# *Heterojunction-Bipolar-Transistor (HBT)*

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## Introduction

Prior to the invention of the transistor, telephone exchanges were built using bulky vacuum tubes and mechanical relays. Bell Labs engineers were tasked with developing the transistor (a portmanteau of "transfer resistor") as a smaller, less cumbersome alternative to the existing technology. The invention in 1947 heralded the beginning of the semiconductor industry which changed the world forever. John Bardeen, Walter Brattain and William Shockley would be awarded the Nobel Prize in Physics in 1957 for their research on semiconductors and their discovery of the transistor effect. Transistors would have profound impacts on the rapid evolution of technologies from wireless communications to computing, and ultimately shape the landscape of the information age. [1,2]

The earliest version of the device to be developed and produced was a homojunction transistor using Germanium. This was soon replaced by Silicon, as Germanium stops working above 75°C [2], which makes it impractical for most applications. Gradual performance improvements, especially in the frequency of operation drove German American physicist Herbert Kroemer to develop the theory of the Heterojunction Bipolar Transistor (HBT) which uses two or more different semiconductor materials with different bandgaps [3] to enable high frequency operation. His work earned him a Nobel prize in 2000 [4]. Though the theory was proposed as early as 1957 [4], production of HBTs had to wait until 1977 for the advent of equipment that was capable of manufacturing it; first with MBE (Molecular Beam Epitaxy) and later with MOCVD (Metal-Organic Chemical Vapor Deposition) [5].

Following the industry trend toward greater adoption of semiconductor technologies, Mini-Circuits introduced the wideband MAR- and MAV-series of MMIC amplifiers, which used Silicon homojunction technology operating to 2 GHz. User-friendliness, outstanding performance and low cost made these devices the darlings of circuit designers. But as HBT technology became available, ERA-series amplifiers using HBT technology were developed, initially pushing the frequency of operation to 8 GHz and later to 20 GHz. These amplifiers not only increased frequency of operation and provided superior OIP3 (output third order intercept point) but also enabled even greater ease of use. Most HBT amplifiers have wideband matching on the die and therefore require minimal external components. In addition, HBTs provide superior 1/f noise compared to pHEMT devices, and are preferred in some applications such as amplifiers and oscillators for this reason.

This article explains the physics behind homo- and heterojunction transistors and discusses the advantages of HBT amplifier designs. Results of reliability studies on Mini-Circuits' HBT amplifiers are presented, and reference is provided to Mini-Circuits full portfolio of MMICs designed using HBT technology. It is highly recommended that readers review the previous two articles in this series on the basics of RF Semiconductors [6] and pHEMT technology [7] published on Mini Circuits' blog to gain the most complete understanding of this article.

**Transistor-Configurations**

Before we get into the advantages of HBTs over homojunction transistors it will help to review basics of transistors, symbols, and modes of operation.

