# Low-Noise High-Power Heterojunction Bipolar Transistors for Mixed-Mode Applications

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## Abstract

A novel heterojunction bipolar transistor (HBT), which provides state-of-the-art noise and record power density through X-band, was developed. This performance is due to advanced design and fabrication techniques. This HBT is readily transferable to mixed-mode applications, such as portable telephones and radar transmit/receive modules.

## Introduction

Considerable interest in the application of heterojunction bipolar transistors (HBTs) in high-speed digital and analog microwave circuits exists. The potential benefits of using HBTs in mixed-mode applications are of particular interest due to the high linearity, high transconductance, large current drive, low 1/f noise, high bandwidth, and uniform turn-on voltage which are possible with the HBT [1]-[4]. By reducing the high frequency noise of HBTs, the monolithic integration of mixed-mode circuits can be further developed. For example, the fabrication of monolithic transmit/receive modules, which require high power and low noise capabilities, or monolithic digitally modulated microwave receivers, which require low-noise devices, would benefit from the development of low-noise HBTs.

The mixed-mode HBT reported in this paper is technically and commercially significant. The technical contribution consists of the design, fabrication, and measured results. The noise results define the state of the art. This novel design incorporates a thermally-shunted dot geometry with a ledge-passivated self-aligned base for optimal noise and power performance. The minimum noise figure is the lowest reported for AlGaAs/GaAs HBTs [4]-[7]. The commercial significance derives from the simple high-yield fabrication process and the ability to produce fully monolithic mixed-mode circuits using HBTs. By employing a single fabrication technology for both the high-power transmitters, low-noise receivers, and high-speed digital controls, the affordability can be improved by reducing manufacturing costs and by utilizing a dual-use industrial base for military and commercial applications [8].

## Mixed-Mode HBT

This mixed-mode HBT combines power and noise performance using a unique design and fabrication process. The device layout is a thermally shunted dot geometry. The dot geometry ensures a lower base resistance than a comparably sized stripe geometry [9]. The thermal shunt consists of a thick metal bridge connecting the emitter dots of the HBT to each other and to a thermal lens [10]. This HBT demonstrated superior power handling capability of 10 mW/μm² and 60% power-added-efficiency at 10 GHz. The high efficiency and uniform lower junction temperature were expected to yield lower noise than standard resistively ballasted HBTs.

The high frequency noise of the HBT is primarily due to shot noise and Johnson noise. While the shot noise is produced by currents flowing in the HBT, the Johnson noise is produced primarily by the parasitic resistance. The Johnson noise power is proportional to the magnitude of the resistance and the temperature of the resistor. This mixed-mode HBT minimizes the Johnson noise by reducing the parasitic resistance and the average operating temperature of the parasitic resistance.

The fabrication process uses a self-aligned base with a wet chemical etch of the emitter. The fabrication process does not require a potentially damaging reactive ion etch (RIE), a silicon nitride sidewall process, or multiple photolithographic steps to define a passivated ledge in the extrinsic base region. The process yields a controlled base metal-emitter edge separation of 0.1 μm. This small separation minimizes the extrinsic base resistance which, in-turn, further minimizes the noise figure. By avoiding potentially damaging RIE processes, the base resistance is further minimized.

The wet etch process also produces a well defined passivated ledge. The ledge and low surface damage reduces leakage; hence, current gain is maintained under low bias operation. A representative emitter dot is depicted in Figure 1. The ledge is visible in the SEM photograph as a gently curved surface below the dot formed by the emitter metal. The low leakage is evident by the low cross-over voltage of the base and collector currents in the Gummel plot in Figure 2. A low-damage etch and a ledge decrease the noise figure of this mixed-mode HBT. The ledge passivation also reduces the low-frequency noise by reducing trap related noise [11].

The effect of the thermal design is evident in Figure 3. Mixed-mode HBTs were fabricated with thermal shunts of various thicknesses. The noise figures of the devices were determined at two power densities for devices of different thermal shunt thicknesses. At relatively high power densities the junction temperatures will vary as the thermal resistance of the devices vary. As depicted in Figure 3, the increase of the noise figure above the baseline value at low power density was reduced by using the thermal shunt design. The noise figure at high power density was reduced 2 dB by increasing the thermal shunt thickness from 1.5 μm to 9 μm.

Various configurations of the mixed-mode HBT were evaluated. Since the device is intended for mixed-mode operations, an epitaxial profile suitable for power amplifiers was selected. The low-noise operation was realized by the combination of layout and electrical bias. Therefore, a single fabrication process could be utilized to produce monolithic high-power and low-noise devices. The high-power capability was characterized using load/pull measurements. The noise parameters were determined using automated on-wafer noise characterization.

Representative noise results are depicted in Figures 4 and 5. Figure 4 illustrates the minimum noise figure and the associated gain of the optimum noise match of a mixed-mode HBT at two bias conditions. This device used two base fingers with four emitter dots with a diameter of 4 μm. At 2 GHz and a collector bias of 2 V and 4 mA, the minimum noise figure was 1.3 dB. The associated gain was 18 dB, and equivalent noise resistance was 12.5 Ω. The magnitude of the optimum noise source reflection was 0.31. As illustrated in Figure 5, these results represent a significant improvement of the minimum noise figure of AlGaAs/GaAs HBTs.

## Conclusion

A novel AlGaAs/GaAs HBT was developed which exhibits low-noise and high-power capability. This device enables the development of monolithic mixed-mode circuits using the HBT. The noise figure is the lowest reported in the literature. The technical development is commercially significant since it utilizes a high-yield process and improves the affordability of HBT-based monolithic mixed-mode circuits.

