# RF Applications Drive Semiconductor Process Technology Choices

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In recent years, consumers' appetite for cellular phones and other wireless products has driven an enormous market for semiconductors and other electronic and mechanical components. All of these wireless products rely on battery technology to provide power, and on low power semiconductors to maximize battery life. These commercial opportunities and technical requirements ultimately create the motivation to develop semiconductor processes and manufacture products that can meet such challenging technical demands.

This article will take a look at three specific semiconductor processes providing an overview of each. Additionally, a comparison of three dual band LNA products designed using these different process technologies will be presented. Suggestions will be made on which technology is best suited for some of the key functions within a cellular phone or other wireless system.

The three technologies that will be discussed are gallium arsenide (GaAs) hetero-junction bipolar transistor (HBT); silicon germanium (SiGe) bipolar/complementary metal oxide semiconductor (BiCMOS); and silicon BiCMOS. The basic transistor and passive component attributes will be provided, allowing the reader to compare these process technologies based on their own specific circuit performance requirements. The majority of data presented will be based on IBM's 4S BiCMOS process, IBM's 5HP SiGe BiCMOS process and RF Micro Devices' GaAs HBT process.


▲ **Choosing the best semiconductor process for a particular application balances performance, cost, reliability and availability.**

### Semiconductor technologies: A brief look

Most semiconductor products today are digital in nature and are manufactured with CMOS technology. CMOS is known to offer comparatively low power consumption, and, due to the high volume production, low cost. We are seeing more wireless products being developed with pure CMOS, with the intent to take advantage of these key benefits. However, CMOS is usually limited to lower performance radios or to the intermediate frequency functions in medium performance radios. CMOS is exclusively used for the baseband processing function within cellular phones and other wireless products.

Bipolar technologies have historically been used where high performance is required. Many of the RF and IF semiconductor products available today are manufactured with bipolar technologies with a transistor $f_T$ of 15 GHz to 25 GHz. Additionally, GaAs MESFET technology has been used for the RF LNA and mixer functions and, in some cases, power amplifiers.

It was about ten years ago that the semiconductor industry was debating whether or not the world would pay for the benefits that BiCMOS technology provides. The combination of CMOS and bipolar transistors on the same die is very attractive for many applications where analog functions with digital control are required in the same device. Other aspects of BiCMOS allow the designer to maximize performance and minimize power consumption. While these technologies were at the leading edge for several years, more advanced process technologies, including GaAs HBT and silicon germanium BiCMOS, now lead the way.

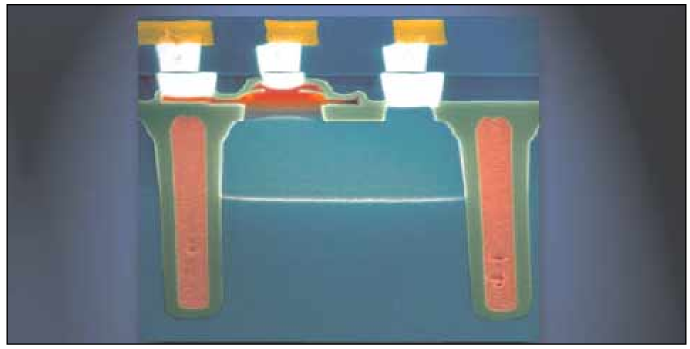
GaAs HBT technology is used in very high volumes to provide the power amplifier function for many of today's mobile phones. This technology is largely accepted as the best solution for applications where linearity — the ability to eliminate signal distortion — is required. While GaAs HBT is well suited for power amplifiers, it would not be considered appropriate for functions where the combination of analog and digital is required on the same die. GaAs HBT is an example where a technology's inherent attributes are used to the maximum benefit of a niche application.

Silicon germanium (SiGe), having been developed over the last ten years, is just starting to surface in new RF products where low noise and linearity are required. High levels of integration plus improvements in performance and cost have been demonstrated with SiGe. The primary weakness of SiGe — its low breakdown voltage — limits its use in certain applications. Similarly, as when BiCMOS was the newest technology, silicon germanium (SiGe) is being promoted as the best technology for all applications, which is unlikely.

