Small-Signal and Noise Model Extraction Technique for Heterojunction Bipolar Transistor at Microwave Frequencies

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Abstract—**The increasing use of Heterjunction Bipolar Transistors (HBT's) in microwave analog circuits requires a valid description of these devices by means of an equivalent circuit including noise sources in an extended bias and frequency range.**

This paper describes a technique to extract the elements of the equivalent circuit from simultaneous noise and S-parameter measurements. Additionally, the conventional high frequency bipolar junction transistor (BJT) noise model is shown to work well with HBT's. Recent results obtained from GaInP/GaAs HBT's are reported.

I. INTRODUCTION

A PHYSICALLY-BASED, small-signal, equivalent circuit of microwave bipolar transistor, valid for multiple bias is very useful for drawing up new circuit design guidelines for microwave linear integrated circuits. This model is obtained by minimizing the difference between the measured and the calculated S-parameters. This is accomplished by an optimization procedure which changes the equivalent circuit parameter (ECP's) values to reach the minimum of a given error function. Usually the problem lies in that there are several solutions providing a good fit and then ECP values depend on the initial values used for starting the optimization [1]. It is therefore possible to accurately fit the measured S-parameters with a nonphysical set of ECP values and still obtain inaccurate results for several applications like those requiring noise parameter knowledge.

To overcome these limitations, different attractive methods have recently been proposed. Additional measurements of test structures located on the same wafer can be performed to determine the parasitic inductances and capacitances [2]. Cutoff mode measurements are also used to reduce the number of unknowns in the optimization procedure [3]. These measurements can be coupled with an analytical method for extracting model parameters [4]. Direct analysis of S-parameter data combined with an appropriate optimization procedure also allows ECP extraction [5].

As previously described for field effect transistors [6], an alternative technique, based on an optimization procedure using an error function involving both small-signal and noise parameters, is proposed for HBT's (Section III). In addition it is shown that the standard high frequency BJT noise model is well-suited for HBT's. Finally recent microwave noise data obtained from GaInP/GaAs devices are discussed (Section IV). In the following section, the small-signal and noise model used in this study is discussed.

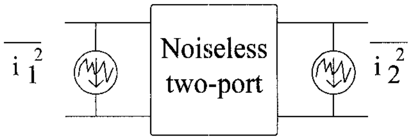

Fig. 1. Parallel representation of a noisy two-port.

II. SMALL-SIGNAL AND NOISE MODEL

The noise behavior of a linear noisy two-port can be accurately described by two noise generators and their complex correlation [7]. The parallel representation is given in Fig. 1 where the noisy two-port is replaced by a noiseless two-port defined by its admittance matrix, combined with two correlated noise current sources i_1 and i_2 set at the input and output of the network, respectively. In the case of an intrinsic heterojunction bipolar transistor in common-emitter mode and according to Van der Ziel's analysis [8], the noise sources i_1 and i_2 in the high frequency range, which is well above the excess noise corner frequency (typically 1 MHz or less in HBT's [9]), result from the shot noise generated at the base-emitter and base-collector junctions. These noise sources are characterized by their mean quadratic value in a bandwidth Δ f centered on the frequency f, and can be given by the following expressions:

$$\overline{i_1^2} = 2qI_b\Delta f \quad (1)$$

$$\overline{i_2^2} = 2qI_c\Delta f \quad (2)$$

where q is the electronic charge and k Boltzmann's constant. I_b and I_c are the base and collector currents, respectively.

The commonly used cross-correlation [10] between i_1 and i_2 obtained by Van Vliet's theory [11] is given by the following equation:

$$\overline{i_1 i_2^*} = 2kT(Y_{12i} + Y_{21i}^*)\Delta f - 2qI_c\Delta f \quad (3)$$

where Y^* is the complex conjugate of Y and T the room temperature (294 K). Y_{12i} and Y_{21i} are the reverse and forward transfer admittance of the intrinsic transistor, respectively. According to (3) the noise behavior strongly depends on the

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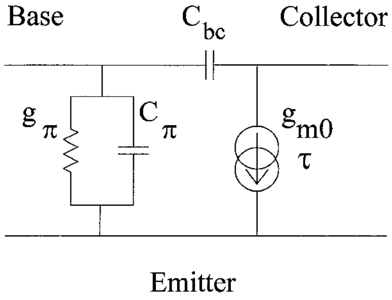

Fig. 2. Equivalent circuit topology for the intrinsic HBT.

values of the Y-parameters of the intrinsic device. An accurate small-signal equivalent circuit is thus a prerequisite for an accurate analysis of the transistor noise properties.

