High-Volume Low Frequency Noise Characterization Technique

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Abstract

This work demonstrates a low frequency noise measurement technique and setup that is suitable for high-volume testing. This measurement setup allows us to collect a high volume of data very rapidly compared to conventional methods, making routine 1/f noise characterization measurements possible. This added capability is very beneficial in studying new device designs or guiding process development.

INTRODUCTION

Devices used in today's communication power amplifiers often times work in nonlinear modes of operation which introduce various types of signal distortion. Among these, the up-conversion of the device low frequency noise, which is commonly referred as 1/f (Flicker) noise, to the frequency band of operation can produce noise in phase modulation as well as in amplitude modulation. Ultimately, this type of distortion deteriorates the system's performance. In addition, 1/f noise has previously been correlated to long-term reliability of III-V power devices [1], as well as to specific device processing steps [2,3]. Therefore, the availability of a high-volume 1/f noise characterization technique and tool proves to be very important during the development of new devices, new epitaxial structures, and associated manufacturing processes. However, the current methods for measuring 1/f noise are time consuming, expensive, and often require very specialized operators.

In this work we demonstrate a low frequency noise measurement technique and setup that is suitable for high-volume testing. The noise parameter extraction used with this technique has proven to be very robust and applicable to a wide variety of devices, such as III-V HBT's, FET's, and Si(Ge) devices.

PREVIOUS IMPLEMENTATIONS

The test methodology is based on a previous implementation by Agilent Technologies [4]. This methodology uses a Stanford Research LNA to amplify the collector/drain noise of the device and an Agilent 35670A low frequency signal analyzer to measure the noise spectral power density of the device. The LNA also supplies the bias to the collector/drain terminal through an internal battery pack. In addition, the base/gate is biased through a low-pass filter.

The Agilent system is not suitable for automation for multiple reasons. First, it requires the operator to manually connect the device in DC measurement mode to determine the required bias point. Secondly, the operator needs to determine the required sensitivity of the LNA and, again manually, configure the LNA for the noise measurement (including setting the collector/drain voltage). These are just two examples of the required operator intervention that makes automation difficult. Finally, the noise parameter extraction technique utilized by Agilent has occasional convergence issues for "non-standard" data, which we observed on GaAs FET devices. In this case, the specific process technology may induce a non-ideal noise behavior over frequency, with many broad peaks and a frequency power coefficient different than unity.

SKYWORKS' SOLUTION

In this work, we demonstrate both a system architecture (Figure 1) and related software automation that allows fully automated 1/f noise measurements for various device types, such as HBT's or FET's. This setup is based on a Stanford Research LNA type SR570 and a low frequency signal analyzer AG 35670A. The Device Under Test (DUT) is biased using a 4142B power supply. The bias is applied to the base/gate of the device through a low-pass filter, similar to the one available in Agilent's solution. The collector/drain is biased through the LNA's internal battery for minimum noise generation from the measuring system itself. The main hardware difference from the previous implementation is the addition of three microwave switches that allow us to be connected in both the DC and noise measurement configurations remotely, through a third bias supply, without introducing unwanted noise. An additional manual switch (not shown in the diagram) allows for switching between a FET low-pass filter and an HBT filter. The two filters have different output low frequency impedance requirements [4].

The data collection and analysis together with all the associated automation is achieved using the ICCAP Data Acquisition and Modeling Software environment. The automation of the measurement is realized as follows: most of the instruments are connected to the controlling computer using a GPIB network; the Stanford Research LNA does not have a GPIB interface but an RS232; therefore, a separate control sequence is built for this instrument using one of the computer's serial communication ports; the control of the three microwave switches is achieved using an additional 4142B bias unit which is turned on/off accordingly (in the schematic, the green routing represents the control lines, the red routing represents the DC path, while the blue routing represents the Flicker noise measurement path).

