design will provide self phase distortion compensation, minimize signal distortion and maintain high efficiency similar to the recently demonstrated MESFET case [16].

HBT Technology Issues

HBTs employ semiconductors with varying bandgaps in different regions of the device. The availability of multiple bandgaps provides additional degrees of freedom for performance optimization. Either just the emitter or the emitter and collector are fabricated in a semiconductor with a bandgap higher than that of the base region. While HBT operation has been demonstrated in many different semiconductors, the GaAs/AlGaAs, GaAs/InGaP and, most recently, Si/SiGe materials systems are the most promising candidates for power amplification. Of these, Si/SiGe HBTs are expected to be useful for low microwave frequencies (<3 GHz) while the other two are expected to be viable at least up to Ka band. In this paper, the GaAs/AlGaAs HBT will be used to describe the salient features and advantages of heterojunction bipolar transistors.

The advantage of GaAs HBTs over the commonly available silicon *homojunction* bipolar transistors (BJTs) is derived from the use of a wide bandgap material (e.g. AlGaAs) for the emitter and GaAs for both base and collector regions. The N-p-n structure (N denotes wider bandgap than p and n regions) has performance superior to the P-n-p structure and, for microwave and high speed analog applications, it is the device of choice. Only N-p-n transistors are discussed in this paper. In GaAs HBTs, the aluminum mole fraction in the emitter is restricted to 30% or below because of the onset of undesirable deep levels known as DX centers in AlGaAs of higher aluminum content. At this level, the bandgap of $Al_{0.3}Ga_{0.7}As$ is larger than that of GaAs by ~0.375 eV. By properly grading the transition from GaAs to AlGaAs, the majority of this bandgap discontinuity is made to appear in the valence band between the base and emitter regions. This suppresses the injection of holes from base to emitter under normal bias conditions and leads to an extremely high intrinsic injection efficiency (J_n/J_p) in accordance with the following expression:

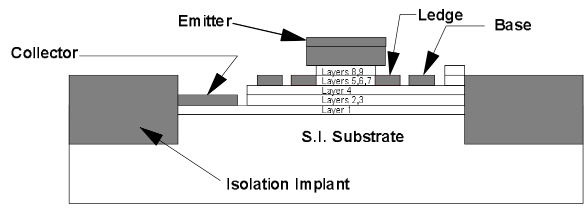
$$v_e = \frac{J_n}{J_p} \propto \frac{n_e}{p_b} \times e^{(-\frac{\Delta E_g}{kT})}$$

where n_e and n_p are the doping densities in the emitter and base regions respectively and ΔE_g is the band gap discontinuity. A large ν_e is required for efficient transistor operation. In Silicon BJTs, where $\Delta E_g = 0$, this is accomplished by making n_e/n_p » 1, i.e. doping the emitter much more heavily than the base. In HBTs, the same effect can be achieved with n_e/n_p « 1 because of the higher bandgap of the emitter as compared to the base; a ΔE_g = 8kT (~ 200 meV) can offset a doping ratio of ~3000! This flexibility is used to dope the base region in HBTs to ~$5x10^{19}cm^{-3}$, almost 100 times the value in a typical Si BJT. The high base doping allows use of thin (≤0.1µm) base layers while maintaining low base sheet resistance (≤ 200Ω/❐). Additional benefits are extremely high base punchthrough voltage, negligible base width modulation (which leads to Early voltages above 300V), and low transit time across the base. The emitter layer is doped in the $10^{17}cm^{-3}$ range, almost 1000 times less than in a typical Si BJT. This benefits the HBT by lowering the base-emitter depletion capacitance and improving the high frequency performance.

Another important benefit of high base doping in HBTs is the ability to use relatively large size emitters. A key process driver in high performance and high frequency Si BJTs is the need to reduce emitter widths below 1 µm to reduce current crowding and base spreading resistance. These concerns are absent in case of the HBT due to its low base sheet resistance. Devices with emitter widths as large as 2 µm are useful up to 18 GHz and, below 3 GHz, emitter widths of 3 - 5 µm are often employed. The larger emitters can be fabricated with near 100% yield. The emitter utilization factor, Ue, is a quantitative measure of how uniformly the current is distributed across the width of the emitter stripe and how effectively the emitter is being utilized. A high value of Ue is required for efficient power amplification. At a given frequency, Ue decreases with increasing emitter width and current density and for a given width, Ue decreases with increasing frequency and current density.

