Outstanding Noise Characteristics of SiGe:C HBT Allow Flexibility in High-Frequency RF Designs

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Abstract – Noise characteristics of Motorola's SiGe:C eHBT (enhanced HBT) are reported with a focus on three key frequencies, 2GHz, 5GHz and 24GHz. Besides achieving extremely low minimum noise figures of 0.34dB at 2GHz and 2dB at 24GHz, key noise characteristics crucial for RF wireless designs such as noise resistance, noise matching, input and output matching, are detailed at each frequency. A simple LNA with 1nH emitter degeneration operating at 2GHz is demonstrated with a noise figure of 0.59dB, maximum available gain of 16.8dB and the amplifier is unconditionally stable. The ease in simultaneously optimizing noise, gain and input return loss at 24GHz for emerging high-frequency RF applications is demonstrated based on measured noise characteristics.

Introduction

The big boom of consumer wireless markets has brought tremendous growth in wireless RF designs since late 1990. As RF design becomes more pervasive, RF designers are faced with ever-growing challenges, such as increasingly difficult specifications, shorter design cycles, and the increase in operating frequencies. One specific complication is process evolution driven by market demand. Examples include the shrinking CMOS L_{eff} and the emergence of hetero-junction transistors, just to name a couple.

In the past two years, SiGe HBT technology has made tremendous improvement in RF performance including transistor speed, gain and noise figure. RF performance of SiGe HBT is now superior to RFCMOS and competitive with GaAs HEMT and FET, while maintaining rather low cost [1, 2].

In this paper, the noise characteristics of Motorola's eHBT are presented in detail. Key noise features crucial to RF designs are shown at frequencies rich in applications. These important noise properties allow great flexibility in RF design over a wide frequency range, up to and beyond 20GHz.

Performance-Enhanced HBT (eHBT) Offered By Motorola's 0.18μm And 0.35μm BiCMOS Technologies

SiGe:C HBT has been offered by Motorola's 0.18μm and 0.35μm BiCMOS technologies since 1999, with 50GHz peak f_T performance [3]. HBT performance has recently been enhanced demonstrating peak f_T beyond 100GHz and a significant reduction in noise figure [4]. Details of process integration to achieve the improvement in RF performance have been reported [4]. A summary of key performance parameters of Motorola's SiGe:C eHBT is shown in **Table I.**

eHBT Parameter	Technology	
	0.35μm	0.18μm
Min. Emitter Width [μm]	0.3	0.25
β @ I_C=10μA	235	500
Peak f_T @ 1.5V [GHz]	78	110
Peak f_{max} @ 1.5V [GHz]	141	123
BVCEO [V]	2.66	2.0
† Fmin @ 2GHz [dB]	0.56	0.34
† Fmin @ 5GHz [dB]	0.71	0.65
† Fmin @ 24GHz [dB]	2.56	2.06

Table I A summary of key performance parameters of Motorola's eHBT. † Fmin is measured on 5-emitter devices with L_E=10μm for both technologies.

Minimum noise figure (Fmin) versus collector bias current density is plotted in **Fig. 1** at three key frequencies, 2GHz, 5GHz and 24GHz, for eHBT offered in both 0.18μm and 0.35μm BiCMOS technologies. Note the extremely low noise figures at various frequencies as well as the rather insensitive response of Fmin to collector bias current.

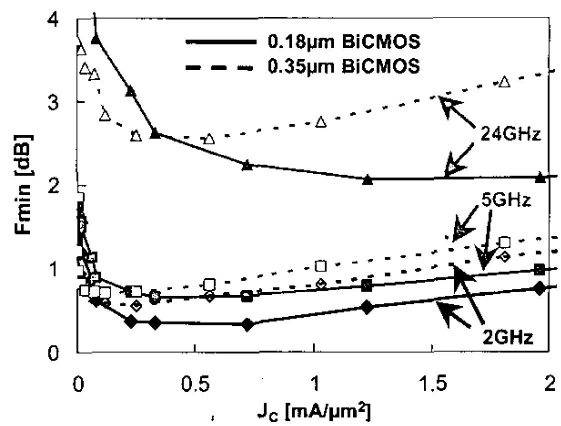

Fig. 1 Minimum noise figure, Fmin, versus collector current density compared between Motorola's SiGe:C eHBT offered in 0.18μm and 0.35μm BiCMOS technologies.

