Direct Parametric Extraction of $1/f$ Noise Source Magnitude and Physical Location from Baseband Spectra in HBTs

D. R. Pehlke, A. Sailer, W.-J. Ho, J.A. Higgins, and M.F. Chang

Rockwell Science Center
1049 Camino Dos Rios, Thousand Oaks, CA 91360

Abstract— **This work describes a novel equivalent circuit representation for the modeling of low frequency $1/f$ noise in Heterojunction Bipolar Transistors (HBTs), and is presented as part of an extraction procedure which combines direct calculation of the HBT equivalent circuit from S-parameters, and separate measurement of the base and collector noise voltage spectra to determine the magnitude and physical location of the dominant intrinsic $1/f$ noise sources within the device.**

I. Introduction

Device low frequency noise can become a severe limitation for many microwave system applications due to its upconversion through nonlinearities to sidebands very close to carrier frequencies of interest. These sidebands degrade spectral purity imposing limits on analog communication channel bandwidth, bit error rates in digital communication systems, and general level detection accuracy in radar and transceiver systems. The understanding of low frequency flicker noise, or 1/f noise, has been a difficult challenge [1] and many areas of its origin and behavior are still not well understood. Many works have described approaches to extracting the intrinsic noise sources producing such 1/f [2], [3], [4], [5] using a combination of bias conditions and external impedance terminations and varied transistor configurations. This work introduces a novel approach that may be performed at a single bias condition and requires only a separate measurement of collector and base spectra. In this way, the bias dependence of the dominant intrinsic noise source may be ascertained accurately in all regimes of device operation, and does not rely on assumptions of impedance values in various bias ranges. The T-model topology of this work differs from the hybrid-π configuration of others in its more physical representation of the current paths within the actual device, which is a critical component of isolating and quantifying the noise magnitudes of those currents. This technique results in an accurate model for the single dominant and physically independent (uncorrelated) actual source of 1/f noise in HBTs and may be coupled with a technique to determine he base-emitter and emitter series resistances of HBTs.

II. Low Frequency Noise Characterization

The set-up used to measure the collector (S_{vC}) and base (S_{vC}) noise spectra is a commercially available noise measurement system, the hp3048. A diagram of the complete system is shown in Figure 1. Both the hp11848 and the hp3561 are computer controlled. The hp11848 contains amplifiers and high/low-pass filters which are used to divide the $10Hz$ to $100kHz$ measurement bands into decade sub-bands, which are separately swept by the FFT analyzer.

Base bias was supplied across a $40k\Omega$ resistor (R_S) and collector bias across a 200Ω resistor (R_L). S_{vB} and S_{vC} (in dBV^2/Hz) are measured across the same resistors.

The measured base and collector voltage noise spectral densities are shown in Figure 3 for a 3 x 1.4μm x 8.5μm AlGaAs/GaAs HBT under the bias conditions $I_C = 14mA$, $I_B = 93uA$, and $V_{CE} = 2.0V$. At this collector current density of $4 \cdot 10^4 A/cm^2$ the current gain is nearing its peak level but is still below high-level injection conditions. Although the noise floor level of the base voltage spectra in Figure 3 is obscured by the white noise floor level of the system under these conditions of test, the lower frequency of 100Hz shows 1/f magnitudes that are resolved cleanly for analysis. It is this lower frequency of 100Hz that is used as the spot measure for all extraction discussed in this work.

III. Derivation of HBT Noise Model

The development of equivalent circuit models for noise requires several critical issues be observed. First, in order to provide scaling and bias dependent accuracy in a physically-based extraction, the separate noise sources should be uncorrelated and result from physically separate phenomena within the device. Second, the current paths within the model must accurately represent the current paths within the actual device. For this reason, the T-model of Figure 2a is favored over the hybrid-π of Figure 2b, because the hybrid-π inaccurately represents the base-emitter impedance as gating only the base current I_B, as opposed to the entire emitter current I_E as is the case in the actual device and T-model representation. In the hybrid-π, the majority of the emitter current never encounters the

0-7803-3246-6/96/$5.00 © IEEE

1996 IEEE MTT-S Digest

base-emitter impedance and so the device low frequency noise current fluctuations through that resistor will not accurately represent the corresponding current fluctuations of the physical device. The third aspect is the location of sources themselves within the equivalent circuit, and this is the focus of section IV. To start, we represent all reasonable locations for 1/f noise generation by a source; including S_{vrB} from base contact, S_{vrE} from emitter contact, S_{iEB} from base-emitter junction recombination and leakage to the surface and base contact, and S_{iEC} from base-collector partition noise and general surface interaction and diffusion effects.