With the exception of GaAs HBT, all of these technologies have gained some of their speed-related performance ($f_T$) improvements through advances in photolithography techniques. HBT photo "technology" is five to ten years old compared to Si. Its speed is derived from epitaxial growth of layers. Performance increases in higher $f_T$ can result in faster circuits or lower power consumption. Power consumption improvements are achieved as a result of lower bias currents for the same speed, as well as lower capacitive loading. It should also be noted that for most process technologies, improvements in linearity and power consumption are ongoing.

## Where technology and products meet

In this section, we will take a closer look at these technologies and discuss situations in which a designer can take advantage of each technology's inherent benefits. Details of each technology will be presented for comparison of key performance attributes.



▲ SiGe Cross section from IBM 5HP process. (Source: IBM)

| Parameter | Units | Standard HBT | High BV HBT |
|---|---|---|---|
| Beta | | 113 | 97 |
| $V_A$ | V | 61 | 132 |
| $B_{vceo}$ | V | 3.3 | 5.3 |
| $B_{vebc}$ | V | 4.2 | 4.1 |
| $f_T$ | GHz | 48 | 28 |
| $f_{max}$ | GHz | 68 | 57 |

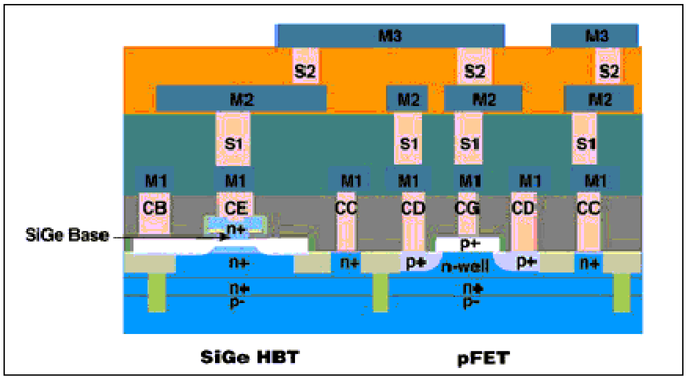
▲ Table 1. Transistor parameters for the two HBT device types on the IBM 5HP process.

| Parameter | Units | NFET | PFET |
|---|---|---|---|
| $V_t$ Linear | V | .58 | –.55 |
| $V_t$ Saturated | V | .56 | –.40 |
| $L_{eff}$ (.5 $\mu$m drawn) | $\mu$m | .36 | .36 |
| $G_m$ | MS/mm | 190 | 103 |
| Series resistance | ohm-$\mu$m | 440 | 2000 |
| $I_{dsat}$ | $\mu$A/$\mu$m | 468 | 231 |
| S/D $C_{junc}$ | fF/$\mu$m$^2$ | .91 | .86 |

▲ Table 2. FET parameters for devices on the 5HP process.

*Silicon germanium technology* — Availability of this advanced technology is partially due to process developments achieved by IBM in the early 1980s. A technique called ultra high vacuum chemical vapor deposition allows small amounts of germanium to be deposited on silicon, creating a material with unique semiconductor properties. The following details describe the IBM 5HP process.

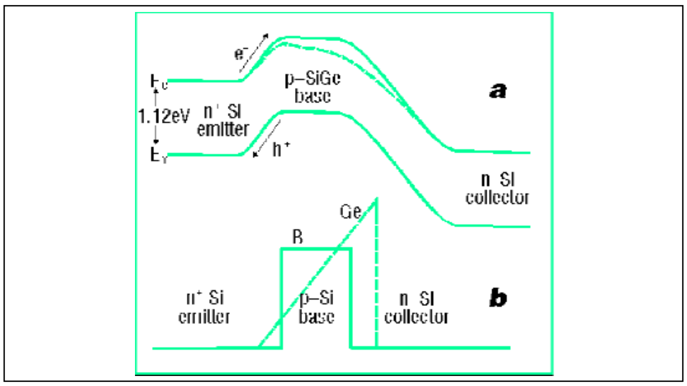
The resultant technology is based on the combination of standard 3.3 volt, 0.5 $\mu$m CMOS technology with epi-base heterojunction bipolar transistors plus a range of passive components. The process provides deep trench isolation allowing the integration of analog and digital functions on the same die. This is one of the key benefits of BiCMOS in general; however, it is the use of deep trench topology that provides approximately 40 dB isolation between functions on the same die.