The common emitter Π-model equivalent circuit used to characterize the intrinsic behavior of HBT is presented in Fig. 2. The bias-dependent intrinsic elements are the dynamic diode conductance g_Π, the base-emitter capacitance C_Π including the diffusion capacitance and the depletion capacitance, the base-collector capacitance C_{bc}, the transconductance g_{m0} and the time delay between base and collector τ. The output conductance has been disregarded in this work since its effect on power gain is only noticeable below 1 GHz [12]. The admittance parameters of the intrinsic transistor are obtained from the theory of linear networks and are expressed as follows:

$$Y_{11i} = g_n + j(C_n + C_{bc})\omega \tag{4}$$

$$Y_{12i} = -jC_{bc}\omega \tag{5}$$

$$Y_{21i} = g_{m0}\cos(\omega\tau) - j[g_{m0}\sin(\omega\tau) + C_{bc}\omega] \tag{6}$$

$$Y_{22i} = jC_{bc}\omega \tag{7}$$

where ω is the angular frequency.

But the real HBT cannot be fully described by the simple equivalent circuit of Fig. 2. Parasitic resistances (including contact and access resistances to the intrinsic transistor) must be added and are supposed to generate thermal noise according to the well-known Nyquist relation:

$$\overline{e_R^2} = 4kTR\Delta f \tag{8}$$

where R is the resistance at ambient temperature ($T = 294$ K).

The complete HBT small-signal and noise equivalent circuit is shown in Fig. 3 including parasitics associated with the contact pads. C_{pbc} represents the extrinsic collector capacitance. The extrinsic capacitance between base and emitter was found to be negligible and can be ignored in the equivalent circuit topology. It can be pointed out that the base resistance is splitted into two parts as generally shown [13]. This equivalent circuit topology provides satisfactory results in the frequency range of interest (up to 20 GHz).

Unlike field effect transistors where diffusion noise is preeminent, no additional noise coefficient is needed in (1)–(3) to obtain the exact values of the noise sources. This provides the theoretical background for the proposed extraction technique described in the next section.

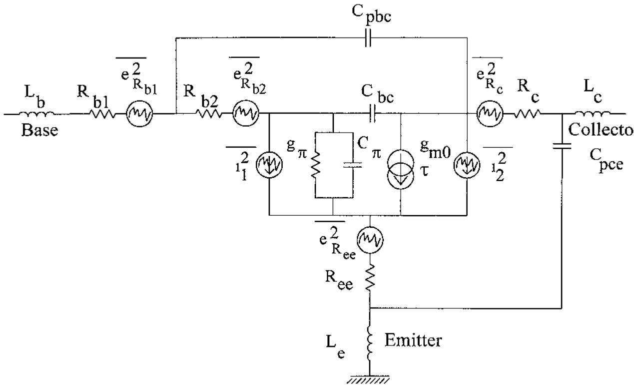

Fig. 3. Complete HBT small-signal and noise equivalent circuit.

III. Extraction Procedure

Scattering and noise measurements are performed on-wafer using an automatic test set coupled with a wafer probe station. The noise parameters derived from the multiple impedance technique [14] are the minimum noise figure $F_{\min}$, the equivalent noise resistance R_n and the optimum noise source admittance $Y_{opt} = G_{opt} + jB_{opt}$ which provides the minimum noise figure. The test set and the method used to extract those parameters are described elsewhere [15]. Measurements are made from 4 to 20 GHz for different base currents I_b ranging from 90 μA to 1200 μA at $V_{ce} = 2$ V. The extraction of the ECP's is done using Hewlett-Packard simulation software MDS.

Our main contribution lies in the introduction of a new error function involivng both small-signal and noise parameters [6] allowing accurate ECP values to be derived from the optimization procedure. Contrary to cutoff [3] or cold device measurements, noise parameter measurements are performed under normal operating bias conditions and therefore provide the actual equivalent circuit elements at a given bias point.