GaAs HBTs are fabricated on epitaxial active layers grown either by MOCVD or by MBE. Other materials systems employ alternate epitaxial growth techniques where needed. A schematic cross-section of the device is shown in Figure-1a with the active layers identified in Figure-1b.

Device parameters such as epitaxial layer thicknesses and doping levels, contact sizes and layout etc. must be optimized for the particular frequency and application at hand. Table-2 lists some of the performance parameters and trade offs that must be considered in designing the HBT and Table-3 illustrates examples of GaAs HBTs which have been optimized for typical commercial and military applications. As expected, optimization of the HBT is most difficult for millimeter-wave frequencies and easiest for RF frequencies where there exists a large performance margin. At millimeter-wave frequencies, the biggest challenge is to reduce C_{bc} in order to obtain gain. Several approaches have been demonstrated towards this goal - self-aligning the base and emitter contacts to minimize ledge width and reducing the parasitic capacitance between the base contacts and the collector by removing the charge under the contacts either by implantation or by etching are two methods with promise. An optimized HBT exhibits many of the requirements for efficient power amplification - high gain, low knee voltage, high breakdown voltage, linearity, compact size, reproducibility and low cost.



(a)

Layer #	Name	Al or In mole fraction	Type	Conc. (cm^{-3})	Thickness (µm)
1	Sub-collector	0	n+	$5x10^{18}$	0.6
2	Collector	0	n	$3x10^{16}$	0.7
3	Base	0	p+	$4x10^{19}$	0.1
4	Emitter grading	0→0.30	n	$5x10^{17}$	0.03
5	Emitter	0.30	n	$5x10^{17}$	0.1
6	Cap grading	0.30→0	n+	$1x10^{18}$	0.03
7	GaAs Cap	0	n+	$5x10^{18}$	0.2
8	InGaAs Cap	0→0.60	n+	$>3x10^{19}$	0.08

(b)

Figure 1. A schematic cross-section of a power HBT and a typical active layer profile.

In addition to all the benefits described above, current GaAs HBTs also have some significant shortcomings, namely: high thermal resistance, “current collapse” and reliability concerns. These are discussed further in the following paragraphs.

Thermal Issues: The thermal resistance of microwave power devices fabricated on GaAs is generally high due to the poor thermal conductivity of this semiconductor; 0.44 $Wcm^{-1o}C^{-1}$ at 25ºC, about 33% of the value for Si. This is especially significant for GaAs HBTs which have an intrinsically high power density, a property of all bipolar devices. For RF applications the most common solution is to back off on the current density (and hence the power density) and use a larger device to obtain the required power. This solution is possible because typical applications have very narrow bandwidth requirements and the HBT has significant gain. At millimeter-wave frequencies device size has to be minimized to maximize gain and it is imperative that the HBT be operated at a high current (and power) density. The thermal resistance of millimeter-wave devices must be reduced without increasing parasitics such as C_{bc}. For these situations, several novel methods for extracting heat generated at the base-collector junction must be employed. These include putting a heat sink on the emitter to extract heat from the top of the device [17,18] and removing the GaAs underneath the active area and replacing it with a high conductivity material (e.g. gold) [4]. Examples will be shown at the conference. GaAs HBTs also suffer from a thermal phenomenon known as "current collapse" where one emitter finger begins to draw all the device current at the expense of other emitter fingers [19]. This can lead to a severe reduction in current gain or catastrophic failure due to localized heating. The solution to this problem lies in designing adequate ballast resistors in series with each base-emitter junction.

Reliability Concerns: Satisfactory reliability of GaAs HBTs has not yet been established for all applications. The typical long term failure mode is a gradual decrease in current gain under both dc and rf stress [20]. The rate of decrease is accelerated by temperature and current density. For RF applications where current density tends to be low (3-15 kA/cm^2), several manufacturers have demonstrated, under dc stress, MTTF $>10^7$ hours at 125ºC junction temperature [21] which is adequate for fabricating reliable products. At higher frequencies and for larger bandwidths the devices must operate at higher (40-60 kA/cm^2) current densities. Under these conditions, MTTF $>10^5$ hours at 125ºC have been obtained. One laboratory has observed MTTF $>10^6$ hours at 200ºC junction temperature at 60 kA/cm^2 by using InGaP in place of AlGaAs in the GaAs HBT structure [22]. This result has not yet been widely duplicated. The failure mechanism in GaAs HBTs is believed to be due to the migration of dislocations to the active base-emitter region and its solution is expected to come from an innovation in the materials technology.