▲ **Cross section of the SiGe HBT transistor. (Source: IBM)**

| Device | Units | Value |
|---|---|---|
| Implant resistor | kohms/square | 1.6 |
| Poly resistor | ohms/square | 342 |
| DC capacitor | fF/$\mu$m$^2$ | 1.52 |
| MIM capacitor | fF/$\mu$m$^2$ | .695 |
| Inductor (G-turn) | nH | 10 |
| Q (0.0 GHz) | | 3.8 |
| SBD $V_r$ (5×5$\mu$m$^2$) | mV@100$\mu$A | 213 |
| PIN $V_r$ (2×2000 $\mu$m$^2$) | mV@100$\mu$A | 790 |
| Varactor $V_r$ (2×2000 $\mu$m$^2$) | mV@100$\mu$A | 810 |

▲ **Table 3. Passive component details.**




▲ **Figure 1. Band gap energy profile. (Source: IBM)**

Two types of HBT transistors are provided, one with breakdown voltage ($BV_{ceo}$) of 3.3 volts and a second at 5.3 volts. A full set of parametric data for each type of transistor is listed in Tables 1 and 2.

The process is self-aligned. Two key manufacturing aspects include etching the base and gate areas simultaneously and providing a low thermal cycle following the epi-base deposition step. The thermal cycle is required for the HBT devices and activates the source/gate/drain dopants.

Some of the performance advantages of this process are higher conductance resulting in higher current gain, excellent noise properties and more stable operation over a wider temperature range than GaAs or silicon.

The primary benefit of this process, speed, is a result of reducing the band gap below what conventional silicon devices can achieve. Figure 1 shows an energy plot of the modified band gap structure. The reduced band gap is achieved by adding germanium to the base region of a bipolar transistor, speeding the electron conduction in the base area. This unique process gives SiGe its ability to provide operating speeds higher than most silicon bipolar and comparable to some GaAs technologies.

Energy band diagrams of conventional silicon bipolar transistor (solid line) and SiGe HBT (dashed line) show band gap modification, which speeds electron conduction across the base region by reducing the band gap and creating a ramped potential surface.

When considering wireless applications, the highest volume applications are below 2.5 GHz operation. These applications drive the use of this raw speed capability to be used most often for benefits in reduced power consumption.

*SiGe Process Details* — A snapshot of the process steps required for silicon germanium is listed below. This list does not indicate the actual mask steps but does represent the basic manufacturing flow.

1. N+ substrate/N– epi
2. Trench isolation
3. pFET wells
4. nFET wells
5. NPN structure
6. Gate (Base) definition
7. pFET source/gate/drain
8. nFET source/gate/drain
9. Emitter anneal
10. Contact and metalization

The active components available to the designer in IBM's 5H process include standard CMOS enhancement FETs, N channel and P channel, two versions of HBT transistors, plus a nominal PNP transistor. Details are listed in Tables 1 and 2.

The process includes the following passive components in addition to the active device transistors:

- Deep and shallow trench isolation
- Ion implant resistors
- Polysilicon resistors
- Oxide/nitrate decoupling capacitors tied to N+ silicon
- Metal-insulator-metal capacitors
- Three metal inductors, using five metal layer process
- Three diodes: SBD (TiSi contact), varactor and PIN

The passive component capabilities are outlined in Table 3.