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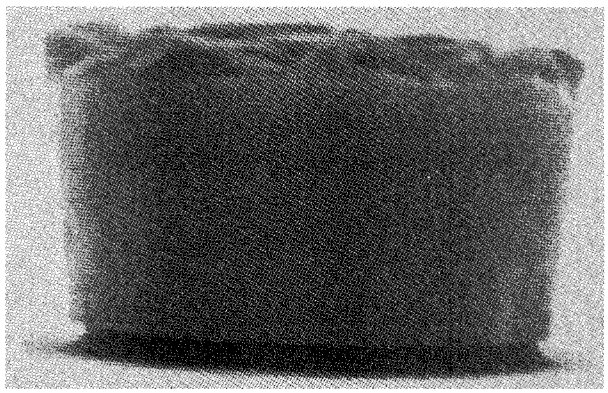

Figure 1. SEM photograph of an etched emitter profile. The beveled semiconductor emitter profile is visible below the larger emitter metal dot.

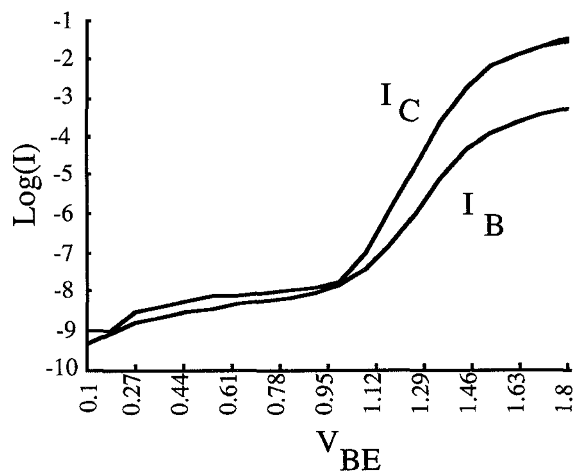


Figure 2. Gummel plot of a mixed-mode heterojunction bipolar transistor (HBT). The base-collector voltage was zero volts.

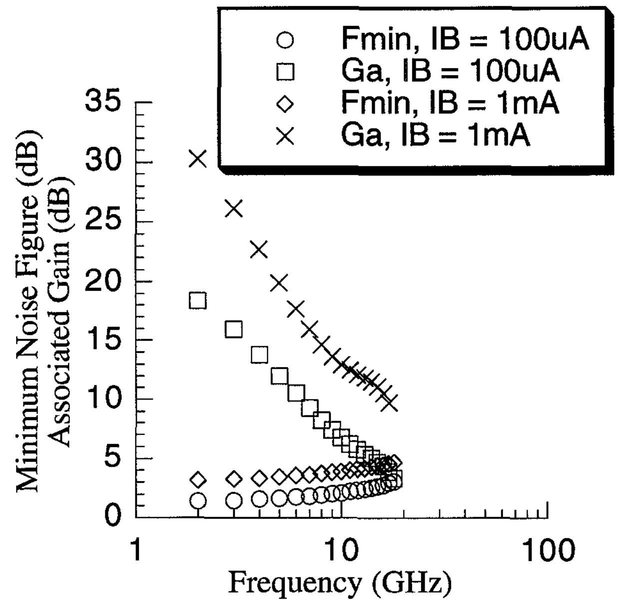


Figure 4. Minimum noise figure (Fmin) and its associated gain (Ga) for the 4μ4d2f HBT biased for low noise operation (base current $I_B$ of 100 μA) and low-noise high-power operation ($I_B$ of 1 mA). The collector voltage was maintained at 3 V.

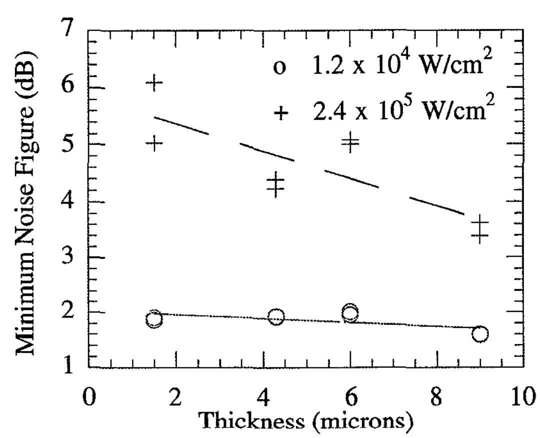


Figure 3. The effect of thermal shunt thickness on minimum noise figure at 5 GHz in low-power (1.2 x $10^4$ W/cm$^2$) and high-power (2.4 x $10^5$ W/cm$^2$) operation of the mixed-mode HBT.

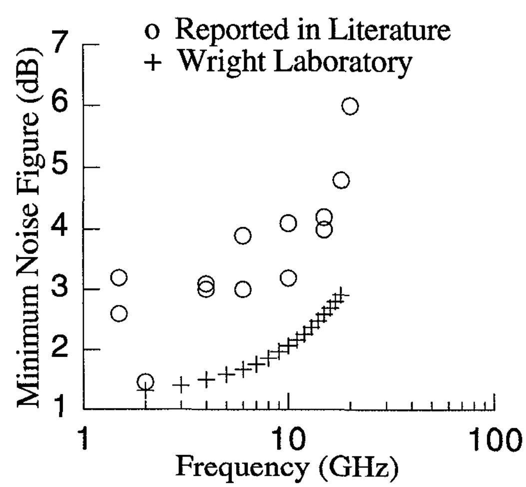


Figure 5. Comparison of the minimum noise figure of the Wright Laboratory's AlGaAs/GaAs mixed-mode HBT and previous results reported in the literature [4]-[7].