Demonstrated HBT Power Amplifiers

Cellular HBT PAs

HBTs have finally made the transition from research labs into the high volume cellular communication market. Both RF Micro Devices (using TRW's HBT process) and Rockwell International have recently introduced plastic packaged power amplifiers for 849 MHz Advanced Mobile Phone Service (AMPS) and 1.9 GHz personal communication services (PCS) respectively. Table-4 provides a performance summary of these products [23,24].

Narrowband and Broadband HBT Power Amplifiers

HBT power amplifiers have been demonstrated from L to Q bands. Narrowband amplifiers with <1 GHz bandwidth (Table-5) are being developed for RF, microwave and millimeter-wave applications. The highest power from a single narrowband chip comes from a MMIC developed at Texas Instruments. This MMIC provided over 10 W at 8.75 GHz with >50% power added efficiency. The bandwidth of this amplifier is too narrow for most phased array radar applications. Highly linear HBT power amplifiers have also been developed as illustrated in Table-6. The PAE of these amplifiers is generally lower because they are operated several dB backed off from saturation.

Power HBT amplifiers at millimeter-wave frequencies have only recently been demonstrated. Research efforts in mm-wave HBTs are as yet quite small as compared to devices for the X and Ku bands. The published data is shown in Table-5. Rockwell has recently demonstrated "Quasi-Optical Amplifiers" with the potential for obtaining large powers at millimeter-wave frequencies [25]. In this method, a large number of small amplifiers, each operating at the maximum power and gain afforded by small devices, are arranged in a rectangular array. Each amplifier in the array is equipped with orthogonal antennas that receive in one polarization and, after amplification, retransmit in the orthogonal polarization; power combining occurs in space. This approach achieves massive parallelization of many small amplifiers without the prohibitive losses of corporate power combining networks. In one demonstration, powers of 36 pairs of small push-pull HBTs were combined at 40 GHz, to achieve 28dBm with a PAE of 14% at the wafer.

Mutli-watt broadband microwave power amplifiers have also been demonstrated in HBT technology. Table-7 is a summary of the most significant results.

Conclusion

Interest in GaAs power HBT technology stems from the *potential* and *demonstrated* performance of circuits employing this device. HBT power MMICs require only one power supply, are linear and extremely efficient, permit mutli-octave bandwidths and are relatively easy to fabricate with good yield. These attributes are attractive to potential users and this has stimulated development of power amplifiers using HBTs for both commercial and military applications. This paper has provided a summary of the products currently available. HBT technology has progressed to the point where reliable products can be fabricated at RF frequencies and, by using novel structures to extract heat from the device, reliable performance at higher frequencies can also be expected. This technology is still relatively young and much improvement is expected as it becomes more widely used.

REFERENCES

[1] M. Salib, A. Gupta, F. Ali and D. Dawson, "A 1.8W, 6-18 GHz HBT MMIC Power Amplifier with 10 dB Gain and 37% Peak Power Added Efficiency," IEEE Microwave And Guided Wave Lett., Vol. 3, No. 9, September 1993, pp. 325-326.

[2] F. Ali, A. Gupta, M. Salib, B. Veasal and D. Dawson, "A 2 Watt, 8-14 GHz HBT Power MMIC with 20 dB Gain and 40% Power-Added Efficiency," IEEE Transactions on Microwave Theory and Techniques, December Issue, 1994.

[3] M. Salib, F. Ali, A. Gupta, D. Dawson and B. Bayraktaroglu, " A 1 Watt, 5-10 GHz HBT amplifier with 58% Peak power-Added Efficiency," IEEE Microwave and Guided-Wave Letters, October 1994.

[4] J. Komiak and L. Yang, “5 Watt High-Efficiency Wideband 7 to 11 GHz HBT Power Amplifier,” IEEE 1995 Microwave and Millimeter-Wave Monolithic Circuits Symposium Digest, pp. 17-20.

[5] M. Khatibzadeh, B. Bayraktaroglu and T. Kim, "12W Monolithic X-Band HBT Power Amplifier," IEEE 1992 Microwave and Millimeter-Wave Monolithic Circuits Symposium, June 1992, pp. 47-50.