The error function is a normalized least-square error function given by:

$$\varepsilon = \sum_{\substack{Y\\ \text{PARAMETERS}}} \sum_{\text{freq}} \left(\frac{\text{Data}_Y - \text{Model}_Y}{\text{Data}_Y}\right)^2 + \sum_{\substack{\text{NOISE}\\ \text{PARAMETERS}}} \sum_{\text{freq}} \left(\frac{\text{Data}_N - \text{Model}_N}{\text{Data}_N}\right)^2 \tag{9}$$

Data_Y and Model_Y refer to the measured and calculated characteristics of the device and correspond to the real part and the imaginary part of admittance parameters obtained from scattering parameters whereas Data_N and Model_N refer to the measured and computed noise parameters. The optimization method is based on the gradient method and the procedure is ended when the relative deviation between measured and calculated data is less than 1%. The initial value of the collector resistance R_c is obtained from DC measurement [16]. The value of the emitter resistance R_{ee} is obtained from low frequency measurement [17] and left unchanged during the optimization process.

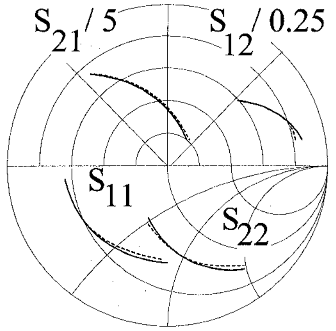

Fig. 4. Measured and computed S-parameters of a GaInP/GaAs HBT at I_c – 2.45 mA, I_b = 250 μA and V_{ce} = 2 V from 4 GHz to 20 GHz. "- - - -": measured data, "——": computed data.

The optimization procedure was performed for 7 different base currents and all parameters (except R_{ee}) have been extracted for each value of the base current. Parasitic elements were found to be weakly bias-dependent. Their mean values were then calculated and left unchanged in a final multiple bias optimization procedure in order to adjust the intrinsic ECP's. The results obtained are discussed in the next section.

IV. RESULTS

The proposed procedure was used to derive a small-signal and noise equivalent circuit of GaInP/GaAs HBT's. HBT's were processed by Thomson-CSF/LCR using self-aligned technology [18], [19]. Epitaxial structures were grown by Low Pressure Metal Organic Chemical Vapour Deposition (LP-MOCVD) and base layers were carbon-doped to insure low P dopant diffusion into the emitter. Devices featuring a 1 μm × 20 μm emitter show an f_T of 45 GHz and f_{MAX} of 55 GHz [9].

In Fig. 4, we compare the measured and computed S-parameters of a GaInP/GaAs HBT operating at I_c = 2.45 μA, I_b = 250 μA and V_{ce} = 2 V. An excellent agreement over the entire 4–20 GHz frequency range was observed. The noise parameters and the associated gain variations versus frequency are also reported in Figs. 5(a)–(c) for the same bias and a good agreement was observed between the computed and the measured values. Minimum noise figure F_{min} was found to be constant with frequency with a 3 dB value. This differs from what had previously been reported [20]–[22] where F_{min} increased with the square of frequency above the 3 dB cut-off frequency of the intrinsic current gain. Numerical simulations have shown the noise figure to be strongly dependent on the extrinsic base-collector capacitance C_{pbc} and time delay τ which reduce the noise figure variations at high frequencies.

The 11.3 dB associated power gain measured at 12 GHz compares well with those observed in FET's. The variation of the equivalent noise resistance R_n versus frequency is reported in Fig. 5(b). Likewise, the decrease of R_n with frequency is due to the time delay τ and the influence of the extrinsic capacitance C_{pbc} in this frequency range.