The spectral derivation to follow is based largely on the work of Kleinpenning [5]. The equivalent circuit of Figure 2 may be analyzed according to the following:

$$\Delta I_E = \Delta I_B + \Delta I_C \tag{1}$$

$$\Delta I_B = \Delta I_{eb} + \frac{\Delta v_{eb}(1-\alpha)}{R_{BE}} - \Delta I_{ec} \tag{2}$$

$$\Delta I_C = \Delta I_{ec} + \alpha\frac{\Delta v_{eb}}{R_{BE}} \tag{3}$$

$$\begin{aligned}\Delta v_{eb} &= -(R_S + r_B)\,\Delta I_B - I_B \Delta r_B \\ &\quad -(r_E)\,\Delta I_E - I_E \Delta r_E + \Delta v_{eb}^N\end{aligned} \tag{4}$$

$$\Delta I_E = \Delta I_{eb} + \frac{\Delta v_{eb}}{R_{BE}} \tag{5}$$

where the equivalent circuit elements and noise source notations correspond to the equivalent circuit of Figure 2b.

As a result of reducing these expressions with multiple substitutions, one is able to express the base and collector noise voltage spectral densities as :

$$\begin{aligned}S_{vC} &= \left[\frac{\beta^2 (R_S + r_B + r_E)^2}{Z^2}\right] R_L^2 S_{ieb} \\ &+ \left[\frac{(\beta+1)^2 (R_S + r_B + r_E + R_{BE})^2}{Z^2}\right] R_L^2 S_{iec} \\ &+ \left[\frac{\beta^2 I_B^2 S_{vrB} + \beta^2 I_E^2 S_{vrE} + \beta^2 S_{vebN}}{Z^2}\right] R_L^2\end{aligned} \tag{6}$$

$$\begin{aligned}S_{vB} &= \left[\frac{(\beta (R_{BE} + r_E) + R_{BE})^2}{Z^2}\right] R_S^2 S_{ieb} \\ &+ \left[\frac{(\beta+1)^2 (R_{BE} + r_E)^2}{Z^2}\right] R_S^2 S_{iec} \\ &+ \left[\frac{I_B^2 S_{vrB} + I_E^2 S_{vrE} + S_{vebN}}{Z^2}\right] R_S^2\end{aligned} \tag{7}$$

where S_{vebN} represents the thermal noise contribution of the series and source resistance and may be expressed as :

$$S_{vebN} = 4kT\,(R_S + r_B + r_E) \tag{8}$$

and where the denominator term Z is expressed as :

$$Z = R_S + r_B + (\beta+1)\,(R_{BE} + r_E) \tag{9}$$

These expressions may be used to determine the location of the dominant 1/f noise source(s) within the device as is outlined in the following section.

IV. Parameteric Extraction of 1/f Noise Sources and Their Physical Location in HBTs

In order to accurately determine the intrinsic noise sources, one must first accurately determine the element values of the equivalent circuit of Figure 2b. Based on a direct extraction methodology from S-parameter measurements [6], the resistances and base transport factor are analytically calculated at the same bias point under which the device is operating when the 1/f noise measurements are taken. In doing this, there is maximum certainty that the extraction of intrinsic noise utilizes accurate de-embedding at each discrete bias point, instead of applying a model for those element values meant to be accurate for all bias regions. This allows more accurate determination, especially at higher bias conditions where 1/f noise magnitudes are much larger. Once these element values are known, the previously derived expressions may be applied using S_{vC} and S_{vB}.

Because we have formulated a system of equations in which S_{vC} and S_{vB} are written in terms of four possible noise sources, we may by the process of elimination determine the combinations of noise sources that are possible from the measurement of two knowns, S_{vC} and S_{vB}. In so doing, we are able to tabulate the data in Table I in which assume a combination of two independent sources. Knowing the equivalent circuit from direct extraction, we are able to calculate these two intrinsic noise sources as a system of two unknowns with two knowns and solve linearly. The table illustrates that there are four combinations that are numerically impossible to generate the measured spectra, that being S_{ieb} and S_{iec} alone, S_{ieB} and S_{vrB} alone, S_{ieb} and S_{vrE} alone, and S_{vrB} and S_{vrE} alone