[6] F. Ali and A. Gupta (Eds.), *HEMTs and HBTs: Devices, Fabrication and Circuits*. Norwood, Massachusetts.: Artech House, 1991.

[7] B. Bayraktaroglu, "GaAs HBTs for Microwave Integrated Circuits," Proceedings of the IEEE, Vol. 81, No. 12, December 1993, pp. 1762-1785.

[8] J. A. Higgins, "GaAs Heterojunction Bipolar Transistors: A Second Generation Microwave Power Amplifier Transistor," Microwave Journal, pp. 176-194, 1991.

[5] W. Liu, S. Nelson, D. Hill, and A. Khatibzadeh, "Current Gain Collapse in Microwave Multi-Finger Heterojunction Bipolar Transistors Operated at Very High Power Density," IEEE Trans. Electron Dev., Vol. 40, 1993, p. 1917-1927.

[6] L. Liou, B. Bayraktaroglu, and C. Huang, "Thermal Stability Analysis of Multi-Finger Microwave AlGaAs-GaAs Heterojunction Bipolar Transistor," IEEE Int. Microwave Symp. Dig., June 1993, pp. 281-284.

[7] D. Dawson, A. Gupta and M. Salib, "CW Measurement of HBT Thermal Resistance," IEEE Trans. Electron Devices, Vol. 39, No. 10, October 1992, pp. 2235-2239.

[8] B. Bayraktaroglu, J. Barrette, L. Kehias, C. Huang, R. Fitch, R. Neidhard and R. Scherer, "Very High-Power Density CW Operation of AlGaAs/GaAs Microwave Heterojunction Bipolar Transistors," IEEE Elec. Dev. Lett., Vol. 14, No. 10, pp.493-495, October 1993.

[9] M. A. Khatibzadeh and B. Bayraktaroglu, "High-Efficiency, Class-B, S-Band Power Amplifier," 1990 IEEE MTT-S Digest, May 1990, pp.993-996.

[10] F. Ali, A. Gupta, M. Salib and B. Veasel, “A Study of Class C operation of GaAs Power HBTs,” 1995 IEEE International Microwave Symposium, May 1995.

[11] F. Ali, C. Aitchison, and B. Hewitt, “GaAs Power HBTs With 84% Power-Added Efficiency Operating in C-X Band,” 1995 European Microwave Conference Digest, September 1995.

[12] N.L. Wang et al., “AlGaAs/GaAs HBT Linearity Characteristics,” IEEE Trans. on MTT, Vol. 42, pp. 1845-1850, October 1994.

[13] S. Maas et al., ”Intermodulation in Heterojunction Bipolar Transistors,” IEEE Trans. on MTT, Vol. 40, pp. 442-448, 1992.

[14] T. Yoshimasu, N. Tanba and S. Hara, “High Efficiency HBT MMIC Linear Power Amplifier for L-Band Personal Communication Systems,” IEEE Microwave and Guided Wave Letters, pp. 65-67, March 1994.

[15] T. Yoshimasu, “High Power AlGaAs/GaAs HBTs and Their Applications to Mobile Communication Systems,” 1995 IEEE IEDM Digest, pp. 786-790, December 1995.

[16] H. Hayashi et al., “Quasi-Linear Amplification Using Self Phase Distortion Compensation Technique,” IEEE Trans. on MTT, November 1995.

[17] B. Bayraktaroglu et al., “Very High Power Density CW Operation of AlGaAs/GaAs Microwave Heterojunction Bipolar Transistors,” IEEE Elect. Dev. Lett., Vol. 14, No. 10, pp. 493-495, October 1993.

[18] J. A. Higgins, “Thermal Properties of GaAs HBTs,” IEEE Trans. on Electron Devices, Vol. 40, No. 12, December 1993.

[19] W. Liu et al., “Current Gain Collapse in Microwave Multi-Finger Heterojunction Bipolar Transistors Operated at Very High Power Density,” IEEE Trans. on Electron Dev., Vol. 40, pp. 1917-1927, 1993.

[20] A. Gupta et al., “Degradation of an X-Ku Band AlGaAs/GaAs Power HBT MMIC Under RF Stress,” IEEE Microwave and Guided Wave Letters, January 1996.

