Predictive Modeling of InGaP/GaAs HBT Noise Parameters from DC and *S*-Parameter Data for Wireless Power Amplifier Design

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Abstract

Noise characterization of bipolar transistors is typically a lengthy and costly process. As a result, routine monitoring of microwave noise does not generally occur for HBT technologies or products. In contrast, vast quantities of parametric DC data and *S*-parameter data are measured during the regular course of technology development and production. In work by Voinigescu et al [1], DC and *S*-parameter data are used to predict Silicon BJT and Silicon-Germanium HBT noise parameters. The goal of this work is to apply and adapt, if necessary, the method of [1] to InGaP/GaAs HBTs.

I. INTRODUCTION

During the technology development and into the product development cycle, it is necessary to periodically examine the noise figure of certain devices and pre-production circuits. This is necessary to ensure that the technology will enable future products to meet design specifications. However, both the equipment and resources required to obtained precise noise parameters throughout the development cycle can be prohibitively expensive. Therefore, it is desirable to develop a method by which noise parameters can be obtained without the use of traditional equipment and leverage already existing measurements.

The composition of a basic noise figure system includes a vector network analyzer, several tuners, noise sources, and a noise figure meter. This suite of equipment easily costs in excess of US$200,000, and requires a single work shift to produce a complete set of noise parameters for a given device. In contrast, vast quantities of parametric DC data and 50Ω, two-port *S*-parameter data are obtained by automated test equipment during the regular course of technology and product development. In a method presented by Voinigescu et al [1], DC and *S*-parameter data are used to predict a device's noise parameters. However, the method was applied only to Silicon BJTs and Silicon-Germanium HBTs. The goal of this work is to apply and adapt, if necessary, the method of [1] to InGaP/GaAs HBTs. This would allow technologists and circuit designers to obtain noise parameters from more readily available and less costly measurements.

II. NOISE MODEL

Although the focus of this paper is noise modeling and characterization, a detailed discussion of noise theory and amplifier noise is not presented here. The reader is referred to Gonzales [2] for additional background material. A review of the noise model and noise parameter formulation presented in [1] follows here.

Fig. 1 shows the π-model small signal equivalent circuit of a bipolar transistor. In addition, the uncorrelated noise sources from terminal resistances, r_B and r_C, and the uncorrelated noise currents, i_B^2 and i_C^2, from junction shot-noise are illustrated. Reduction of these uncorrelated noise sources to their correlated input-referred noise source equivalents, v_n^2 and i_n^2, is shown in Fig. 2. Visualization of an ideal, noise-free bipolar transistor with two distinct correlated noise sources allows a compact formulation of noise parameters: R_n, source noise resistance; Y_{SOP}, the optimum source admittance; and F_{MIN}, the minimum noise figure in terms of basic device parameters, r_B, r_E, I_B, I_C, and corresponding *Y*-parameters. Equations (1)-(5) summarize this formulation. Now that the noise parameters are expressed in terms of measurable quantities, I_B, I_C, [*Y*], and extracted parameters, r_B, r_E, two port *S*-parameter measurements are all that are required to complete this analysis method.

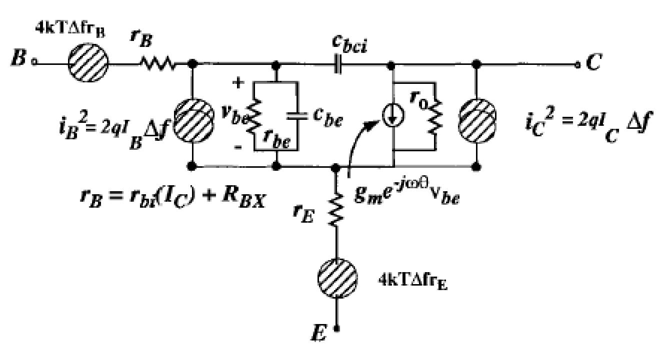

Fig. 1. Small signal and noise equivalent circuit used in the bipolar transistor noise parameter derivation. It features the uncorrelated shot-noise currents i_B^2 and i_C^2. Reproduced from [1].