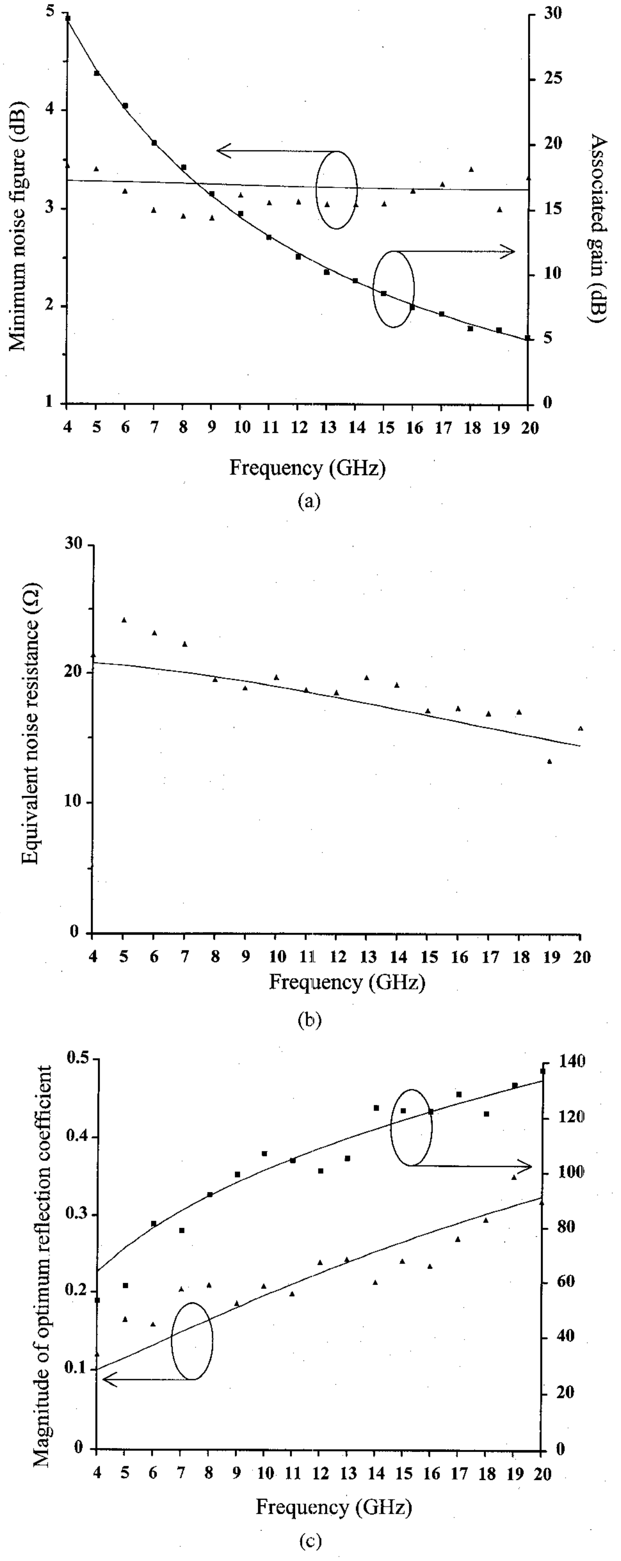

Fig. 5. Noise parameters versus frequency of a GaInP/GaAs HBT at I_c = 2.45 mA, I_b = 250 μA and V_{ce} = 2 V. (a) Minimum noise figure F_{min} and associated gain G_a versus frequency. "▲" F_{min} measured. "■": G_a measured. "——": computed data. (b) Equivalent noise resistance R_n versus frequency. "▲": measured data. "——": computed data. (c) Magnitude and phase of the optimum reflection coefficient Γ_{opt} versus frequency. "▲": $|\Gamma_{opt}|$ measured: "■": $\angle\Gamma_{opt}$ measured. "——": computed data.

With respect to the optimum reflection coefficient Γ_{opt} depicted in Fig. 5(c), the following may be stated: the low-value of $|\Gamma_{opt}|$ (less than 0.3), compared to the field effect transistors, facilitates the noise parameter measurement procedure and increases the accuracy of the noise parameter

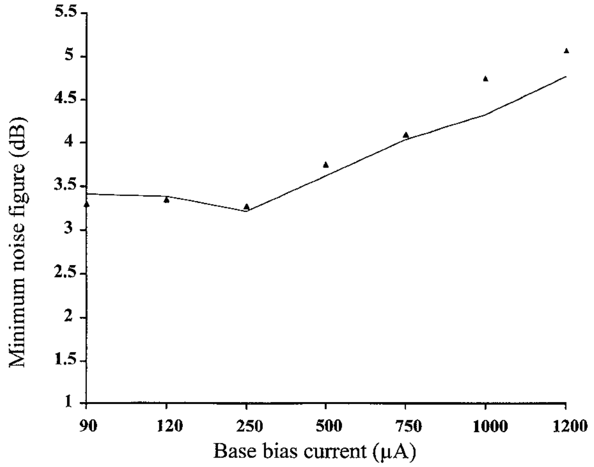

Fig. 6. Measured and computed minimum noise figure F_{min} versus base current I_b at $f = 18$ GHz. "△": measured data. "——": computed data.

extraction technique [15]. Moreover, the low noise matching condition is more easily obtained. The variations of measured and calculated F_{min} versus base current I_b are reported in Fig. 6 at $V_{ce} = 2$ V and $f = 18$ GHz. The minimum noise figure decreases when decreasing the base current according to the shot noise theory and a minimum occurs at $I_b = 250$ μA. The slight increase of F_{min} for base currents lower than 250 μA is related to the decrease of the current gain at low injection level due to surface recombinations.