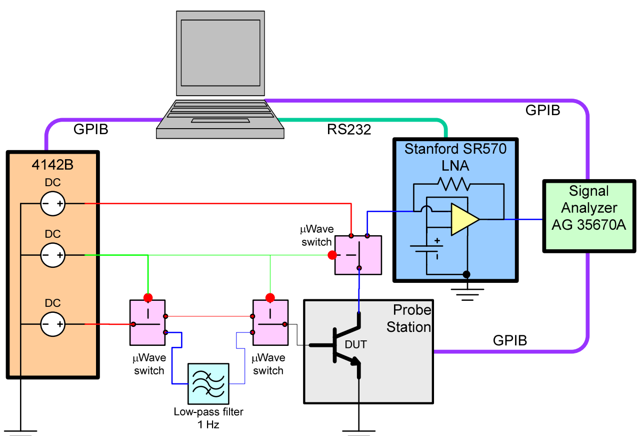

Figure 1. Diagram of the 1/f noise test setup.

First, we need to determine the DC bias points to be used. A Gummel sweep (swept V_{be} with fixed V_{ce}) for HBT devices and transfer curve measurement (I_d vs. V_{gs} for fixed V_{ds}) for FET devices is performed. Subsequently, four bias points are determined (base current for HBTs and gate voltage for FETs) such that the output current densities of the DUT are evenly distributed on a logarithmic scale, within the current limitations of the system. These limitations involve an upper output current limit of 5 mA, imposed by the LNA, and a lower limit of 1 uA base current, in the case of the HBT devices, due to the HBT low-pass filter limitations.

Next, the LNA bias and sensitivity is setup remotely through the RS232 communication line. The sensitivity of the LNA for each bias point is determined by assuming a specific power function of the noise spectrum density with the output DC current of the device (***A_f***, shown in Eq. 1). Empirically, this parameter is approximately 1.2 for HBTs and 0.7 for FET devices.

The noise spectral density of the DUT is measured using the low frequency signal analyzer AG 35670A. A special system noise "de-embedding" is applied to the measured data to make sure the output represents only noise induced by the DUT. For this purpose, the noise spectral density of the system is measured at each different sensitivity setting of the LNA while the DUT is replaced by a microwave ceramic THRU device, before a batch of tests or if hardware changes occurred. This system noise data is stored in a library and is subtracted from the DUT measured data according to the specific LNA setting. Figure 2 shows the measurement of a GaAs HBT device together with the highest system noise (worst). This demonstrates that the effective device noise density is at least two orders of magnitude higher than the system noise in the frequency interval of interest.

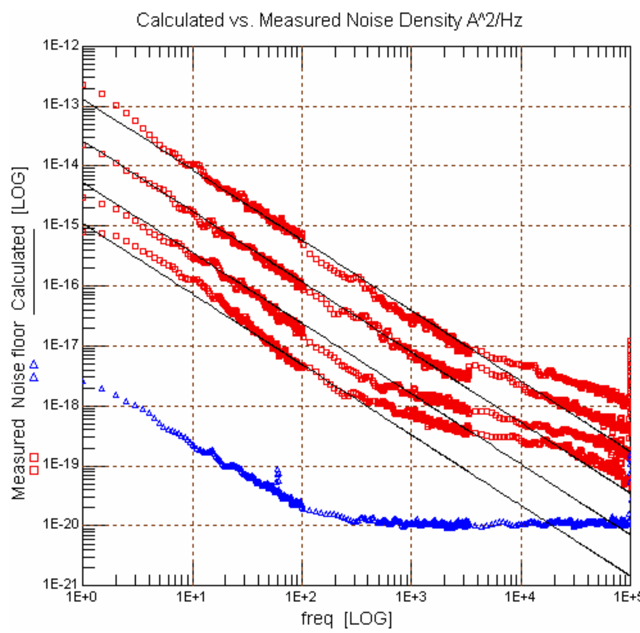

Figure 2. Example of measured 1/f noise spectral density at HBT collector (GaAs) versus the worst system noise floor.