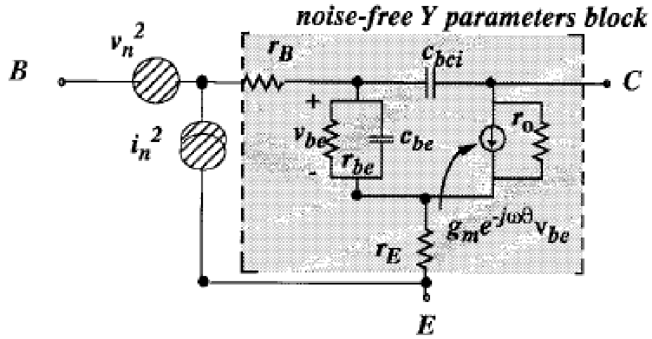

Fig. 2. The equivalent input-referred noise model with correlated noise sources, i_n^2 and v_n^2, and noise-free [Y] block. Reproduced from [1].

$$R_n = \frac{I_C}{2V_T|Y_{21}|^2} + (r_E + r_B) \tag{1}$$

$$V_T = \frac{kT}{q} \tag{2}$$

$$\alpha = 2V_T|Y_{21}|^2 (r_E + r_B) \tag{3}$$

$$Y_{SOP} = \sqrt{\frac{I_B|Y_{21}|^2 + I_C|Y_{11}|^2}{\alpha + I_C} - \left(\frac{I_C \operatorname{Im}\{Y_{11}\}}{\alpha + I_C}\right)^2} - j\frac{I_C \operatorname{Im}\{Y_{11}\}}{\alpha + I_C} \tag{4}$$

$$F_{MIN} = 1 + \frac{I_C}{V_T|Y_{21}|^2} \times \left(\operatorname{Re}\{Y_{11}\} + \sqrt{\left[1 + \frac{\alpha}{I_C}\right]\left[|Y_{11}|^2 + \frac{I_B|Y_{21}|^2}{I_C}\right] - (\operatorname{Im}\{Y_{11}\})^2}\right) \tag{5}$$

III. Experimental Results

In order to verify the method presented in [1], several devices were manufactured at Skyworks Solutions Inc. Gallium-Arsenide fabrication line in Newbury Park, CA. The process technology features a single hetero-junction HBT, utilizing an InGaP emitter, optimized for wireless communication power amplifiers. For this work, the technology is treated as a black box as the method requires little intimate knowledge of the technology itself. However, discussions in section IV will highlight the need for a greater understanding of the technology in order to refine the noise parameter extraction method.

Noise parameter measurements were performed using an NP5 on-wafer measurement system from ATN Technologies Inc. Since cellular and other commercial wireless communication bands are of interest, only a limited set of measurements between 2 and 6 GHz are presented. Furthermore, measurements focused on a single power amplifier cell configuration with an emitter area of 56μm^2 and a larger array of this cell with a total emitter area of 896μm^2. Figs. 3 and 4 present the measured F_{MIN} and G_A of the smaller 56μm^2 device. Discussion of the larger 896μm^2 array will be treated in section V.

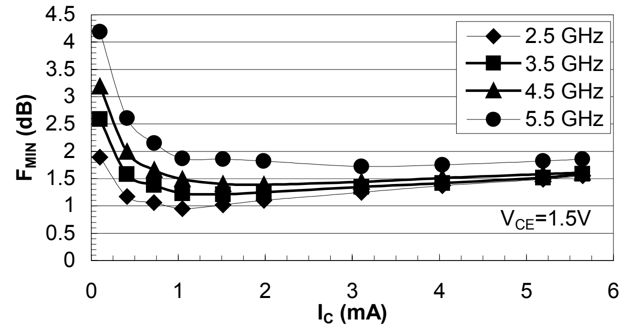

Fig. 3. Measured minimum noise figure as a function of collector current for a 56μm^2 InGaP/GaAs SHBT. V_{CE} is fixed at 1.5V.

