Bias and Temperature Dependent Noise Modeling of HBTs

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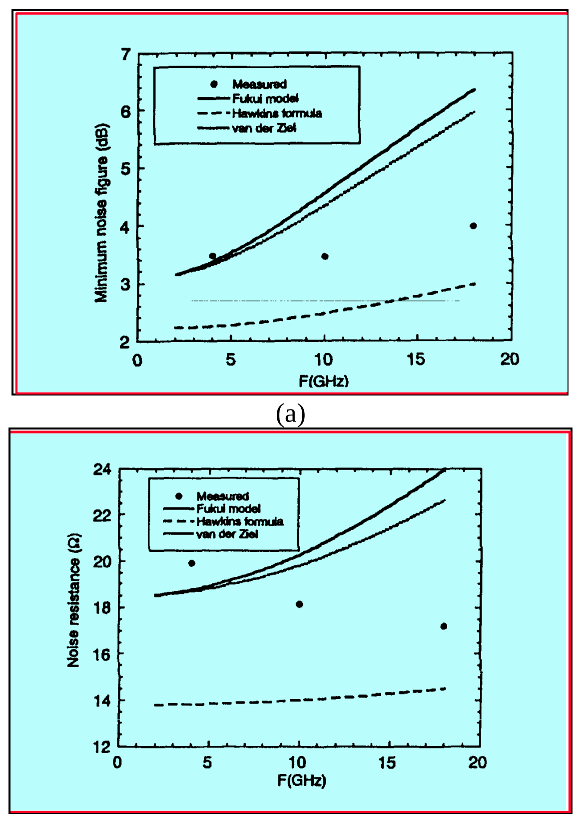
Abstract – This paper presents a detailed model which accurately predicts the bias and temperature dependent noise characteristics of AlGaAs/GaAs heterojunction bipolar transistors (HBTs). The features introduced to the intrinsic noise model are the following: (i) correlation of the noise sources and (ii) the frequency dependency of the noise sources. Compared to the present noise models, this study provides significant improvement in predicting small signal and large signal noise for HBT based circuits. These models can be implemented easily into any SPICE or harmonic balance simulators. The results of this study are validated using devices from different foundries.

Introduction

Heterojunction bipolar transistors (HBTs) are rapidly becoming viable candidates for low-noise amplifier (LNA) applications across the entire microwave frequency spectrum including well into the millimeter bands. A particularly important application is in monolithic microwave integrated circuits (MMICs) where highly accurate bias and temperature dependent noise models are critical, especially for first pass design success.

The noise models [1-3] in use today, though adequate for most silicon bipolar circuit applications, have been reduced to over-simplified formula sets, or are based on approximations which disqualify them for use with HBTs. Figure 1 illustrates the inadequacy [4]. It is evident that all of the models demonstrate relatively poor agreement with the measured data, and in particular all the three models show a frequency dependence of R_N, which is opposite to the experiment. Similar limitations are also observed in the SPICE shot-noise model [4]. Moreover, the present models do not explicitly include bias and temperature dependencies.



(a)

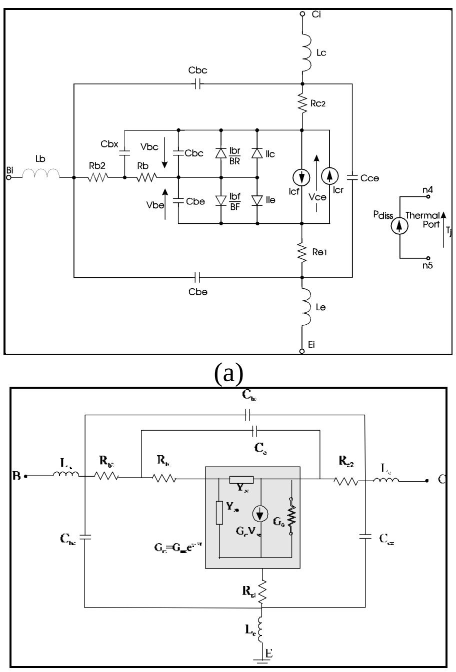
(b)

Figure 1. Comparison of measured noise parameters: (a) F_{min} and (b) R_n of an HBT with predictions of three contemporary noise models [4].

0-7803-4603-6/97/$5.00 (c) IEEE

Noise Model

Our approach is based on the equivalent circuit shown in Figure 2. The linearized hybrid-π equivalent circuit is derived from the modified Gummel-Poon model described in Ref. [5-8]. As shown in Figure 2a, the thermal port determines the internal temperature during analysis. The thermal port is modeled using a thermal equivalent circuit where the device power dissipation is represented by an electrical current source and the voltage across the source is equivalent to the device temperature.