They do not allow calculation of positive spectral densities and as such are logically eliminated as possibilities for modeling the device. The other four possible combinations of two intrinsic 1/f sources are eliminated for the reason that when one calculates the spectra expected from a single source alone, and that value is very nearly equal to its value when assumed to combine with a second source, this indicates that although there is a possible value for the second intrinsic source, its contribution is negligible and may be disregarded. That leaves the aforementioned single source calculations of Table II, in which we assume all the 1/f is attributable to either S_{ieb} alone, S_{iec} alone, S_{vrB} alone, or S_{vrE} alone. We see in Table II that S_{vrB}, S_{vrE}, and S_{iec} when separately calculated from S_{vC} and S_{vB} produce largely different numbers, and relative errors (at a collector current of 4mA) in dB of roughly 56%, 30%, and 6% respectively. However; the assumption of S_{ieb} as the dominant source results in separate calculation of that intrinsic source with only 0.5% relative error, indicating that it is not only sufficient, but an accurate assumption to attribute all the 1/f noise at these bias levels to be due to S_{ieb}, and we are able to extract out this intrinsic noise sources actual value. Shown in Figure 4 is the resulting extracted value for S_{ieb} as a function of collector current, with self-consistent correspondence when extracted from both S_{vC} and from S_{vB}. In contrast, the attempted extraction of S_{iec} as the single dominant source results in Figure 5, with a large discrepancy between the calculation from the collector spectra versus the base spectra, verifying that it could not possibly be the single dominant source of the HBT noise.

V. Use of Noise Spectra to Calculate the Base-Emitter and Emitter Series Resistances

The formalism as presented allows the calculation of the base-emitter and emitter series resistances for the case when $\beta >> 1$ and $R_S >> r_B + r_E$, and may be described by

$$R_{BE} + r_E \approx R_L \sqrt{\frac{S_{vB}}{S_{vC}}} \tag{10}$$

These values are entirely consistent with the aforementioned technique of direct extraction [6] as shown in Figure 6.

VI. Conclusions

This work presents a novel technique for accurate extraction of the location and magnitude of the dominant intrinsic noise source(s) for heterojunction bipolar transistors. Based on a T-model topology, the current paths of the device are more accurately represented, and when combined with direct extraction of the equivalent circuit from S-parameter measurement, measurement of the collector and base spectra at a given bias condition allows isolation of the single noise source, or combination of noise sources responsible for those output spectra. This technique allows isolation of not only the magnitudes of the noise sources involved in the transistoir operation, but their location within the equivalent circuit. This provides a tool to isolate the bias dependence of technological and material related causes of 1/f noise generation in state-of-the-art devices and has been applied to AlGaAs/GaAs HBTs with excellent 1/f noise performance and determined that these devices are dominated by a single noise source whose location has been identified as being across the base-emitter junction resistance, and whose magnitude is investigated vs. bias. This technique is also used in an alternative approach to calculate the base-emitter and emitter series resistances of these devices, and serves as an important tool to establish the physical phenomena and technological effects limiting the low frequency noise performance in state-of-the-art HBTs.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of Derek Cheung and Jon Rode of the Rockwell Science Center, and the technical correspondence of G.P. Li of University of California at Irvine concerning 1/f noise testing.

Intrinsic Noise Source Pairs	$I_C = 2mA$	$I_C = 4mA$	$I_C = 10mA$
$S_{ieb}(dBA/\sqrt{Hz})$	-206.2	-204.2	-198.1
$S_{iec}(dBA/\sqrt{Hz})$	NP	-210.1	NP
$S_{ieb}(dBA/\sqrt{Hz})$	-207.8	-203.1	-200.7
$S_{vre}(dBV/\sqrt{Hz})$	-48.86	NP	-57.29
$S_{ieb}(dBA/\sqrt{Hz})$	-207.8	-203.1	-200.7
$S_{vrb}(dBV/\sqrt{Hz})$	-89.0	NP	-100.6
$S_{iec}(dBA/\sqrt{Hz})$	-207.9	-203.2	-200.7
$S_{vre}(dBV/\sqrt{Hz})$	-43.8	-49.5	-53.8
$S_{iec}(dBA/\sqrt{Hz})$	-207.9	-203.2	-200.7
$S_{vrb}(dBV/\sqrt{Hz})$	-83.9	-91.1	-97.1
$S_{vrb}(dBV/\sqrt{Hz})$	NP	NP	NP
$S_{vre}(dBV/\sqrt{Hz})$	NP	NP	NP