[21] F.M. Yamada et al.” Reliability Analysis of Microwave GaAs/AlGaAs HBTs with Beryllium and Carbon Doped Base,” IEEE MTT-S Digest, pp. 739-742, 1992.

[22] T. Takahashi et al., “High Reliability InGaP/GaAs HBTs Fabricated by Self-Aligned Process,” IEDM Tech. Digest, pp. 191-194, 1994.

[23] P. Walters et al., “A Low Cost Linear AlGaAs/GaAs HBT MMIC Power Amplifier With Active Bias Sensing for PCS Applications,” IEEE GaAs IC Symposium Digest, pp. 67-70, October 1995.

[24] RF Micro Devices, “A High Efficiency HBT Analog Cellular Power Amplifier,” Microwave Journal, pp. 168-172, January 1996.

[25] C. Liu et al., “Monolithic 40 GHz 670mW HBT Grid Amplifier,” 1996 Microwave Symposium, June 1996.

Table-1 Differences Between Cellular & Military PA Requirements

Parameters	Cellular PA	Military PA
Frequency	0.8 - 2GHz	S thru W Band
Bandwidth	< 50 MHz	> 2 GHz
Supply Voltage	≤5V, Single +ve	≥9V, Dual, +ve or -ve
Mode of Operation	CW or Digital Modulation	Pulsed
Power Output	≤1 Watt (compressed or linear)	≥2 Watt (compressed)
PAE	>60% (CW), >40% (DM)	>40% (3 GHz BW in X-Band)
Development Cycle	Packaged product in < year	State of the art result in a year
Reliability	Extremely Important	Something to worry about IF system goes to production
MMIC cost	Free ! (+ Package & Test cost)	Medium to High
Quantity	1M / month	1M / Million Years (i.e. very low)

Table-2 HBT Design Tradeoffs

Parameter	Notation	Design Considerations
Emitter contact width	We	• Emitter utilization factor decreases with an increase in We, frequency and current density • Device fabrication is easier with larger We
Emitter ledge width	Wl	• Slow improvement in device reliability with Wl > 0.5μm • Increasing Wl increases base resistance and Cbc
Base contact width	Wb	• Decreasing Wb below 0.75μm increases base contact resistance • Increasing Wb increases Cbc
Base layer doping	Pb	• High Pb reduces base resistance (Rb), improves emitter utilization factor and increases Early voltage • Current gain declines with increasing Pb • Current gain stability degrades with very high Pb
Base layer thickness	Lb	• Increasing Lb increases base transit time and reduces f_T • Increasing Lb reduces base sheet resistance with corresponding improvement in Rb and emitter utilization factor
Collector layer doping	Nc	• Decreasing Nc increases base-collector junction breakdown voltage and Cbc • Decreasing Nc reduces the maximum current at which the device can be operated due to Kirk effect
Collector layer thickness	Lc	• Increasing Lc increases collector transit time, reduces f_T and increases base-collector breakdown voltage
Base-collector capacitance	C_{bc}	• Cbc is one of the most significant device parasitic in common-emitter operation. • Power gain increases with lower Cbc
Unity current gain frequency	f_T*	• f_T is determined by the total transit time across the device (τ_{ec}). It should be at least 1.5 times the operating frequency
Max. frequency of oscillation	f_{max}*	• f_{max} is determined by f_T and device parasitics Rb and C_{bc}. It should be at least twice the operating frequency
Thermal resistance	R_{th}	• Reducing R_{th} reduces junction temperature, increases device reliability and permits device operation at higher current density

* $f_T = \frac{1}{2\pi\tau_{ec}}$ and $f_{max} \approx \sqrt{\frac{f_T}{8\pi C_{bc} R_b}}$

Table-3 Characteristics of Typical HBTs Designed for Commercial/Military Applications

	We (µm)	Wl (µm)	Wb (µm)	Pb (cm^{-3})	Lb (µm)	Nc (cm^{-3})	Lc (µm)	f_T (GHz)	f_{max} (GHz)
RF (portable)	3-5	0.8-1.0	1.25	$1\text{-}3x10^{19}$	0.15	$3x10^{16}$	0.5	20	40
RF (base station)	3-5	0.8-1.0	1.25	$1\text{-}3x10^{19}$	0.15	$1\text{-}2x10^{16}$	1.0	15	30
microwave	1.5-2.0	0.3-0.6	1.0	$4x10^{19}$	0.08-0.1	$1\text{-}2x10^{16}$	1.0	25-35	>50
millimeter-wave	1-1.25	0.2	0.7	$4\text{-}6x10^{19}$	0.05-0.07	$2\text{-}5x10^{16}$	0.6	40-70	>100

