Very Low Frequency S-Parameter Measurements for Transistor Noise Modeling

O. Sevimli[1], A. E. Parker[1], A. P. Fattorini[2], J. T. Harvey[2]

Abstract – **Correct measurement of low frequency noise in a transistor requires prior knowledge of its s-parameters but the measurement of s-parameters at very low frequencies are difficult due to long time constants of the measurement setup and instabilities in the transistors. We report a method to stabilize and measure the s-parameters of GaAs heterojunction bipolar transistors (HBT) at frequencies as low as 10 Hz to 1 MHz, and discuss an industry standard transistor model at these frequencies.**

1 INTRODUCTION

Low frequency noise in transistors is the dominant contributor of phase noise in fully integrated microwave oscillators as the high-Q filters are not available on chip. The accuracy of phase noise prediction therefore relies heavily on the accuracy of the transistor model at very low frequencies.

The GaAs Heterojunction Bipolar Transistors (HBTs) generate less low frequency noise compared to other type of microwave transistors and widely used in integrated oscillators. The theory of low frequency noise on the other hand is still not fully understood forcing the models to be empirical, relying on measurements.

The measurement of low frequency noise in a transistor follows the same well developed theory of noise measurement in two-terminal devices in general, [1], [2]. The measured noise includes the noise generated by the transistor as well as the noise generated by the measurement system, which has to be removed from the data mathematically [3]. However, the noise generated by the measurement system depends on the device under test and calculation of it requires prior knowledge of the impedances presented by the transistor to the measurement system. The transistor impedances at such low frequencies are sometimes measured as h-parameters [4] or y-parameters [5]. We attempted to measure the s-parameters instead to be able to compare them to the more familiar behavior of the transistor at higher frequencies.

The low frequency s-parameters of GaAs HBTs are not generally available as the microwave circuit manufacturers normally measure their transistors above 0.1 GHz where most circuits are designed, and provide good models valid at these higher frequencies. At the very low frequencies, however, the transistor behaves differently, showing dispersion because of self heating, and low frequency s-parameters cannot be extrapolated from the high frequency data.

In this paper we explained a method for measuring on-wafer s-parameters of GaAs HBTs at very low frequencies. We proposed using resistive bias connections instead of the conventional inductive bias networks to maintain stability.

We then used the measured s-parameters to develop a low frequency extension to a non-linear transistor model supported by the circuit manufacturer. This model was also suitable for predicting the oscillator behavior including the noise up-conversion.

2 TRANSISTOR STABILITY

We found that GaAs HBTs with emitter sizes of 10x1 μm^2 or larger could become unstable during low frequency measurements; this is generally a known problem although rarely formally reported [6]. Our HBTs had very large gain below 10 MHz due to self heating and they showed large negative input impedances at both ports as shown in Figure 1, when the other port is not terminated. Resistive terminations at these frequencies were needed for stability. In addition, high frequency instabilities could occur during a low frequency measurement; there is some anecdotal evidence in literature on this and 50 Ω terminations are usually recommended. It is usually difficult to predict where the oscillations occur as the transistor models rely on the measurements that can't be made unless stability is achieved. We tried to use well characterized terminations and equipment at all frequencies between DC and 50 GHz because our HBTs had available gain up to 50 GHz.

We constructed a High Frequency (HF) 50 Ω termination using commercially available coaxial components: a tee junction, a dc-blocking capacitor and a 50 Ω load as shown in Figure 3 (in red shaded box). The term HF is used here to indicate the frequencies higher than the measurement band, i.e. greater than 10 MHz. The value of the coaxial

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[1] Department of Electronic Engineering, Macquarie University, NSW, 2109, Australia
e-mail: oya.sevimli@ieee.org tonyp@ieee.org
[2] Mimix Broadband, P.O. Box 471, North Sydney, NSW, 2059, Australia
e-mail: tfattorini@mimixbroadband.com.au jharvey@mimixbroadband.com.au

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dc-blocking capacitor was approximately 90 pF and it was effective above 10 MHz as indicated by the measurements shown in Figure 2. The coaxial components were SMA type and higher order waveguide modes were visible (as expected) in the measurements above 20 GHz. We used an additional coaxial 3 dB attenuator with higher frequency rating to suppress these.