*Applications for SiGe* — From a radio perspective, SiGe's high linearity and low noise capability have been demonstrated to provide superior LNA and mixer performance compared to BiCMOS and comparable to GaAs. This is especially true when characterized over temperature and process variation. The ability to achieve high levels of integration encourages its use for combined RF and IF functions and complete transceiver products.

As volumes increase and costs decrease, SiGe may end up being the best choice for applications where the combination of high performance radio circuits are integrated with baseband controller functions. However, it should be noted that with 40 dB of isolation between circuits on the same die, full duplex radios would suffer from transmit-to-receive feed through. This cross-talk can desensitize the receiver, resulting in poor performance.

*Cost of SiGe* — Cost of SiGe is surprisingly low considering its technical strengths and capabilities. This is partially because standard CMOS fabrication equipment and fabrication lines are used with minimal additions unique to SiGe. The use of 200-mm (8-inch) wafers improves manufacturing efficiency. Additionally, SiGe uses epitaxially grown base regions instead of ion implanted base regions. This provides a substantially improved control over the size and shape of the base region and layer, resulting in high reliability and tight performance distribution across process variables, which maximizes yields.

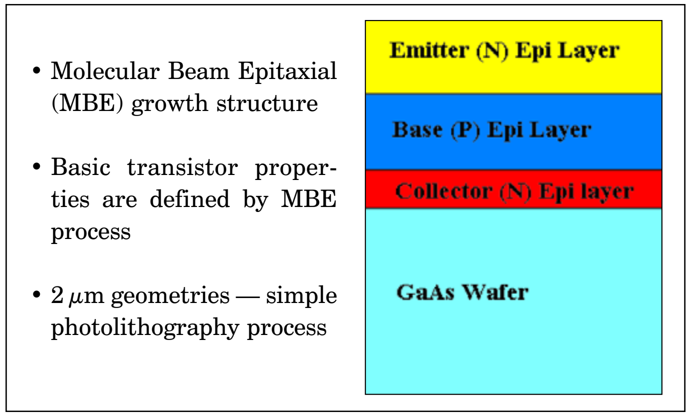
## BiCMOS technology

The IBM 5S BiCMOS process is essentially the same as the 5HP silicon germanium HBT process, without the addition of germanium to the base region of the bipolar transistors. Other differences do exist but are not critical for the intent of this article.

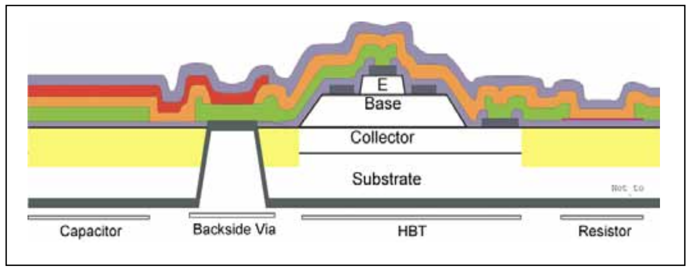
BiCMOS continues to be a viable process technology. One of the primary benefits of BiCMOS over SiGe BiCMOS is cost. This is achieved as a result of fewer process steps and mask layers. In handset radio applications, this technology is useful for receive intermediate frequency (IF) integrated circuits where noise and linearity are less critical than circuits interfacing directly to the antenna. Additionally, there are many low frequency circuits that are well supported by this and other BiCMOS process technologies.