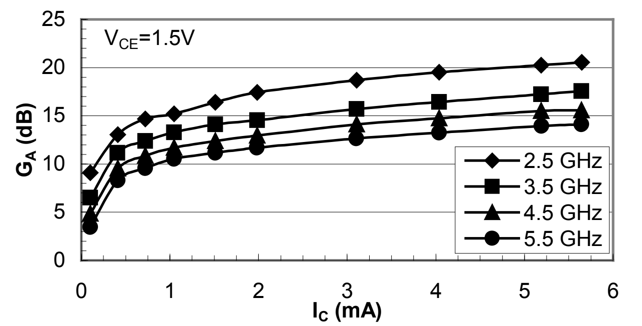

Fig. 4. Measured associated gain, G_A, as a function of collector current for a 56μm^2 InGaP/GaAs SHBT. V_{CE} is fixed at 1.5.

It is imperative that this work be viewed as a feasibility assessment of a specific noise parameter extraction method to the InGaP/GaAs HBT technology under study. Further measurements and analysis would be required to assess the validity of this method to all GaAs HBT devices and a more general application space.

IV. Noise Parameter Extraction

In this section, the determination of device parameters necessary for accurate noise parameter prediction will be discussed. The parameter extraction methods described here follow the general practices used by device modelers [1],[3],[4]. Once the appropriate two port *S*-parameters are measured for an HBT, the success of the noise parameter extraction process depends heavily on the determination of the emitter resistance, r_E, and base resistance, r_B.

First, a value for r_B is extracted from the real part of (Z_{11}-Z_{12}). Only frequency values below 1GHz are considered and then averaged to yield an I_C dependent base resistance, $r_B(I_C)$. Fig. 5 shows the extracted $r_B(I_C)$ as a function of I_C. Further examination of $r_B(I_C)$ shows that the I_C dependency is weak at moderate I_C, but pronounced at low I_C. Caution should be exercised when examining the effective r_B at low I_C as GaAs HBTs are prone to high base leakage currents and poor base current ideality factors. In addition, this $r_B(I_C)$

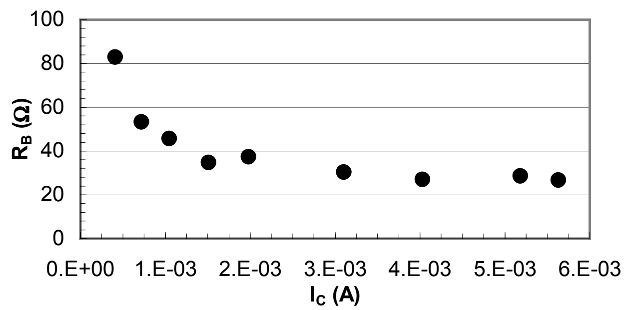

Fig. 5. Base resistance from measured *S*-parameters versus collector current

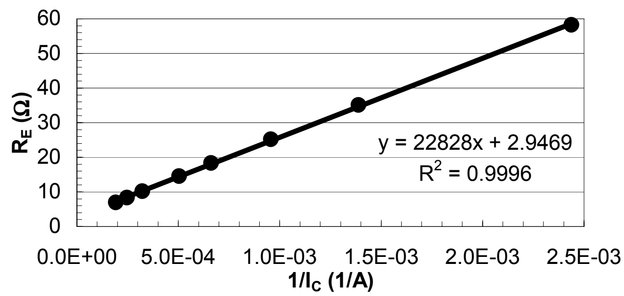

Fig. 6. Emitter resistance from measured *S*-parameters versus inverse collector current.

represents the real part of the base impedance, rather than the actual base resistance since, for III-V transistors, the components of the total base resistance are more evenly distributed between intrinsic and extrinsic portions of the device. Even at moderate I_C, we expect the portion of the r_B under and surrounding the emitter to show some variation with I_C, but the majority of the r_B, composed of the base link region, should be invariant with I_C. Due to the small range of I_C considered here, a fixed value of 25Ω is adopted for the purposes of noise parameter extraction.

The r_E is determined from the averaged low frequency (<1GHz) values of the real part of Z_{12} at low V_{CE} and I_C. In Fig. 6, the various bias dependent Re{Z_{12}} values are plotted versus inverse I_C. The true r_E can be determined from the y-intercept, and linear regression yields a value of 2.947Ω for the r_E. The determination of this parameter is complicated by the pronounced self-heating behavior of GaAs HBTs. It is imperative that r_E be extracted under minimal bias conditions so that the isothermal condition is maintained. The use of Gummel curves and the $1/g_m$ versus $1/I_C$ method is not recommended as the high current region, the region of interest for this method, is highly influenced by device self-heating [5]. The use of RF measurements to determine the small signal equivalent r_E has produced the best noise parameter extraction results.