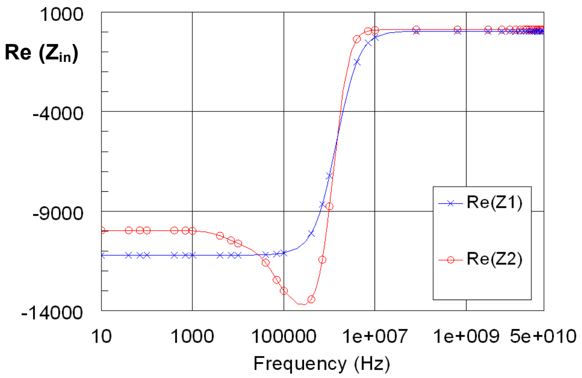

Figure 1: Simulated input impedance of the transistor at each port when the other port is left open.

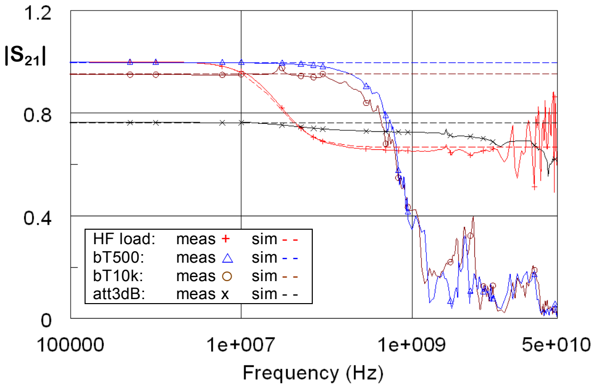

Figure 2: Measured and simulated |S21| of coaxial terminations used for stability and bias.

The DC bias of the transistor needs to be decoupled from the AC signal throughout the measurement frequency band. For this purpose we used 10 mF electrolytic capacitors and carbon resistors mounted on multipurpose printed circuit boards (PCB) as shown in Figure 3, labeled as bT500 and bT10k. These bias networks provided very good decoupling between 10 Hz and 10 MHz (see measurements in Figure 2). The values of the bias resistors were a compromise depending on the transistor bias currents and the DC voltage available from the supply, also on the amount of transmission loss we could torelate. The base currents were much smaller than the collector currents and a 10 kΩ resistor at port 1 (base) and a 500 Ω resistor at port 2 (collector) were suitable. The bias networks on PCBs and the low frequency network analyzer itself were not expected to present well defined terminations above 10 MHz therefore the HF load and the coaxial attenuator was needed.

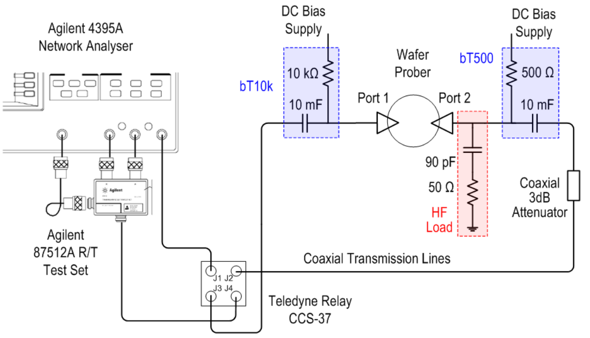

Figure 3: Measurement setup used for on-wafer low-frequency s-parameters.

For the GaAs HBTs with emitter sizes of 10x1 µm^2 one HF load on the collector side, together with one 3 dB attenuator and the bias networks as shown in Figure 3 were sufficient for stability. Larger HBTs with higher gains might require custom designed terminations with higher frequency rating than SMA type and better defined impedances up to 50 GHz.