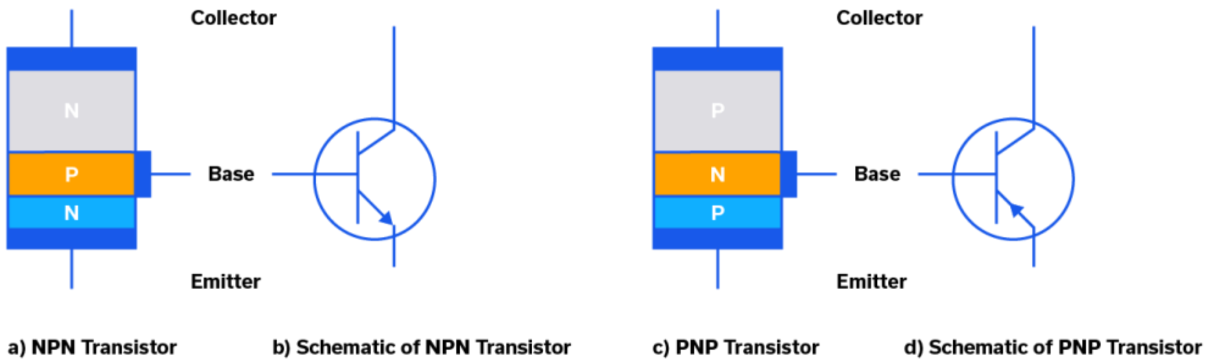



**Figure 1: NPN and PNP transistors.**

A transistor has three zones; emitter, base and collector, and can be built two different ways, as NPN or PNP. An NPN transistor has an N doped emitter, a P-doped base followed by an N-doped collector as shown in Figure 1a) and represented schematically in Figure 1b). Not surprisingly then, A PNP transistor has P doped emitter and an N-doped base followed by P-doped collector as shown in Figure 1c) and schematically represented in Figure 1d). The direction of the arrow in schematics 1b) and 1d) indicates current flow when the emitter-base junction is forward biased.

The emitter-base and base-collector junctions can be forward or reverse biased resulting in four possible combinations and uses [8] as shown Table 1. This article specifically addresses NPN forward-active mode as used in amplifiers. In an NPN transistor, current flow is driven by electrons having higher mobility than holes, which results in higher frequency of operation.

| Emitter-Base | Base-Collector | Mode |
|---|---|---|
| Forward Bias | Reverse Bias | Forward-Active |
| Reverse Bias | Reverse Bias | Cutoff |
| Forward Bias | Forward Bias | Saturation |
| Reverse Bias | Forward Bias | Reverse-active |

**Table 1: Different biasing combinations of emitter-base and base-collector junctions and corresponding modes.**

Figure 2 shows three possible configurations of an NPN transistor: common emitter, common base and common collector. A PNP transistor also has similar configurations.

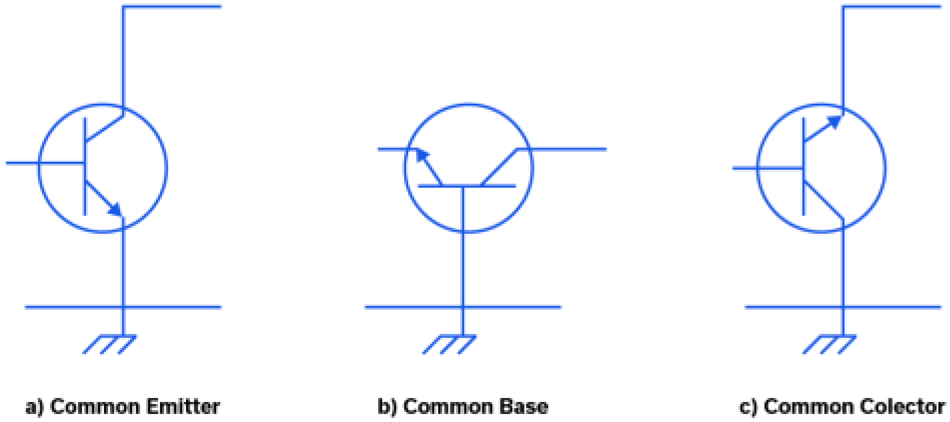



**Figure 2: Biasing configurations for an NPN transistor.**

In a transistor, the emitter “emits” electrons or holes to be “collected” by the collector. So what is the base? This is a question asked by many novice and experienced engineers alike. William Shockley, one of the inventors of the transistor [9] and a Nobel Laurate describes the base as “The original point-contact transistor structure comprising the plate of n-type germanium and two line-contacts of gold supported on a plastic wedge.” He continues, “The name ‘base,’ which arose from this structure, does not have functional significance as do the “emitter” and collector.” See Figure 3a for a visual of the original point contact transistor and 3b) for a schematic representation of the same [9, 10].