## GaAs HBT technology

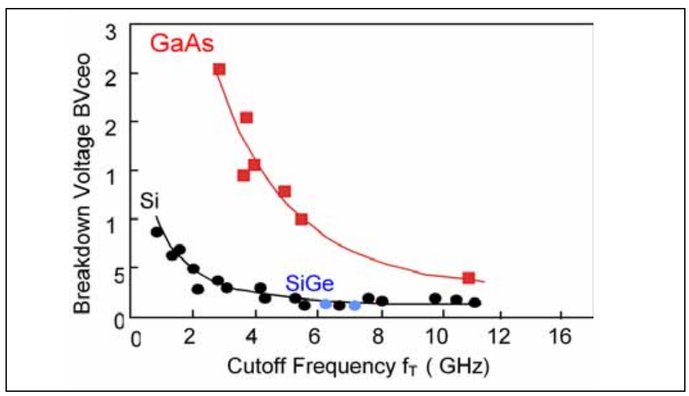
The concept of the heterojunction bipolar transistor (HBT) has been around since the time the first transistor was developed in 1948 [1]. The HBT is a vertical structure that requires an accurate and repeatable semiconductor layer growth process. It wasn't until the late 1970s when MOCVD (Metal-Organic-Chemical-Vapor-Deposition) and MBE (Molecular Beam Epitaxy) reactor technology was available to actually build up these devices. In the 1980s, TRW developed a gallium arsenide/aluminum gallium arsenide (GaAs/AlGaAs) based HBT process using a proprietary MBE technology, initially developed for military and space applications. With the help of RFMD, this technology has been successfully implemented for commercial wireless and wired applications.




▲ **Figure 2. MBE-based process.**



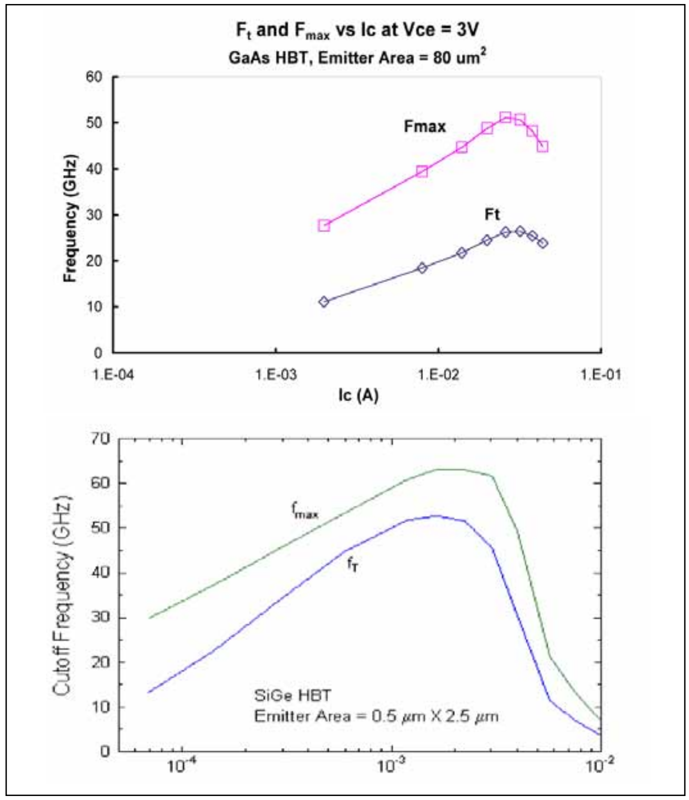

▲ **Figure 3. Cross section of TRW/RFMD GaAs HBT.**




▲ **Figure 4. Breakdown voltage vs. $f_T$. (Source: TRW)**

Figures 2 and 3 show the vertical structure of the HBT where the emitter, base and collector semiconductor layers are grown on top of each other. Current flows vertically, rather than laterally, providing for a more efficient usage of chip area for current handling. The advantage of this structure is that the layer thickness is the critical geometry for the semiconductor device. Since each layer is grown over the entire wafer at once, no photolithography is required for this step. The benefit of this approach is that mask alignment and optical resolution issues are minimized, resulting in a high-yielding process. In addition, wafers can be stockpiled, reducing a critical path in the manufacturing process, which allows the factory to respond quickly to changing market demands.

Although GaAs wafer material is more expensive, when compared to Si devices, it offers higher breakdown voltages vs. cutoff frequencies. The semi-insulating substrate results in higher *Q* passives. Even SiGe HBT cannot match GaAs HBT's $f_T$ vs. breakdown voltage (see Figure 4). Furthermore, GaAs HBT $f_T$ performance does not degrade appreciably as collector current increases (see Figure 5).