Transistor gain versus frequency is shown in **Fig. 2** for the eHBT offered in the 0.18μm BiCMOS technology. The 110GHz-eHBT provides more than a 7dB boost in h21 at 10GHz compared with the earlier 50GHz-HBT. This improvement of transistor speed enables designs for applications such as a frequency divider operating above 20GHz. Furthermore, transistor |S21| remains above 10dB up to 17GHz.

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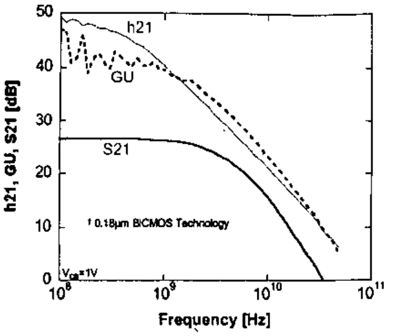

Fig. 2 Current gain (h21), unilateral gain (GU) and Mag{S21} of a $0.25\times10\mu m^2$ eHBT. The indicated values of peak f_t and f_{max} are extracted at 10GHz assuming -20dB/dec slope in h21 and GU, respectively. Both input and output are terminated with 50Ω for this measurement.

In **Fig. 3**, measured Fmin is plotted from 2GHz up to 26GHz for both the 50GHz HBT and 110GHz eHBT. Fmin has improved significantly over the wide frequency range shown. Additionally, Fmin remains below 1dB up to 10GHz and the advantage of eHBT for low-noise RF applications increases with frequency.

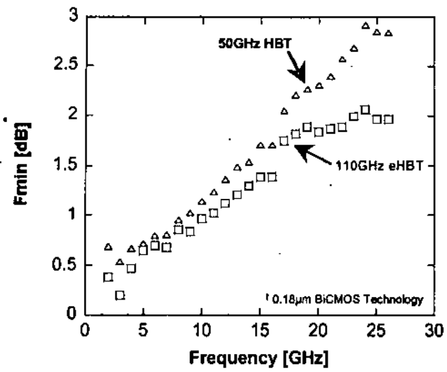

Fig. 3 Fmin has improved significantly over a wide frequency range migrating from 50GHz HBT to 110GHz eHBT.

As a result of the extremely low noise figure and high gain, a very significant reduction in minimum noise measure, Mmin (=(Fmin-1)/[1-(1/GASS)]), is achieved, almost 40% at 24GHz and 60% at 2GHz, as shown in **Fig. 4**. Due to the integration schemes adopted to achieve f_t performance, the optimized bias point for Mmin has moved to higher current.

Before presenting more details on important noise properties such as optimized source impedance (Γ_{opt}) and noise resistance, an indication of the quality of both noise parameters can be realized by comparing Fmin with NF (50Ω termination), as shown in **Table II**. Note that NF remains below 1dB up to 5GHz and merely rises to 2.5dB at 24GHz, reflecting the fact that (1) Γ_{opt} is relatively close to 50Ω, and (2) the transistor has very low noise resistance.

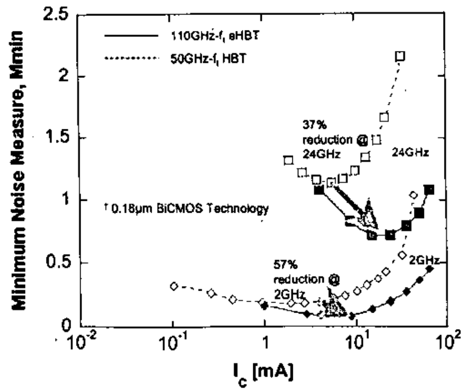

Fig. 4 Minimum noise measure, Mmin, at 2GHz and 24GHz, plotted versus collector current bias. As a result of high gain and low noise figure, an impressive reduction in minimum noise measure is obtained in comparing 50GHz-f_t HBT with 110GHz eHBT.