TABLE I

Calculation of Possible Intrinsic Noise Source Pairings to Produce Measured Spectra (NP = Non-Physical Result)

Intrinsic Noise Source Pairs	I_C 2 mA	I_C 4mA	I_C 10mA
$S_{ieb}(dBA/\sqrt{Hz})$ from S_{vC}	-207.8	-203.1	-200.7
$S_{ieb}(dBA/\sqrt{Hz})$ from S_{vB}	-206.2	-204.1	-198.4
$S_{iec}(dBA/\sqrt{Hz})$ from S_{vC}	-207.8	-203.2	-200.7
$S_{iec}(dBA/\sqrt{Hz})$ from S_{vB}	-191.4	-192.1	-189.6
$S_{vrb}(dBV/\sqrt{Hz})$ from S_{vC}	-21.7	-21.5	-25.4
$S_{vrb}(dBV/\sqrt{Hz})$ from S_{vB}	-43.7	-49.2	-53.4
$S_{vre}(dBV/\sqrt{Hz})$ from S_{vC}	-61.8	-63.0	-68.7
$S_{vre}(dBV/\sqrt{Hz})$ from S_{vB}	-83.8	-90.7	-96.7

TABLE II

Calculation of Possible Single Dominant Intrinsic Noise Sources to Produce Measured S_{vC} Spectra and S_{vB} Spectra

References

[1] M. N. Tutt, D. Pavlidis, D. Pehlke, R. Plana, and J. Graffeuil, *1/f Noise in AlGaAs/GaAs HBTs Using Ultrasensitive Characterization Techniques for Identifying Noise Mechanisms*, Inst. Phys. Conf. Ser No. 120, Chapter 6, Int. Symp. GaAs and Related Compounds, Seattle 1991, pp. 317-322.

[2] J.L Plumb and E.R Chennette, IEEE Trans. on Electron Devices, Vol. ED-10, p.304, 1964.

[3] A. Van Der Ziel, X. Zhang, A.H. Pawlikiewicz, *Location of 1/f Noise Sources in BJTs and HBJTs - I. Theory*, IEEE Trans. on Electron Devices, Vol. ED-33, No. 9, p.1371, September 1986.

[4] J. Kilmer, A Van Der Ziel, and G. Bosman, *Presence of Mobility Fluctuation 1/f Noise Identified in Silicon p+-n-p Transistors*, Solid-State Electronics, Vol. 26, No. 1, pp. 71-74, 1983.

[5] T. G. M. Kleinpenning, *Location of Low-Frequency Noise Sources in Submicrometer Bipolar Transistors*, IEEE Trans. on Electron Devices, Vol. ED-39, No. 6, p.1501, June 1992.

[6] D. Pehlke and D. Pavlidis, *Evaluation of the Factors Determining HBT High-Frequency Performance by Direct Analysis of S-Parameter Data*, IEEE Trans. on Microwave Theory and Techniques, Vol. 40, No. 12, p.2367-2373, December 1992.

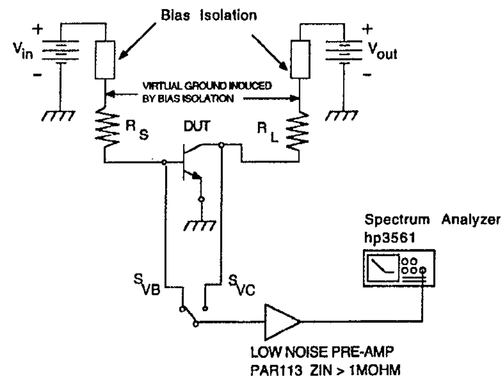

Fig 1. 1/f Noise measurement test set using an hp3048 including peripheral stabilizing and biasing circuitry

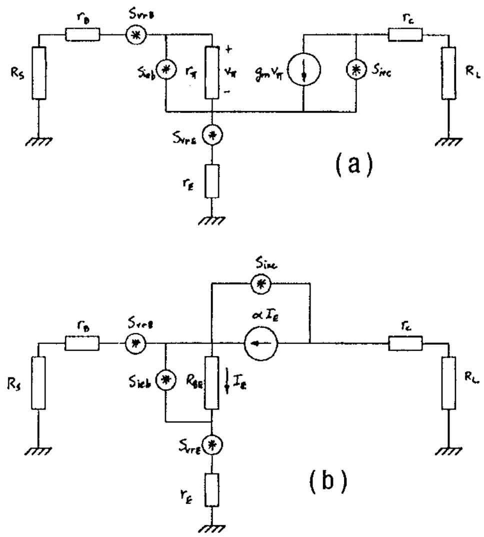

Fig 2. Equivalent Circuit representing noise behavior of AlGaAs/GaAs HBTs. (a) Hybrid-π (b) T-Model of this work.