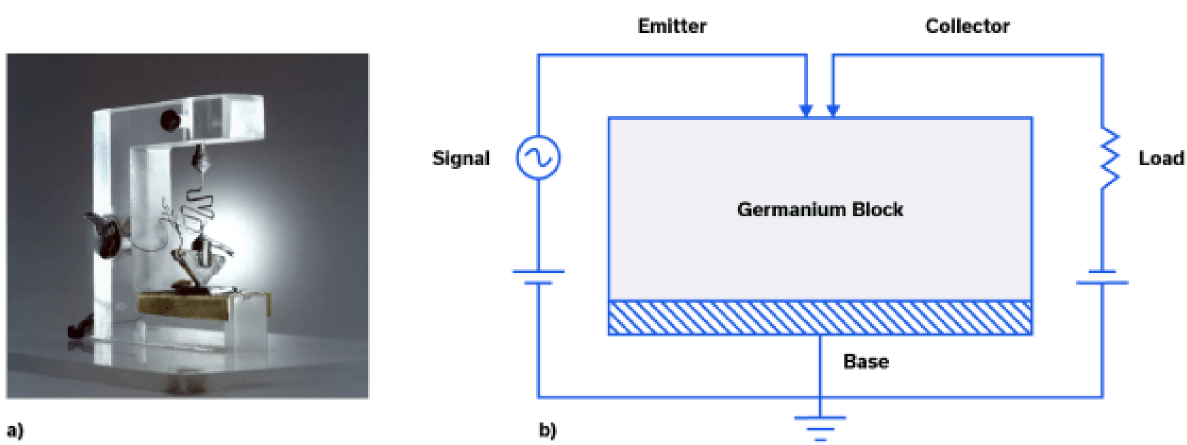



**Figure 3: Original point contact transistor.**

In a transistor, in forward-active mode, a small base current controls a large collector current which results in amplification. Hence, we have an amplifier. In an NPN transistor, electrons from the emitter enter the base by diffusion, and their momentum carries them to the collector where they are collected. As the base is relatively thin, very few electrons are lost in the base.

**Review: Compound Semiconductors**

For reasons we will explain shortly, HBTs use compound semiconductors. Let us review basics of compound semiconductors.

Table 2 shows a partial list of usable elements in the central portion of the periodic table.

| III | IV | V |
|---|---|---|
| Al | Si | P |
| Ga | Ge | As |
| In | | Sb |

**Table 2: Central portion of periodic table [4].**

Two or more discrete elements in Table 2 may be used to form compound semiconductors. In the center of the table are Silicon (Si) and Germanium (Ge). The alloy of Si and Ge, SiGe (pr. "SIGH-gee") is used as one of the materials in silicon HBTs.

According to Kramer [4], every element in column III may be combined with every element in column V to form a so-called III-V compound. GaAs is one such example. In HBTs, a common example is aluminum-gallium-arsenide, $Al_xGa_{1-x}As$ where x is the fraction of column III sites in the crystal occupied by Al atoms, and 1-x is occupied by Ga atoms. Hence, we have not just 12 discrete compounds, but a continuous range of materials depending on the concentration of each in the crystal structure. As a result, it becomes possible to make compositionally graded heterostructures in which the composition varies continuously rather than abruptly throughout the device structure. This was the focus of Kroemer's Nobel lecture on the discovery of HBTs. See Figure 4 for a pictorial view of some of the compounds [7].

| | Lattce Constant (Å) | Bandgap (eV) |
|---|---|---|
| GaAs | 5.65 | 1.420 |
| AlAs | 5.66 | 2.120 |
| InP | 5.87 | 1.35 |
| AlP | 5.46 | 2.45 |
| InAs | 6.06 | 0.36 |
| GaP | 5.45 | 2.26 |
| Ge | 5.65 | 0.66 |
| Si | 5.43 | 1.12 |