Frequency [GHz]	Fmin [dB]	NF [dB]
2	0.35	0.89
5	0.65	1
24	2.05	2.5

Table II Fmin and NF (50Ω termination) measured with identical biases at three important frequencies. † 0.18μm eHBT.

Important Features of Noise Performance Allowing Great Flexibility in Bias And Matching For Optimized Gain And Noise Performance

One of the most important tradeoffs in LNA design is between gain and noise performance. The tradeoff applies both in device biasing and input impedance matching. While best-case Fmin can be achieved at a specific bias current for a given device size, HBT gain is typically not optimized at this bias point for optimized noise performance (best-case Fmin). For frequencies below 5GHz, 5dB or more of gain is given up by biasing for best-case Fmin, as shown in **Fig. 5**. Besides, noise resistance is generally 30% worse at the bias where best-case Fmin occurs than at a higher current, making noise performance sensitive to input matching. Finally, transistor linearity is not optimized at low bias current. Granted, power consumption is a constraint that needs to be considered carefully in the mean time.

In the next section, important features of the noise characteristics of Motorola's eHBT offered in both 0.18μm and 0.35μm BiCMOS technologies are presented. While transistor gain and noise performance can be further optimized by appropriate device sizing in a design, measured data of a 5-emitter $0.25\times10\mu m^2$ eHBT is chosen to demonstrate various features of noise performance.

(i) Features of Noise Performance at 2GHz and 5GHz

Minimum noise figure (Fmin) compared between SiGe:C eHBT offered by Motorola's 0.18μm and 0.35μm BiCMOS technologies has been shown in **Fig. 1**. Fmin, associated gain (GASS) and noise resistance (Rn) versus collector bias current of a 0.25μm×10μm eHBT with 5 emitters are shown in **Fig. 5**. Various attractive properties are observed from these results and are summarized as the following:

- eHBT demonstrates outstanding Fmin of 0.34dB at 2GHz, 0.65dB at 5GHz in 0.18μm technology; 0.56dB at 2GHz, 0.71dB at 5GHz in 0.35μm BiCMOS technology.
- Transistor Fmin is rather insensitive to collector bias current (with a slope less than 0.02dB/mA for 0.18μm technology) allowing tremendous flexibility in biasing to optimize power gain as well as linearity without trading off noise performance.
- Noise resistance is low and the penalty for non-optimal input matching is minimized. Further, noise resistance decreases with increasing collector current. As a result, the sensitivity of noise performance to input matching is relaxed in cases where high gain is required at increased collector current.

Noise characteristics (Γ_{opt}, constant noise circles, S11* and S22) at 5GHz with swept collector current are shown in **Fig. 6**. Low noise resistance leads to noise circles with large radii at low noise figures. As the transistor is biased for best-case noise (V_{BE}~0.84V) or high gain (best-case gain at V_{BE}~0.9V), Γ_{opt} moves toward 50Ω. Although S11* is not close to Γ_{opt}, optimized gain and noise matching can be achieved rather easily with emitter inductor degeneration while achieving amplifier stability. This is demonstrated next in an example of a LNA.

A simple LNA circuit, with 1nH emitter degeneration and input, output matching networks, operating at 2GHz is designed using a 5-emitter 0.25μm×10μm eHBT in the 0.18μm BiCMOS technology. The passive elements in input and output matching networks are ideal. Simulation is performed in Agilent's ADS simulator, using the measured s-parameters and noise parameters of the transistor. As a consequence of the excellent NF performance of eHBT, a slightly higher bias current can be used to improve linearity. The design was accomplished by first matching the input and output impedances for the best NF at Γ_{opt}. Continued tuning of the circuit yielded acceptable return losses and the design is completed with circuit elements that provide for unconditional stability.