3 ON-WAFER CALIBRATION

An Agilent vector network analyzer 4395A and an 87512A Reflection/Transmission Test Set were used to measure the low frequency s-parameters as shown in Figure 3. An electrically controlled coaxial switch CCS-37 was used to automatically measure the full 2-port s-parameters. Two 100 µm pitch wafer probes (Picoprobe Model 40A) were used to make contact with the HBT at ports 1 and 2.

On-wafer calibration standards: open, short, load and through, were included on the same 100 µm thick GaAs wafer and the calibration was achieved by correcting the measured data using the 12-term error correction equations [7].

The 12-term error correction theoretically removes all the linear errors introduced by the measurement setup and the corrected s-parameters are obtained at the device terminals. However, as the loss in the measurement setup increases and the AC power level decreases, the received signal becomes very small and the measurement error becomes relatively large. In our case the setup loss was higher than usual due to the resistive bias networks and the attenuator; and the AC power level had to be kept at a minimum to avoid saturation of the transistor. As a result, measured s-parameters had some ripple on them especially visible in S_{22}. Nevertheless they were suitable for modeling between 10 Hz and 1 MHz. The loss of HF load (in addition to the attenuator loss) above 1 MHz was too high for the s-parameters to be considered reliable.

4 MEASURED S-PARAMETERS

The s-parameter measurements at such low frequencies created some interesting challenges, for example biasing the transistors through the large capacitors required a significant amount of time. The charging time of the 10 mF capacitor for typical base bias was calculated to be 22.7 minutes. In addition, each frequency sweep of the network analyzer, with averaging of 24 sweeps, took 19 minutes of real time due to very narrow IF filtering at the lowest frequencies.

The measured s-parameters of a 10x1 μm^2 GaAs HBT between 10 Hz and 10 MHz are shown in Figure 4. The transistor was in common-emitter configuration and at room temperature. Simulated s-parameters using the foundry supported HBT model fitted to the measurements are also shown. The measured and simulated $|S_{12}|$, $\angle S_{11}$, and $\angle S_{22}$ were very small, close to zero.

5 LOW FREQUENCY HBT MODEL

An industry standard non-linear transistor model of the type VBIC (Vertical Bipolar Intercompany) [8] could be used to model the low frequency dispersion of the HBT with the addition of simple thermal networks. The advantages of this model are its suitability for VCO design including phase noise simulation and its availability with most of the commercial microwave circuit simulators.

We have adjusted the parameters of a 4-stage thermal resistor and capacitor (RC) ladder network [9], [10] as shown in Figure 5 so that the simulated s-parameters were a good fit to the measurements. The adjusted RC values of the ladder network scaled approximately with the increasing area of the cross section of the heat flow in the direction from its source towards the base of the GaAs wafer. However, with a linear RC network, it was not possible to obtain a very accurate fit. For example, as the error in S_{11} and S_{22} increased with increasing bias currents, the opposite was observed with S_{21}. This was not a problem for noise measurements [3] as each bias point could be simulated separately, but the simulation of noise upconversion in an oscillator needs the model to be accurate at all bias conditions.