Examining equations (1) and (3), we see that R_n and α are dependent on the sums of r_B and r_E. In the case of the 56μm^2 device, the extracted r_B value is significantly greater than the r_E value. We would expect r_E to have little effect on the extracted noise parameters, but an accurate value of r_B is crucial. Fig. 7 shows the extracted R_n versus frequency for various I_C. Notice that the correlation between extracted and measured noise parameters is reasonable, but the curvature of the experimental data is not parallel to the extracted data. It is expected that r_B, r_E, I_C, and V_T remain constant over frequency, but Y_{21} could vary considerably.

Further examination of the remaining noise parameters yields additional evidence that the *Y*-parameters are the cause of the deviation. F_{MIN} is plotted on Fig. 8, and the magnitude and phase of Γ_{SOP} are plotted on Figs. 9 and 10, respectively. F_{MIN} is a reasonable fit with no more than 0.2dB deviation, but the extracted curves also have the incorrect curvature. Only Y_{11} and Y_{21} are frequency variant quantities located in equation (5). Further deviation is more apparent on the plots of Γ_{SOP}. Looking at equations (4) and (5), it is unlikely that r_B, r_E, I_B, I_C, and V_T are the cause of the curvature mismatch. However, a systemic error in the *Y*-parameter matrix is likely to be cause of the error.

For low power densities, the 56μm^2 device has a thermal resistance independent of temperature, and the anticipated rise in junction temperature should be negligible. Under these conditions, we have assumed that the 56μm^2 device is in an isothermal state with its ambient. Examining equations (1), (4), and (5), we find that the noise parameters vary no more strongly than linear or inverse linear with the device junction temperature. Furthermore, perturbations of approximately 6K will only perturb the value of V_T by ~2%. Therefore, we can expect temperature to have little impact on the extracted noise parameters.

V. Large HBT Arrays and Amplifiers

Due to the large size of power transistors, r_B, r_E, and V_T are difficult to obtain with high accuracy. However, base and/or emitter ballasting can increase the effective r_E and r_B such that they are easy to determine with the methods described above. The remaining parameter, V_T, grows in complexity significantly. Due to the poor thermal conductivity of GaAs and the high power densities of power amplifier operation, the junction temperature will be significantly higher than the ambient temperature. Furthermore, each device within an amplifier experiences a slightly different thermal environment. Figs. 11 and 12 compare F_{MIN} and R_n, respectively, for the 896μm^2 device where the array temperature is equal to the ambient. Despite these difficulties, the extracted noise parameters correlate well to the measured data.

VI. Conclusions

The noise parameter extraction method described in [1] has been shown to correlate reasonably well to InGaP/GaAs SHBTs for wireless communication power amplifiers. However, issues concerning extracted noise parameter behavior over bias and frequency have yet to be reconciled.

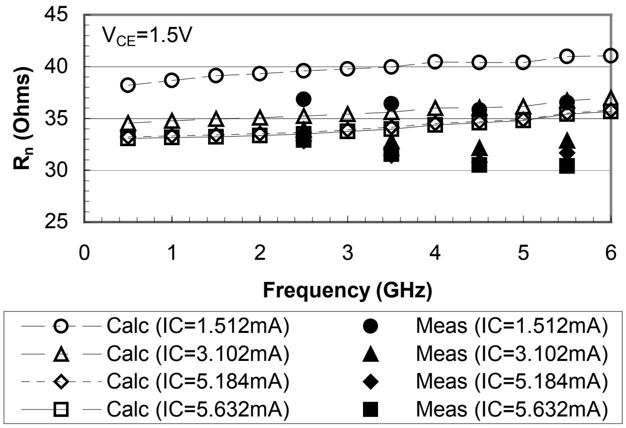

Fig. 7. Measured and extracted input referred noise of the 56µm^2 device.