(a)

(b)

Figure 2 (a) Gummel-Poon representation and (b) the hybrid-π linearized representation (shaded region denotes the intrinsic device)

The intrinsic noise model is developed by incorporating the correlation of the noise sources and the frequency dependency of the noise sources. The normalized noise correlation matrix is then given as,

$$C_y = \frac{1}{4KT_o B}\begin{bmatrix} \overline{i_b i_b^*} & \overline{i_b i_c^*} \\ \overline{i_c i_b^*} & \overline{i_c i_c^*} \end{bmatrix}$$

where

$$\begin{aligned} \overline{i_b i_b^*} &= 4KT_o \,\mathrm{Re}[Y_{11}]B - 2qI_b B \\ \overline{i_c i_b^*} &= 2KT_o\left(G_m - 2\,\mathrm{Re}[Y_{12}]\right)B - 2qI_c B \\ \overline{i_c i_c^*} &= 4KT_o \,\mathrm{Re}[Y_{22}]B + 2qI_c B \end{aligned} \tag{1}$$

Y_{11}, Y_{12}, *and* Y_{22} correspond to the intrinsic Y-matrix of the device as shown in Figure 2 (shaded region).

At zero frequency (DC), the noise power terms, $\overline{i_b i_b^*}$ and $\overline{i_c i_c^*}$ of the primitive device reduce to the SPICE shot noise model. Also, the cross-correlation terms reduce to zero indicating that there is no noise component common to both the collector and base currents.

Each of the parameters in equation (1) are related to the bias (V) and temperature (T), given by the following set of equations,

$$\begin{aligned} G_{m0}(V,T) &= \frac{{}_{dc}(V,T)}{R_e(V,T)} \\ R_{be}(V,T) &= \frac{h_{fe}(V,T)}{G_{mo}(V,T)} \\ R_e(V,T) &= \frac{KT}{qI_e(V,T)} \\ G_o(V,T) &= \frac{}{V_{ce}}\left[\frac{I_{bf}(V,T)}{K_{qb}(V,T)} - \frac{I_{br}(V,T)}{K_{qb}(V,T)}\right] \\ G_{bc}(V,T) &= \frac{1}{R_{bc}} = \frac{}{V_{be}}\left[I_{lc}(V,T) + \frac{I_{br}(V,T)}{B_r(V,T)}\right] \end{aligned} \tag{2}$$

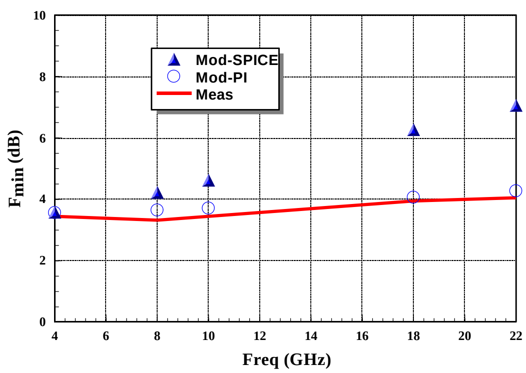
where ${}_{dc}$ is the DC current gain and h_{fe} is the short circuit current gain.

A correlation matrix approach is employed to account for the extrinsic thermal noise sources of the full topology device. The noise parameters (R_n, F_{min}, ${}_{opt}$t) are derived from the correlation matrix [C].

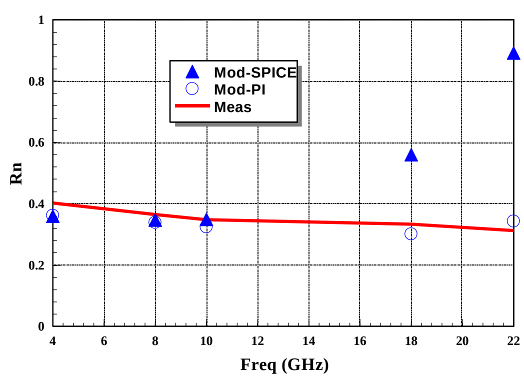
$$R_n = C_{11}$$
$$G_{sopt} = \sqrt{\frac{C_{22}}{C_{11}} - \left[\frac{\mathrm{Im}(C_{12})}{C_{11}}\right]^2} \qquad (3)$$
$$B_{sopt} = \frac{\mathrm{Im}(C_{12})}{C_{11}}$$
$$F_{\min} = 1 + 2\sqrt{C_{11}C_{22} - \mathrm{Im}(C_{12})^2} + \mathrm{Re}(C_{12})$$

These models are implemented into Microwave Harmonica [8].

To validate the model, on-wafer bias and temperature dependent noise parameter measurements are performed using the ATN-NP5 system for various foundries. Parameter extraction is performed using an in-house extraction routine.

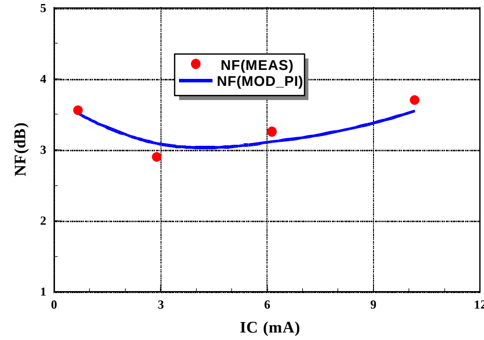


(a)



(b)

Figure 3 Comparison of measured and modeled (present work and SPICE) noise parameters as a function of frequency for V_{ce} = 2.0V, I_b = 428 µA, I_c=5.9mA, V_{be}=1.478