The LNA performance at 2GHz is summarized in **Table III**. A NF of 0.59dB (Fmin=0.37dB) is achieved with maximum available gain (MAG) of 16.8dB while the amplifier is unconditionally stable from 100 MHz to 10 GHz and the return losses are better than -10 dB. Noise and gain circles, together with NF and Fmin versus frequency are shown in **Fig. 7**. Again note the attractive property that NF is very close to Fmin up to 5.5GHz. S-parameters of the LNA versus frequency are shown in **Fig. 8**.

Key Parameter	Value
Bias	I_C=8.8mA, V_{CC}=1.5V
NF [dB]	0.59
Fmin [dB]	0.37
MAG [dB]	16.8
|S21| [dB]	15
Input Return Loss [dB]	-10.8
Output Return Loss [dB]	-10.8
Reverse Isolation [dB]	-20.1

Table III A summary of LNA performance at 2GHz.

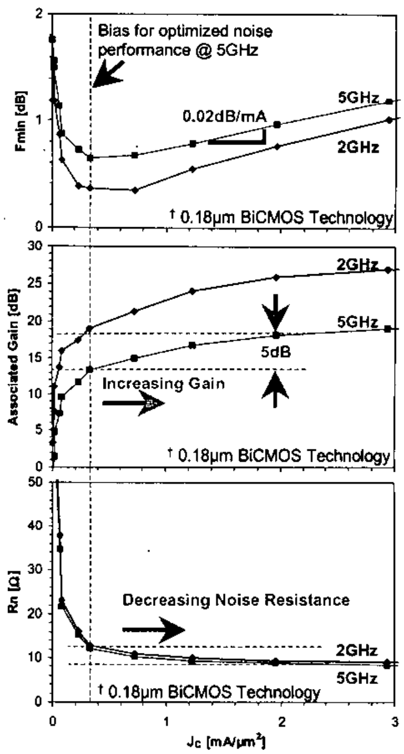

Fig. 5 Minimum noise figure (Fmin), associated gain (GASS) and noise resistance (Rn) are plotted versus collector current density of a 5-emitter 0.25×10μm² eHBT. As an example at 5GHz, while the eHBT is biased at best noise performance of 0.65dB, ~5dB or more of gain is given up. Meanwhile, noise resistance is more than 30% higher than the value seen at a higher bias current.

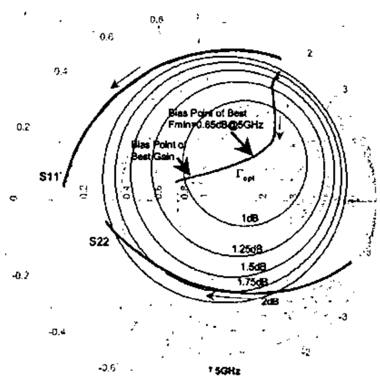

Fig. 6 Noise characteristics, including Γ_{opt}, S11*, S22 with I_C sweep and constant noise circles while the transistor is biased for best-case Fmin, at 5GHz. Arrows indicate the direction of increasing bias. As transistor is biased for best-case noise (V_{BE}~0.84V) or high gain (best-case gain at V_{BE}~0.9V), Γ_{opt} moves toward 50Ω. Although S11* is not close to Γ_{opt}, optimized gain and noise matching can be achieved rather easily with emitter inductor degeneration while achieving amplifier stability, as demonstrated in the example of a simple LNA.