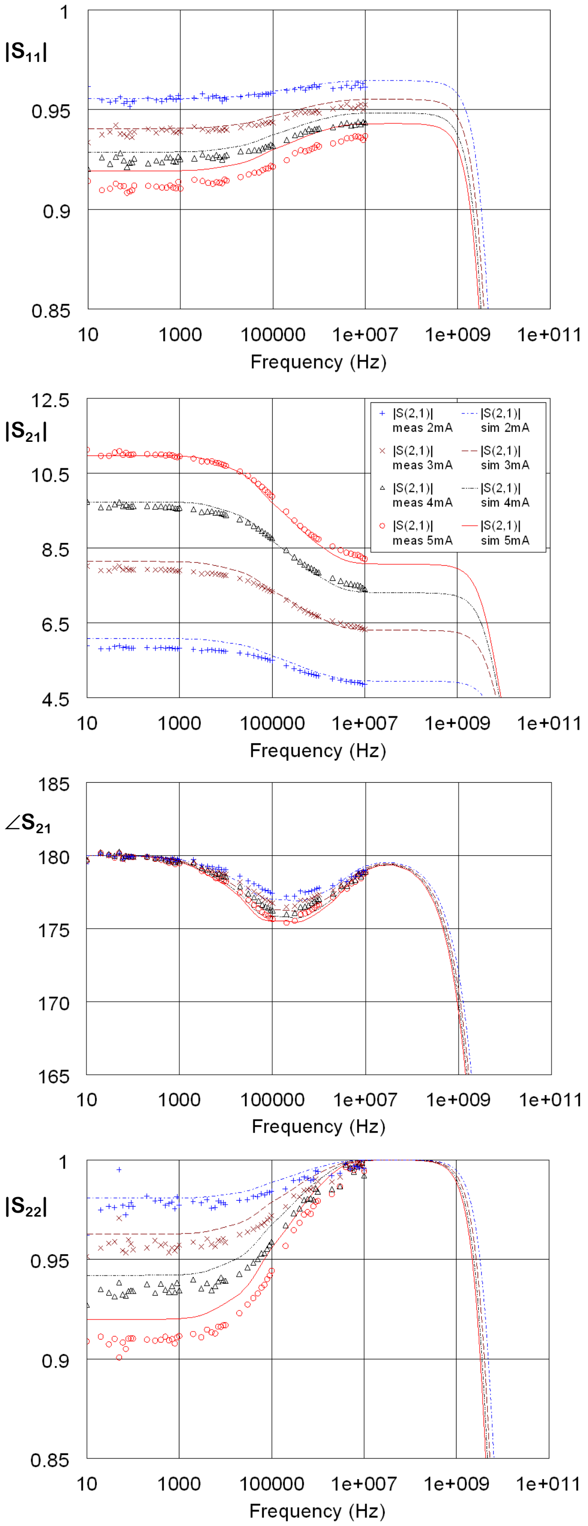

Figure 4: Measured (symbols) and simulated (lines) s-parameters of a 10x1 μm^2 GaAs HBT. The collector-emitter voltage was 2.5 V and the collector currents varied between 2 mA and 5 mA as shown.

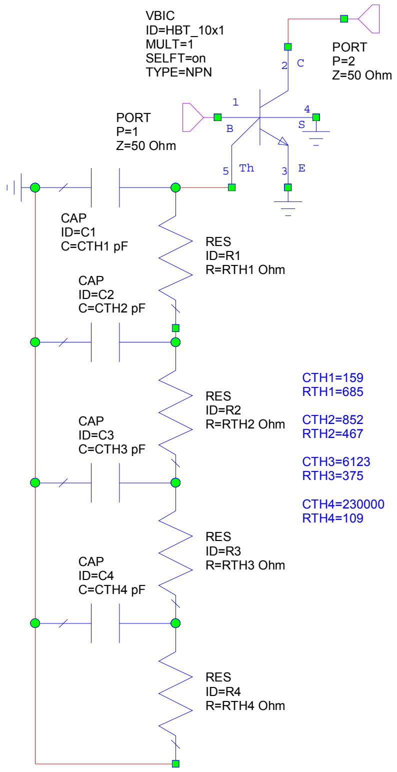

Figure 5: The thermal RC ladder network added to the foundry supported HBT model.

Conclusions

The instabilities during low frequency s-parameters of HBTs are caused by their large low frequency gains due to self heating and their available high frequency gain up to 50 GHz. Stability can be achieved with the use of resistive bias networks at low frequencies and 50 Ω terminations at high frequencies. The standard on-wafer 12-term error correction is suitable, although extra loss due to resistive bias networks and attenuators cause some ripple in the measured s-parameters. The industry standard VBIC transistor model, with the addition of a thermal network to model the low frequency dispersion, is very convenient for modeling the low frequency noise and its upconversion. However, in this case, self heating effects predicted by the model with increasing bias currents did not follow the same trend as the measurements.

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