▲ **Figure 5. GaAs/AlGaAs HBT (top) and SiGe (bottom) cutoff frequency vs. collector current. (Source: IBM)**

## RFMD™ GaAs HBT process details

The RFMD process flow begins with growing the epi layers on the wafers using MBE. The wafers are then processed using standard photolithographic techniques. Because the MBE process determines the critical geometries, the minimum feature size is 2 mm, making these devices much more manufacturable. The GaAs HBT process is much simpler than SiGe BiCMOS, so there are far fewer masks and thus the manufacturing time is greatly reduced. The TRW/RFMD process has around 15 masks, while a SiGe BiCMOS process has around 35. Generally, the fewer the mask steps, the shorter the FAB cycle time. The process steps include:

- 12 front-side masks
- 2 back-side masks
- Semi-insulating substrate
- Structure grown by MBE for high precision and high quality
- Thin, heavily doped base layer for high beta, $f_T$, $f_{max}$ and $V_A$
- Self-aligned base metalization
- Non-alloyed emitter metal
- NiCr TFR
- 3-layer high density capacitor
- Inductors
- 2 levels interconnect metal
- Backside vias/metal

The process includes the following components in addition to the active device transistors:

- Schottky and PIN diodes
- NiCr thin-film resistors
- Capacitors
- Inductors

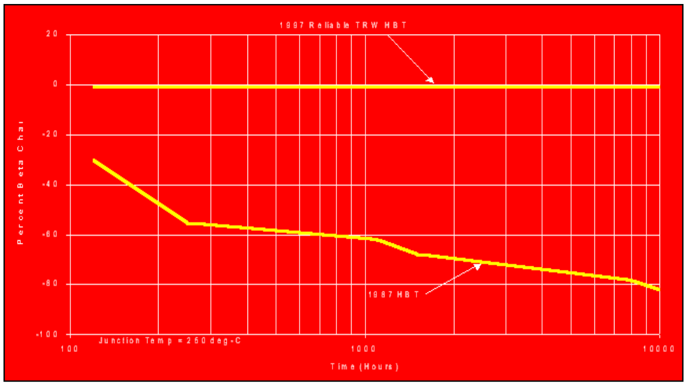
*Cost of GaAs/AlGaAs HBT* — GaAs HBT technology has evolved from a laboratory curiosity to a mainstream, high volume semiconductor process. RFMD has success-

| Parameter | Units | RFMD GaAs HBT (power device) |
|---|---|---|
| Beta | | 100 |
| $V_A$ | V | 1000 |
| $BV_{ceo}$ | V | 14 |
| $f_T$ | GHz | 25 |
| Fmax | GHz | 50 |
| Max. Signal Gain | dB | 27 dB, (1.9 GHz, JC = 25 kA/cm$^2$) |
| Discrete Gain | dB | 17, (load-pull, 3 V, 1.25 kA/cm$^2$) |
| Discrete efficiency | % | 45, (load-pull, 3 V, 1.25 kA/cm$^2$) |
| Linearity, ACP | dBc | –55, (load-pull, 3V, 1.25 kA/cm$^2$) |

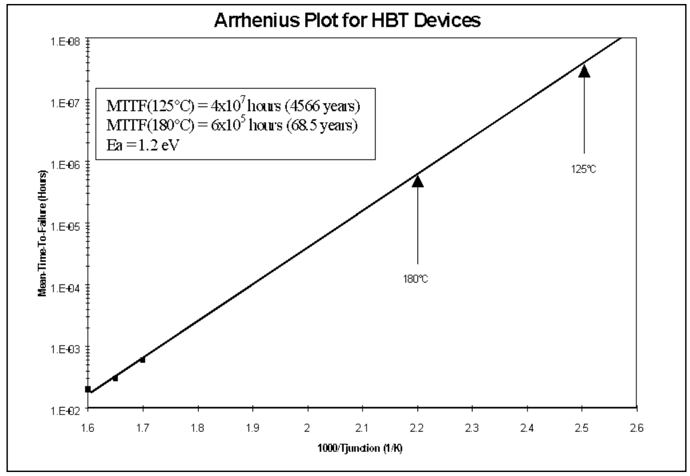
▲ **Table 4. RFMD GaAs/AlGaAs HBT Device Parameters (AE = 80 μm$^2$ device).**

| Parameter | Units | RFMD GaAs HBT (power device) |
|---|---|---|
| TFR | ohm/sq | 100 |
| Capacitor | pF/ mm$^2$ | 135 or 430 |
| Inductor | nH | 10, $Q$=9 |