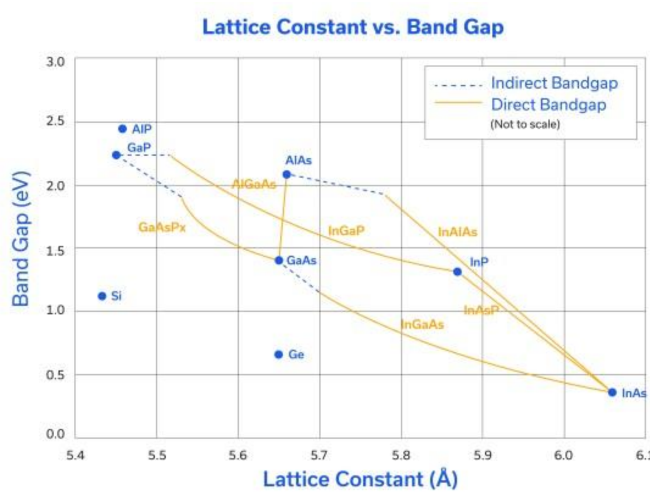


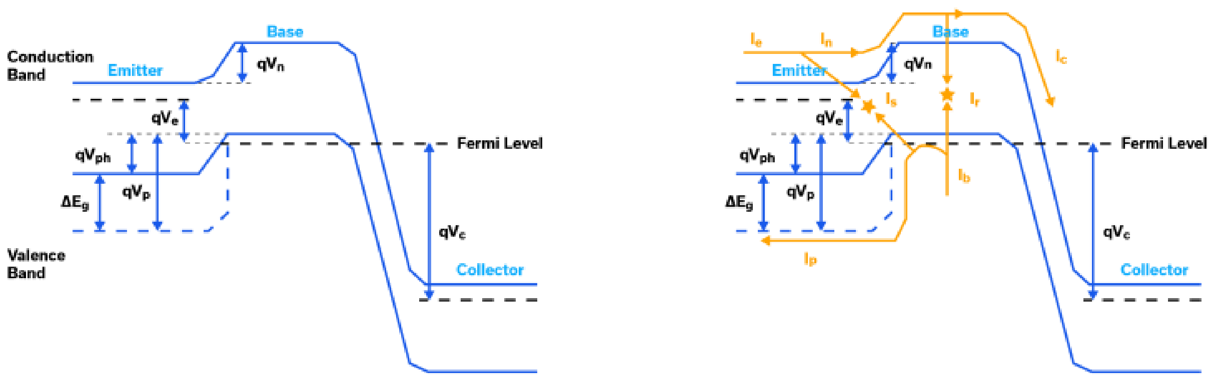

**Figure 4: Lattice constant vs. band gap of various semiconductor materials.**

**The Physics of Homo- and Heterojunction Bipolar Transistor (HBT) Operation**

The main question at hand is what is HBT and how do heterojunction structures improve transistor operation? The energy band diagram can be used to help answer this question. For a tutorial on energy band diagrams refer to the previous article [6] on the Mini Circuits blog. Figure 5 shows the energy band diagram for HBTs versus homojunction NPN transistors in forward-active mode. The vacuum level is not shown for simplicity.

Electrons injected from the emitter overcome the energy barrier $qV_n$ by diffusion and enter the base. In general, the base width is small, and therefore most of the electrons travel through the base due to their momentum, and are collected by the collector. However, a small number of electrons are lost due to recombination in the emitter-base depletion region and in the base region.