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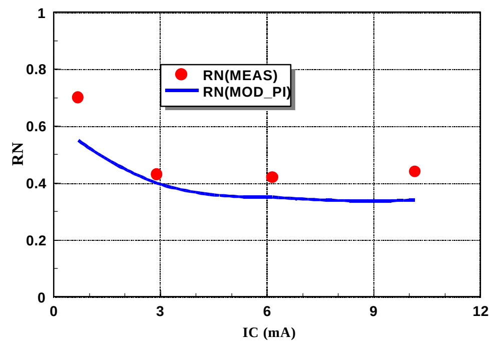

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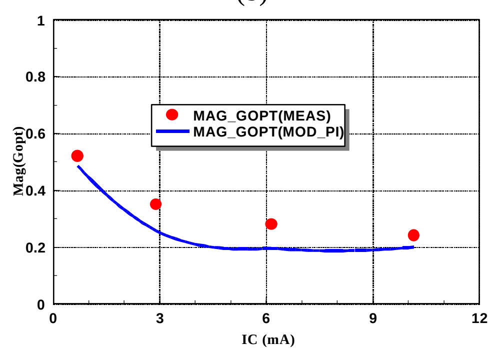
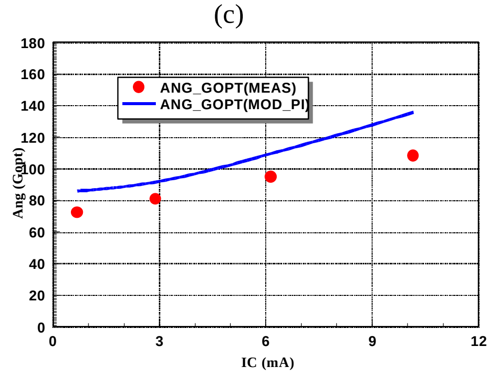


(c)



(d)

Figure 4. Bias dependency of the noise parameters versus collector current @ 10GHz,biased at V_{ce}=2V and IB varied from 50uA to 200uA (a) NF (b) RN (c) $|\Gamma|$ (d) $\angle\Gamma$

Figure 3 compares the measured and modeled noise parameters for the Raytheon HBT biased at Vce=2V and Ib=428µA. Two models are compared with the measured result; the present work, referred to as *'Mod_PI'* and the SPICE shot noise model (referred as *'MOD_SPICE'*), used in SPICE and harmonic balance simulators. From the results it is evident that at lower frequencies both models predict the same, as noted earlier, however, at higher frequencies the SPICE noise model deviates rapidly from the measurement.

The next step in the validation process is the model's accuracy with bias. For this case, the base current is varied from 50µA to 200µA, and V_{ce} set to 2V. Also, the frequency at which the validation is performed is at 10GHz. Figure 4 illustrates the bias dependent noise characteristics for the TRW HBT and can notice the good correlation obtained between the measured and modeled noise parameters.

Finally, the temperature dependent model is validated as shown in Figure 5. The noise figure of the HBT is plotted versus temperature in Kelvin. In this case, the device is biased at $V_{ce} = 1V$ and $I_b = 100$ µA and the temperature varied from 293K to 373K (20C to 100C). As can be noticed, good correlation has been obtained between the measured and modeled results.

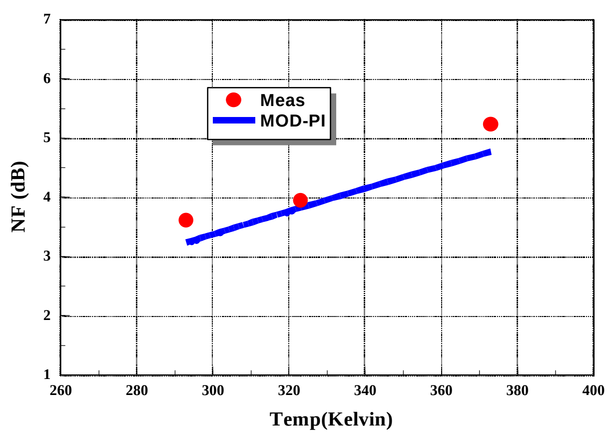


Figure 5. Temperature dependency of the noise figure @ 10GHz, biased at Vce=1V and IB=100µA. Temperature was varied from 20C to 100C.

Conclusions

In conclusion, an accurate bias and temperature dependent noise model for AlGaAs/GaAs HBT, which takes into account (i) correlation of the noise sources and (ii) the frequency dependency of the noise sources**,** is presented. Measurements and validation are performed for various foundry HBTs. These models can be implemented easily into any SPICE or harmonic balance simulators thereby facilitating the design of integrated circuits which incorporate HBTs.

Acknowledgments

This work is sponsored by the Air Force Phase II program on *Bias Dependent Noise Modeling of HBTs*. The author gratefully acknowledges the useful discussions had with Dr. Reza Tayrani and Dr. Bob Pucel and the assistance of Mr. Bob Neidhard of Wright-Patterson Air Force Base with the measurements. Participation of the TRW and Raytheon foundries towards model validation is greatly appreciated.

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