▲ **Table 5. Passive component details.**




▲ **Figure 6. DC Beta degradation vs. time.**




▲ **Figure 7. RFMD™ GaAs HBT device MTTF.**

fully capitalized MBE technology to process its HBT wafers in high volume. MBE's superior uniformity over MOCVD-processed HBT wafers provide substantially improved performance and a highly reliable yield. Furthermore, when compared to other lateral semiconductor processes, the HBT vertical structure allows for reduced die size for a given function. The vertical device current flow is a key feature of the HBT structure that results in a very efficient use of die area. The smaller die corresponds to an increase in die per wafer. These are some of the reasons that GaAs HBTs have become the preferred low cost solution for many cellular handset applications.

*GaAs/AlGaAs HBT reliability* — As with any newer technology, reliability and volume production are always questioned. In the early days of HBT development, some papers were presented that questioned the long-term reliability of HBT devices. Since then, a lot of R&D has been invested to address the long-term reliability. Earlier HBT devices experienced premature failure, due to DC beta degradation. The TRW HBT approach utilizes a proprietary MBE process to address this issue (see Figure 6). The TRW proprietary process allows GaAs/AlGaAs HBTs to operate with *much* higher reliability than any other similar HBT. The RFMD HBT has been characterized with the MTTF vs. temperature, and there is very predictable response. Figure 7 is the corresponding MTTF based on Arrhenius's equation MTF = $Ce^{-Ea/kt}$ where C is a constant, Ea is the activation energy, $k$ is Boltzman's constant and $t$ is the temperature in Kelvins. The results indicate that the TRW/RFMD HBT has two orders of magnitude higher MTTF than a comparable MOCVD-based HBT. That is the primary reason the other HBT suppliers are moving to InGaP — it is the only way they can approach the proprietary TRW/RFMD MBE-processed HBT reliability. Another benefit of this HBT process is its uniformity and resulting high yields. These attributes are why RFMD partnered with TRW to develop this technology and adopt it in their FABs. To date, RFMD has shipped more than 130 million PAs to handset suppliers and other major consumer electronic companies.

## Comparison of three LNA products

At RFMD, combined LNA devices have been designed and implemented in BiCMOS, BiCMOS SiGe and GaAs HBT. In Table 6, three dual band LNA products are summarized. The same design was used for the BiCMOS and SiGe BiCMOS devices.

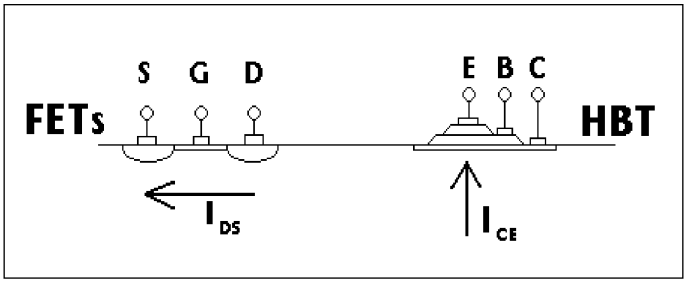
Performance improvements should be achievable by optimizing the design for the process. However, by using the exact design for both the BiCMOS and SiGe, the performance differences largely represent the improvements in technology. The BiCMOS, SiGe and GaAS HBT devices were all designed for CDMA handset applications.