Now consider the holes in the base which comprise the majority. They enter the emitter, overcoming the energy barrier $qV_{ph}$ and $qV_p$ in a homojunction and heterojunction transistor, respectively. Note that $qV_p$ is greater than $qV_{ph}$ by $\Delta E_g$, which is the key to improved HBT operation as we will see later.




a) energy band diagram of Home Junction BJT (solid lines) and HBT with wide band gap emitter (dashed line) (Emitter-base forward biased & collector-base reverse biased)

b) Same as a) except DC current components added (emitter-base forward biased & collector-base reverse biased)

**Figure 5: Energy band diagram, currents; homojunction vs. heterojunction bipolar transistor.**

The various currents in the transistor shown in Figure 5b) are as follows:

$I_n$ : electron current from emitter to base

$I_p$: hole current from base to emitter

$I_s$: current due to electron / hole recombination within forward biased emitter-base space charged layer

$I_r$: current due to bulk recombination in base

$I_e$: emitter current= $I_n + I_p + I_s$

$I_c$: collector current= $I_n – I_r$

$I_b$: base current= $I_p + I_r + I_s$

Neglecting $I_{CO}$, the collector-to-base reverse current, common emitter current gain is defined by:

$$\beta = \frac{Ic}{Ib} = \frac{In - Ir}{Ip + Ir + Is}$$

Neglecting $I_r$ and $I_s$, the maximum achievable β is [11]:

$$\beta_{max} = \frac{In}{Ip} = \frac{N_e}{P_b}\frac{v_{nb}}{v_{pe}} \exp\left(\frac{\Delta E_g}{k_b T}\right)$$

Where:

$N_e$ and $P_b$ are doping levels of the emitter and base, respectively.

$v_{nb}$ and $v_{pe}$ are the mean velocities of electrons from emitter to base and holes from base to emitter, respectively, typically 5 < / < 50.

$k_b$ is Boltzmann's constant.

$\Delta E_g$ is the bandgap difference between emitter and base materials.

T is the temperature in K.

In a Homojunction transistor, $\Delta E_g$=0 and therefore, equation (2) simplifies to:

$$\beta_{max} = \frac{In}{Ip} = \frac{N_e}{P_b}\frac{v_{nb}}{v_{pe}} \exp\left(\frac{\Delta E_g}{k_b T}\right) = \frac{N_e}{P_b}\frac{v_{nb}}{v_{pe}} \exp(0) = \frac{N_e}{P_b}\frac{v_{nb}}{v_{pe}}$$

Therefore, to obtain a high $\beta_{max}$ (>100), the emitter needs to be doped heavily compared to the base ($N_e$ > $P_b$).

Heavy doping of the emitter widens the more lightly doped base depletion region, resulting in base width change vs. base-emitter voltage change, which in turn causes base width modulation, decreased linearity, and in the worst case, punch-through.

In a good HBT such as one using AlGaAs for an emitter and GaAs for a base,

$\Delta E_g \approx 0.2eV$

At room temperature $k_bT$= 0.025eV and $\Delta E_g / k_bT = 8$.

Therefore $\Delta E_g / k_bT \approx 3000$.

In a typical HBT, $N_e/P_b \approx 1/10$. That is, the base is heavily doped compared to the emitter, minimizing base width modulation.

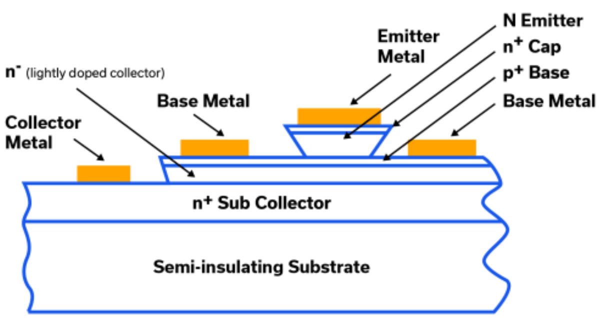
Therefore $\beta_{max} = 5 \times 0.1 \times 3000 \approx 1500$, which is a huge number.

Therefore $I_p = I_n/\beta_{max} = I_n/(1500)$, which is negligibly small compared to $I_n$ and can be ignored. This is a big advantage in HBT, as it maximizes current gain.