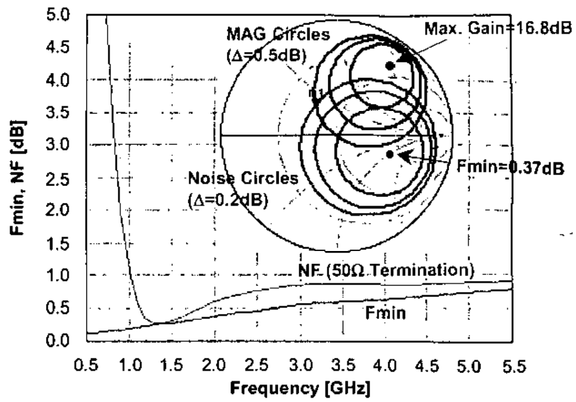

Fig. 7 LNA noise, MAG circles and NF, Fmin versus frequency.

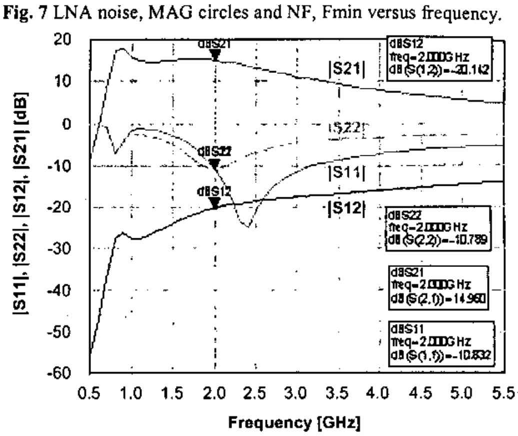

Fig. 8 LNA s-parameters plotted versus frequency up to 5.5GHz.

(ii) Features of Noise Performance at 24GHz

The performance of eHBT is examined at 24GHz to evaluate the suitability for applications such as 24GHz collision-avoidance radar sensors [5]. Several attractive features at 24GHz are summarized here:

- Fmin has a low value of ~2dB at 24GHz.
- Fmin of ~2dB occurs at a bias collector current (J_C~1.2mA/μm^2) where associated power gain is close to maximum at 24GHz. Therefore, a single optimized bias point can be established easily for maximum gain and best noise performance.
- As a result of low Fmin and high gain at 24GHz, transistor noise measure, Mmin, has decreased from 1.14 to 0.72, a 40% improvement comparing 50GHz-HBT and 110GHz-eHBT.
- eHBT Γ_{opt} at 24GHz is close to S11* providing the ability to match for best noise performance, optimized gain and minimized input return loss simultaneously, as shown in **Fig. 9**.
- Measured S22 is relatively close to 50Ω at the desired bias point making output matching a trivial matter at 24GHz, as shown in **Fig. 9**.
- Although reverse isolation (S12) degrades with the increase of frequency and becomes significant at 24GHz, the value of S12 actually diminishes to negligible magnitude as collector current increases; thus, while biasing eHBT for optimized noise performance at 24GHz, reverse isolation is reasonable at -20dB, as shown in **Fig. 9**.

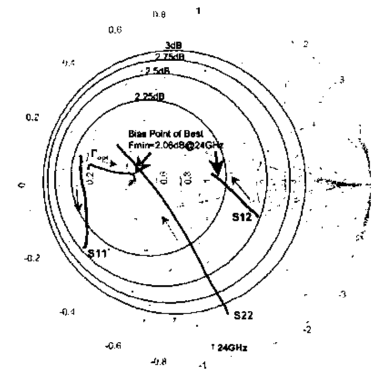

Fig. 9 Γ_{opt} and s-parameters at 24GHz with swept collector current. Arrows indicate the direction of increasing current. Also shown are the constant noise circles while the eHBT is biased for best-case Fmin of 2.06dB (I_C=1.2mA/μm^2).

Summary

Important noise characteristics beneficial for high-frequency RF designs are reviewed. Extremely low noise figures, similarity between NF and Fmin over frequency, robustness of noise performance over a wide range of frequencies, insensitivity of noise performance to collector current, low noise resistance as well as its flat response to current, together with ease of gain/noise matching make Motorola's eHBT attractive for high-frequency wireless RF designs. In conclusion, the advantage of eHBT for low-noise RF applications increases with frequency and bias current.

Acknowledgments

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