The results indicate that shot noise dominates the noise behavior of the HBT's used in this study. Higher values of current gain β are then needed to decrease the minimum noise figure. The agreement between the calculated and the measured values of F_{min} for base current values lower than 750 μA($I_c > 10$ mA) is excellent while a slight discrepancy occurs at high values. This occurs probably, because of the device self heating. Further investigations are being carried out to include the junctions temperature of the device in the small-signal and noise model.

In order to evaluate the weight of the noise parameters in the error function, Table I lists the results of two different extraction methods for $I_c = 2.45$ mA, $I_b = 250$ μA and $V_{ce} = 2$ V. In the first case, only Y-parameters are optimized while in the second, both Y- parameters and noise parameters are considered. Both methods provide an equivalent good fit of scattering parameters. Nevertheless the noise parameters calculated for Case I widely differ from the experimental ones, while an excellent agreement is obtained in Case 2 as shown in Figs. 5(a)–5(c). Additionally in Case 2 after many trials, it was found that, in our case, the final values of ECP's are insensitive to the starting point values with the suggested new error function including noise data.

Other GaInP/GaAs HBT's exhibiting different emitter dimensions as well as Si/SiGe HBT's fabricated at Daimler-Benz [23] have also been modeled with similar good results. Although the frequency dependence of noise parameters in Si/SiGe HBT's is slightly different from the one observed in the GaInP/GaAs devices previously investigated, the accuracy of the proposed technique turns out to be very satisfactory.

TABLE I
ECP VALUES EXTRACTED FROM A CONVENTIONAL PROCEDURE (USING S-PARAMETERS ONLY) AND FROM THE PROPOSED TECHNIQUE (USING S-PARAMETERS AND NOISE PARAMETERS) AT $I_c - 2.45$ mA, $I_b = 250$ μA AND $V_{ce} = 2$ V

ECP's	Optimization through Y-parameters only	Optimization through Y-parameters and noise parameters
L_c (pH)	36.8	25.5
L_b (pH)	36.1	32.1
L_e (pH)	23.3	21.7
C_{pbc} (fF)	73.2	45.0
C_{pce} (fF)	43.8	33.2
R_c (Ω)	3	3
R_{b1} (Ω)	0.3	0.1
R_{b2} (Ω)	10.8	8.6
R_{ee} (Ω)	2.9	2.9
C_{Π} (pF)	0.391	0.407
C_{bc} (fF)	37.1	69.9
g_{Π} (mS)	7.47	9.88
g_{m0} (mS)	82.9	88.5
τ (ps)	0.61	1.79

V. CONCLUSION

We have used a sensitive extraction technique involving both scattering and noise measured data to derive an accurate small-signal and noise equivalent circuit of HBT's. This technique provides correct parameter values and does not require additional test structures or special bias measurement.

We have found that two correlated intrinsic noise current generators provide a satisfactory description of the observed HBT's noise behavior as expected from the conventional high frequency BJT noise model.

Furthermore, the proposed technique can easily be implemented on commercially available CAD software and the appropriate parasitic elements can be added to the proposed equivalent circuit to enhance the frequency range validity.

GaInP/GaAs HBT's have been investigated using this technique under several bias conditions. A noise figure of about 3 dB with a 5 dB associated gain has been obtained at 20 GHz. Further technological improvements that could provide higher values of β will thus provide a further decrease in minimum noise figure.

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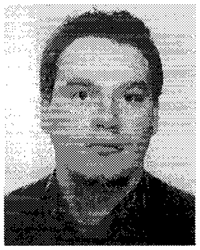

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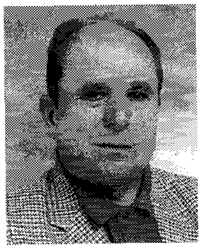

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