Going back to equation (1), neglecting $I_p$,

$$\beta = \frac{Ic}{Ib} = \frac{In}{Ir + Is}$$

A well designed HBT has β around 100.




a)

| Device Layer | Thickness (Å) | Doping (cm -3) |
|---|---|---|
| $n^+$ Cap (GaAs) | 500 | $1 \times 10^{19}$ |
| N Emitter (AlGaAs) | 2000 | $1 \times 10^{17}$ |
| $p^+$ (GaAs) | 700 | $10^{19}$ to $10^{20}$ |
| $n^-$ Collector (GaAs) | 7000 | 3-6 $10^{16}$ |
| $n^+$ Subcollector (GaAs) | 6000 | $5 \times 10^{18}$ |

b)

**Figure 6: Typical HBT cross section, layer thickness and doping [12].**

Now let us review the practical implementation of HBT with an example [12]. Figure 6(a) shows a typical HBT cross section in its planar implementation and Figure 6(b) the layer function, material, thickness, and doping. The structure consists of:

1. Semi-insulating GaAs on which the epi layers are formed.
2. A GaAs N+ sub collector meant to provide a high conductivity interface to the lightly doped n- collector and collector metal.
3. A P+ GaAs base heavily doped to reduce base resistance and thin depth to reduce base transit time.
4. An N emitter in which an AlGaAs epilayer forms a heterojunction with the P+ GaAs base (note the emitter is lightly doped compared to the base).
5. An N+ cap meant to provide a high-conductivity interface to the N emitter and emitter metal.

This structure has a maximum frequency of oscillation ($f_{max}$) of 200 GHz [13]. Compare this to advanced homojunction transistors with an $f_{max}$ of 20 GHz [5], an improvement by a factor of 10.

**Figures of Merit for HBTs [5]**

$f_T$ ,common-emitter current gain/cut-off frequency and $f_{max}$,maximum frequency of oscillation are used as figures of merit for HBT.

Common-emitter current gain / cutoff frequency is defined as:

$$f_T = \frac{1}{2\pi(t_{ee}+t_b+t_c+t_{cc})}$$

Where:

$t_{ee}$ = emitter-base charging time, which is proportional to emitter-base capacitance. In HBTs, this is generally low.

$t_b$ = base transit time, also low in HBTs due to the thin base layer.

$t_c$ = collector depletion layer transit time, which is proportional to collector-base capacitance. This is kept low through low collector doping.

$t_{cc}$ = collector transit time.

Maximum frequency of oscillation is defined as:

$$f_{max} = \frac{f_T}{\sqrt{(8\pi R_B C_{BC})}}$$

Which states that lower base resistance $R_B$ and lower collector to base capacitance $C_{BC}$ increases the maximum frequency of oscillation.

Epi designers optimize all these parameters to achieve desired performance.

In summary:

1. HBT uses an emitter semiconductor material with a wider bandgap compared to the base.
2. HBT uses higher base doping than in homojunction transistors, resulting in decreased base resistance.
3. Emitter-base heterojunction provides a high energy barrier for hole injection and a lower energy barrier for electron injection, which results in high emitter injection efficiency.
4. Lower emitter doping results in a negligible minority carrier storage, reducing base-emitter capacitance and enabling higher frequency operation.
5. High electron mobility and lower electron transit time due to the thinner base result in higher frequency operation.

6. Semi-insulating substrates help reduce pad parasitics and allow convenient integration of devices.

HBT technology complements pHEMT for higher frequency of operation but comes with few distinct advantages as shown below:

**Advantages of HBTs over pHEMTs [5].**

| HBT | pHEMT |
|---|---|
| Electron speed is governed by thin vertical layers realized by epitaxial growth resulting in operation up to millimeter wave range. 1-3 μm lithography is adequate. | Requires 0.2 to 0.5 μm lithography for similar frequency of operation, which makes it more expensive. |
| Reduced trapping effects and lower 1/f noise result from carrier flow primarily through active junctions isolated from surfaces and substrate and is comparable to Silicon homojunction transistors. | In FETs, the carriers travel between surfaces and active channel-substrate interfaces, experiencing greater trapping effects. |

## Noise

Noise is the unwanted fluctuation of current passing through or voltage developed across semiconductor bulk materials or devices [13]. As unwanted noise is superimposed on a desired signal, it degrades signal-to-noise ratio.