## Applications for GaAs/AlGaAs HBT

When considering the appropriate technology for a specific application, RFMD relies on the Optimum Technology Matching® (OTM) approach. For digital wireless power amplifier (PA) applications, the ideal device should have very good linearity, be efficient at low

| Parameter | BiCMOS Cellular | BiCMOS PCS | SiGe Cellular | SiGe PCS | GaAs HBT Cellular | GaAs HBT PCS | Units |
|---|---|---|---|---|---|---|---|
| Gain | 14 | 12 | 14 | 13.7 | 15 | 12 | dB |
| Noise | 2.3 | 1.9 | 1.8 | 1.47 | 1.3 | 1.35 | dB |
| Input IP3 | +3 | +3 | 3.25 | 4 | 4 | 7 | dBm |
| Output IP3 | 17 | 15 | 17.25 | 17.7 | 19 | 19 | dBm |
| Current | 4 | 4 | 4 | 4 | 4 | 4 | mA |

▲ **Table 6. A comparison of key parameters.**




▲ **Figure 8. HBT structure provides a more efficient usage of chip area for current handling.**

voltage operation and need only simple biasing control. In addition, the technology must have a high enough breakdown voltage to be able to withstand high VSWRs and handle the heat dissipation. Generally, the heat dissipation precludes adding other RF functions to the power amplifier. Therefore, the level of integration for power amplifiers is moderate at most. GaAs/AlGaAs HBT offers these attributes and is optimal technology when compared to MESFETs and SiGe HBT.

While SiGe HBT does offer excellent linearity and noise figure for such applications as front end LNAs, it does lack the high voltage-handling attribute required for PA applications. As mentioned, SiGe HBT breakdown voltages are substantially lower vs. GaAs HBTs, for a given $f_T$. Furthermore, the trend in cellular handset designs is to eliminate the isolator. The lack of an isolator puts more burden on the PA to survive higher VSWR (high voltage) conditions that it may encounter.

In the past, GaAs MESFET was the prevalent technology for PA applications. It's clear that GaAs HBT PAs offer several advantages over GaAs MESFET PAs. GaAs HBTs can operate off a single 3-volt supply. Whereas, MESFETs typically require a negative bias/drain bias switch to control the bias point and minimize leakage current in the off state. GaAs HBTs are more efficient. MESFETs typically have saturation voltages that approach 1 V vs. <0.4V for GaAs HBTs, causing efficiency to degrade quickly when $V_{cc}$ is reduced [2]. HBTs vertical structure allows for a very small device geometry providing a more efficient usage of area for current handling when compared to the lateral structure of a MESFET (see Figure 8). Even though the MBE process adds cost to the processing, the resulting small geometry of the HBT and uniformity combine for a high die yield rate per wafer resulting in lower overall cost over MESFETs.

In conclusion, we have provided information to the reader on GaAs HBT and SiGe BiCMOS, indicating processing details and associated performance attributes. The article shows where SiGe is very useful for many applications in the radio due to its high linearity, low noise and speed capability. We show that GaAs HBT, similar in high linearity, speed and low noise, is a better choice for power amplifier applications because of its higher breakdown voltage. The use of standard BiCMOS technology can provide advantages in cost.

Knowing which technology is used, and for what function, can help you make a more informed decision when either designing or choosing a semiconductor product for your system design. ■

## Acknowledgements

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## References

1. Marie Meyer, "Will HBTs be the Next Semiconductor Success Story?" *Compound Semiconductor*, May/June 1997.

2. Paul J. Augustine, James Leake, "GaAs HBT Performance Capitalizes on Low-Voltage Power Amplifier Applications," RFMD internal article, 1998, *RF Design*, February, 2000.

3. D. C. Ahlgren, "IBM's SiGe Technology for Telecommunications and Mixed Signal Applications," *IBM MicroNews*, Vol. 3, No. 1, 1997: 22-25.

4. D. C. Ahlgren et al, "A SiGe HBT BiCMOS Technology for Mixed Signal and RF Applications," *BCTM Proc.*, p. 195, 1997; http://www.chips.ibm.com/bluelogic/showcase/sige/technology.html

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