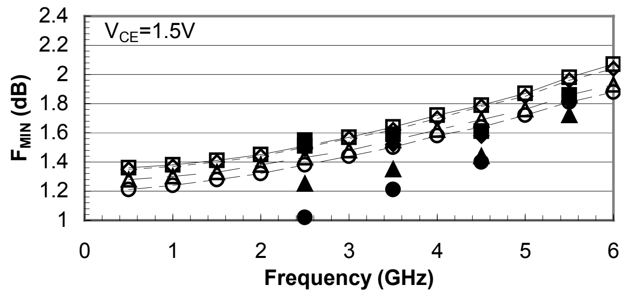

Fig. 8. Measured and extracted minimum noise figure of the 56µm^2 device. Line symbols are identical to those in Fig. 7.

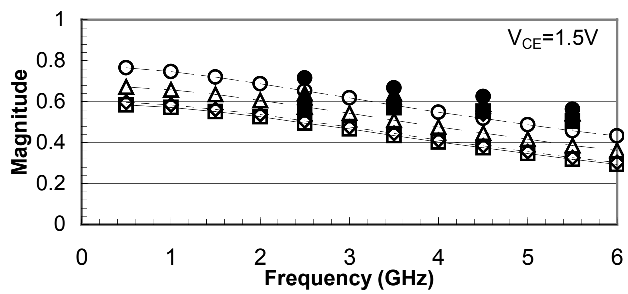

Fig. 9. Measured and extracted magnitude of Γ_{SOP} of the 56µm^2 device. Line symbols are identical to those in Fig. 7.

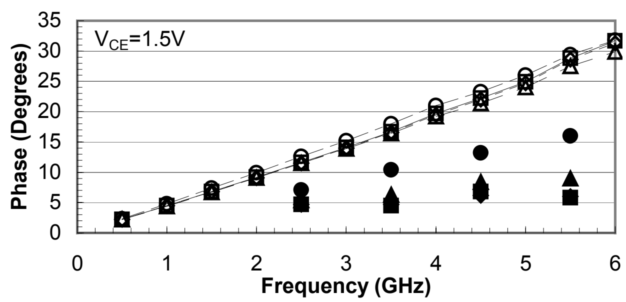

Fig. 10. Measured and extracted phase of Γ_{SOP} of the 56µm^2 device. Line symbols are identical to those in Fig. 7.

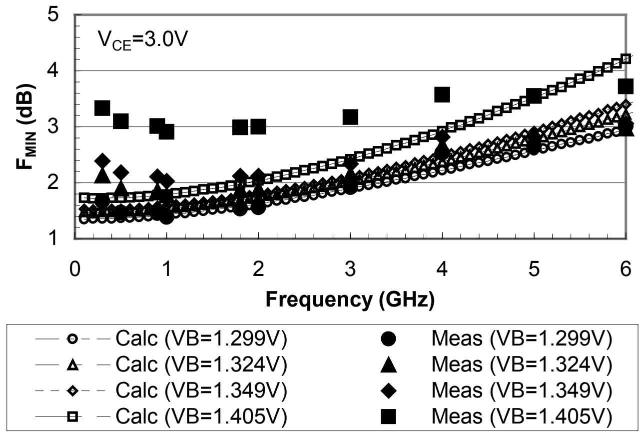

Fig. 11. Measured and extracted minimum noise figure of the 896µm^2 device. Array temperature is 25K and V_{CE} = 3.0V.

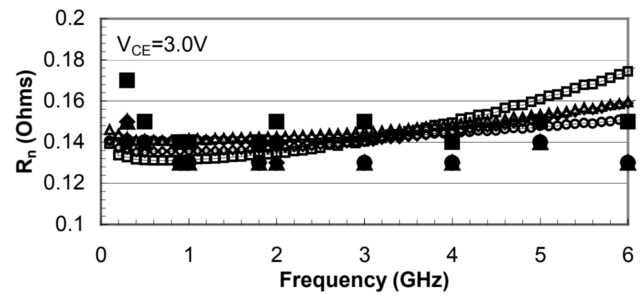

Fig. 12. Measured and extracted input referred noise of the 896µm^2 device. Array temperature is 25K and V_{CE} = 3.0V. Line symbols are identical to those in Fig. 11.

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ACRONYMS

HBT: Hetero-junction Bipolar Transistor
SHBT: Single Hetero-junction Bipolar Transistor
BJT: Bipolar Junction Transistor