Flicker noise is inversely proportional to frequency and is popularly called 1/f noise, which increases as frequency decreases. It is therefore very important at low offset frequencies from the carrier frequency. Flicker noise is a function of surface defects. In HBTs, current flows perpendicular to the surface (see Figure 7a) and therefore the 1/f noise contribution is minimal. Compare this to pHEMT where current flows along the surface, (see figure 7b) and therefore 1/f noise is generally higher in pHEMTs than in HBTs.

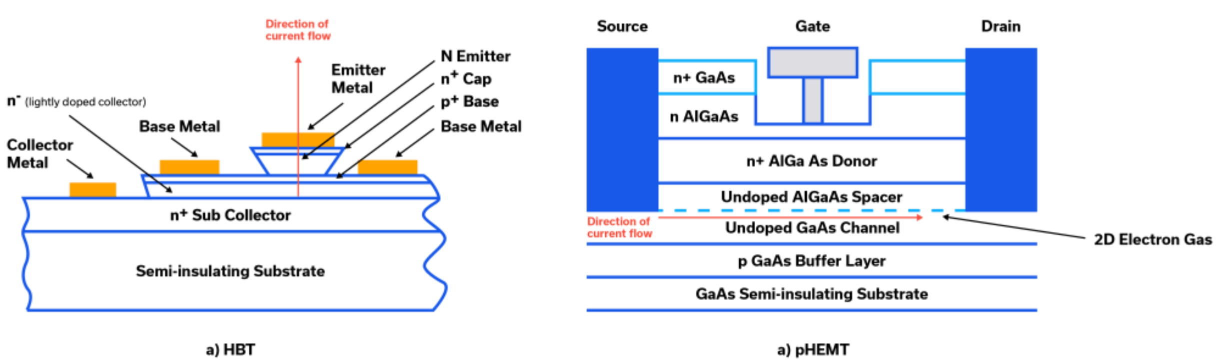



**Figure 7: Direction of current flow in HBT and pHEMT.**

Measured additive phase noise and amplitude noise of HBT amplifiers (GALI-39+, ERA-39+) and pHEMT amplifier (PSA-545+) is shown in Figure 8.

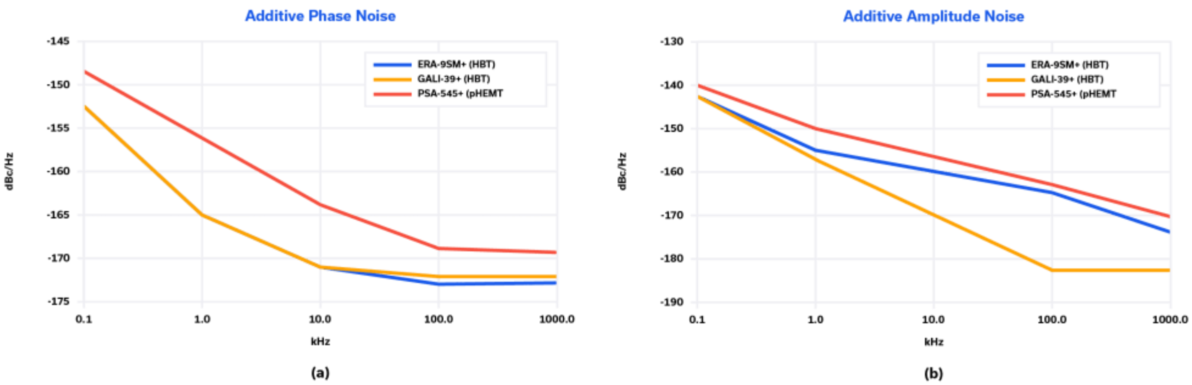



**Figure 8: Additive phase and amplitude noise of HBT and pHEMT amplifiers.**

Figure 8 clearly shows the superior performance of HBT amplifiers and chosen for demanding Amplifier and oscillator applications.