Table-4 Cellular HBT Power Amplifier Products

Company	**RF Micro Devices**	**Rockwell International**
Frequency	824 - 849 MHz	1850 - 1910 MHz
Application	AMPS/ETACS	PCS
Gain(dB)	25	22
Power Out (dBm)	30.8 (CW)	29 (linear)
PAE (%)	60	40
Vcc (Volts)	4 to 4.8	5
Power Down Feature	Yes	Yes
Adjacent Channel Power Rejection (ACPR)	----	>30 dBc
Out of Band Noise Power	-90 dBm / 30 KHz	----
Reliability (MTTF)	10^7 Hrs @ 125 °C	6 x 10^8 Hrs @ 50 °C
Plastic Package Type	SOIC 16 Lead	SSOP 16 Lead
Cost	<$5 in Volume	$15 in 1000 Qty

Table-5 Narrowband HBT Power Amplifiers

Organization	Frequency (GHz)	No. of stages	Pout (dBm)	PAE (%)	GP (dB)	Year Reported
Rockwell	1.8	1 (CE)	34.0	51	14	1991
Texas Instruments	3	1 (CE) Hybrid	30.4	61	12.3	1990
Texas Instruments	9.5	2 (CE)	41.0	31	10.8	1992
Texas Instruments	8.75	2 (CE)	40.1	53	13.1	1994
Rockwell	35	1 (CB) Hybrid	17.0	30	7.8	1992
Raytheon	35	3 (CE)	19.6	11	12.6	1994
Raytheon	35	2 (CE)	29.0	15	5	1994
Rockwell	44	1 (CB) Hybrid	24.0	23	5	1993

Table-6 HBT Linear Power Amplifiers

Organization	Circuit Implementation	Frequency (GHz)	Pout two-tone (dBm)	PAE two-tone (%)	dB backed-off from 2dB	C/I (dBc)
RF Micro Devices (TRW process)	MMIC + Hybrid	0.8 - 0.95	21.3	33	*	-31
Martin Marietta	MMIC + Hybrid (output) (Cascode)	4.9	37.2	34.7	5	-29
Martin Marietta	MMIC (Cascode)	5.4	32.0	37.4	5	-29
Texas Instruments	Hybrid	7.5	*	*	6	-28.7
Rockwell	MMIC (CE)	7.5-12	26	*	2.5	-30

* not reported

Table-7 Wideband HBT Power Amplifiers

Organization	Bandwidth (GHz)	No. of stages	Frequency (GHz)	P_o (dBm)	PAE (%)	G_P (dB)
Texas Instruments	8-10	1 (CE)	8.0	37	23	5
			9.0	37	21	5
			10.0	36.5	19	5
PM/Rockwell/ Hughes	6-10	1 (Cascode)	6.0	30	33	12
			8.0	31	46	13
			10.0	29	26	11
Rockwell	7.0-12.0	1 (CB)	7.0	34.8	32	6
			9.5	36.0	24	5
			12.0	34.8	15	3.5
General Electric	6-10	1 (Cascode)	6.0	32.5	43	12.5
			8.0	31	31	11
			10.0	31	46	9.5
Westinghouse	8-13	1 (CE) (hybrid)	8.0	30	28	6
			10.5	31	42	7
			13.0	31	44	7
Westinghouse	9-14	1 (CE)	9.0	29	30	6
			11.5	31	41	8.5
			14.0	29	37	7.5
Westinghouse	6-18	2 (CE)	6.0	32	30	9
			12.0	32.5	25	10
			18.0	31	29	8
Westinghouse	8-15	2 (CE)	8.0	29.5	26	14.5
			11.5	31	42	16.5
			15.0	29.5	43	15
Westinghouse	8-14	2 (CE)	8.0	33.4	45.0	16.5
			11.0	33.5	45.0	16.5
			14.0	33.2	42.0	16.3
Martin Marietta	7-11	1 (Cascode)	7	37	49	12
			9	37.8	38	13
			11	37.2	44	11