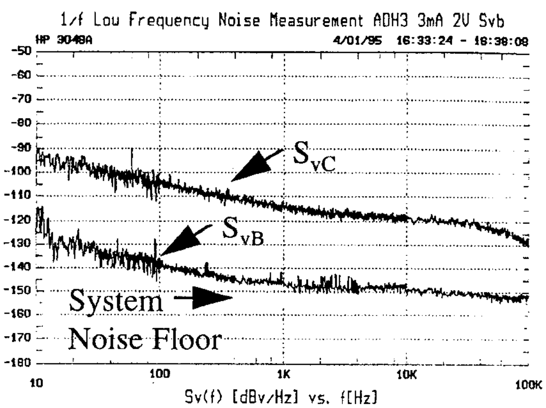

Fig 3. Measured collector (S_{vC})and base (S_{vB}) noise voltage spectral densities (dBV/ $Hz^{1/2}$) for a 3 x 1.4 um x 8.5 um emitter geometry at a collector current of I_C = 3 mA and V_{CE} = 2 V.

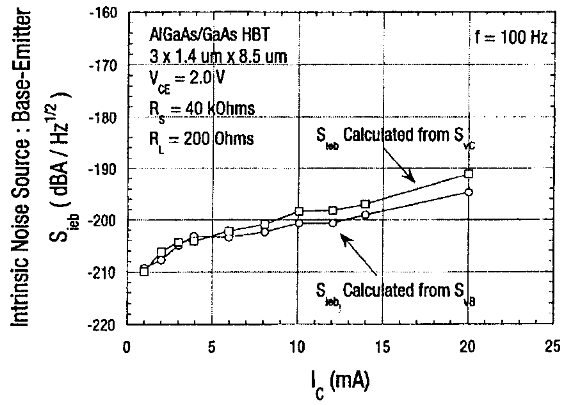

Fig 4. Extracted intrinsic noise source S_{ieh} located at base-emitter heterojunction. Calculation from S_{vC} and from S_{vB} self-consistently establish same dominant noise source magnitude verifying S_{ieh} as the single dominant noise source in this device

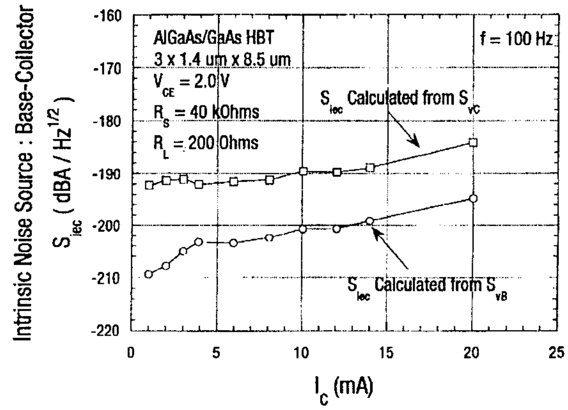

Fig 5. Attempt to extract intrinsic noise source S_{icc} located at base-collector junction from S_{vC} and from S_{vB} results in significantly different noise source magnitudes, verifying that S_{iec} alone is insufficient to model the HBT noise behavior.

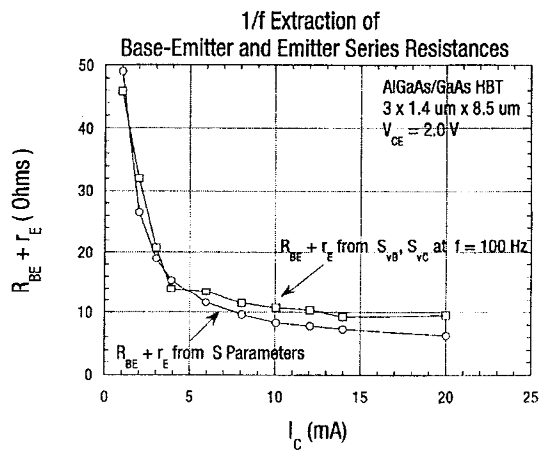

Fig 6. Extraction of the sum of base-emitter junction and emitter series resistances from S-parameter direct extraction and from the collector and base spectra showing good correspondence.