## Reliability

Mini-Circuits conducts HTOL (High temperature operating life tests) on its HBT-based amplifier models to demonstrate reliability and to compute Mean-Time-To-Failure (MTTF). An example follows.

Model GVA-81+ is subjected to HTOL for 5000 hours at a junction temperature of 148℃ on 80 samples. Computed MTTF based on these tests is shown in Figure 9.

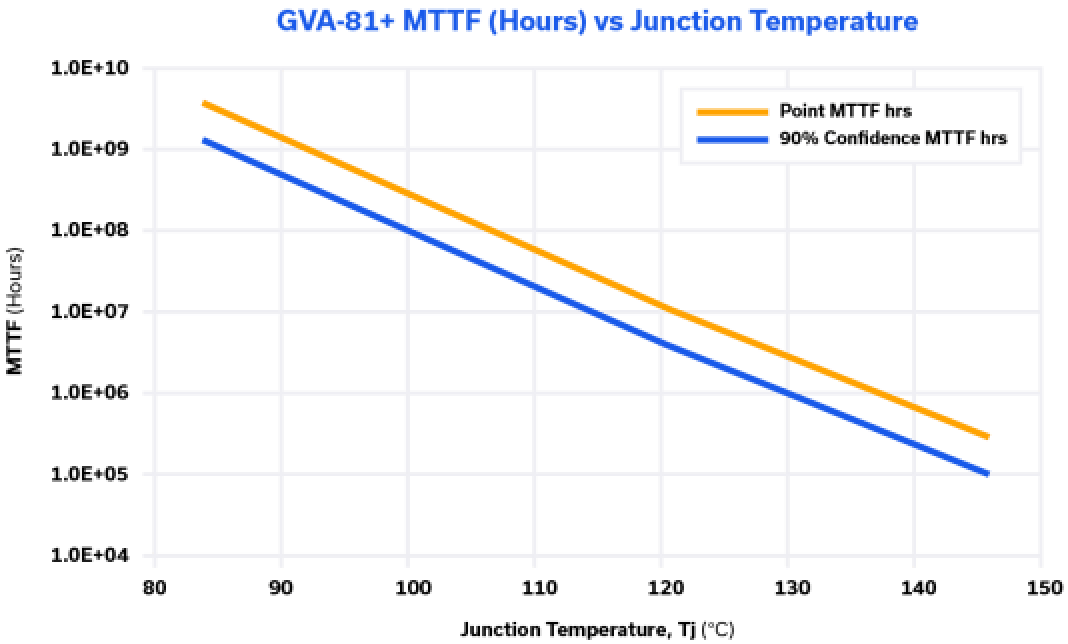



**Figure 9: MTTF vs. junction temperature for GVA-81+ HBT-based MMIC amplifier.**

Note that at max operating temperature and nominal current, Tj is 121℃ . From Figure 7 at 121℃ , MTTF is 3.6 x$10^6$ hours (or 415 years) at 90% confidence. This is extremely reliable.

Mini-Circuits parts are designed with high reliability as a design requirement. Designers take into consideration thermal aspects and target Tj to be below 130℃ at the highest ambient temperature. This is validated with thermal imaging and reliability is validated with HTOL (note 1). If these conditions aren't met, the product is redesigned.

**Conclusions**

HBT technology has matured over the years resulting in highly reliable microwave and millimeter amplifier products with excellent wideband performance up to 20 GHz. The 1/f noise performance of HBT is comparable to that of silicon transistors and is therefore preferred in critical amplifiers. Mini-Circuits has an extensive portfolio of HBT amplifiers available in various plastic and ceramic packages.

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