The noise spectrum density of the device is modeled by the following relationship:

$$S_{iB} = K_f \frac{I_{Bi}^{A_f}}{f^{B_f}} \qquad \text{Eq. 1}$$

where ***S_{ib}*** is the noise spectral density at the base for HBTs or ***S_{id}*** for FETs, ***K_f***, ***A_f***, and ***B_f*** (***E_f*** in other notations) are the noise model parameters, ***I_{bi}*** (***I_{di}*** for FETs) is the base (drain) current for each measurement ***i***, and ***f*** is the frequency.

The extraction algorithm does not assume that ***B_f*** is always unity. Our measurements show that, HBTs follow this general relationship with this coefficient varying between 0.9 and 1.3, GaAs FETs we have measured have a frequency exponent lower than unity. For this reason, the first step of our extraction method determines this coefficient. The challenge of this step is removing all the noise peaks, both sharp and broad, that are due to other non Flicker noise related device characteristics, from the data. Our extraction algorithm uses such averaging methods. An example case is presented in Figure 3.

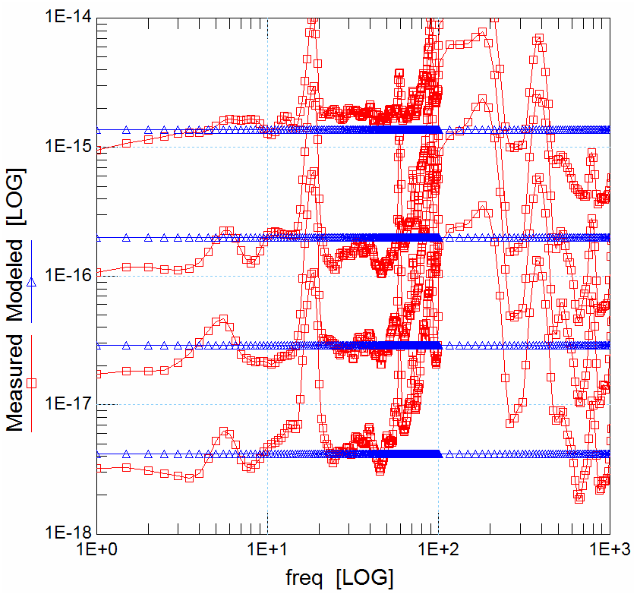

Figure 3. Extreme case of non-1/f noise behavior (GaAs MESFET device, noise spectral density is frequency-normalized, in units of A^2). The extracted frequency exponent value is in this case 0.73.

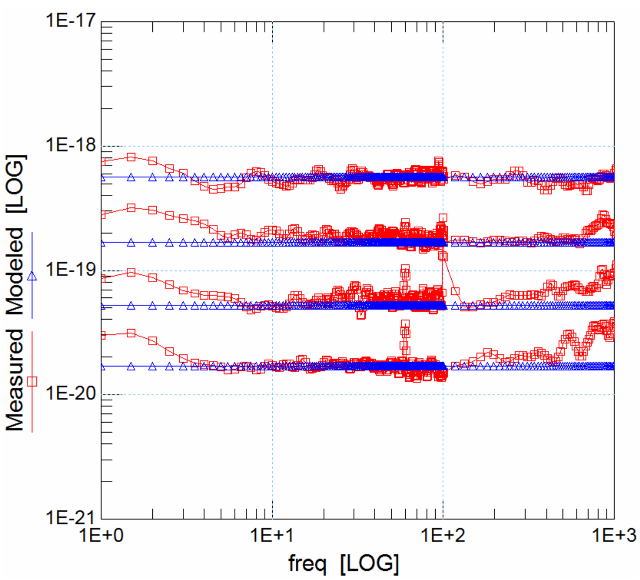

Figure 4. Close to ideal 1/f noise behavior (Si bipolar device, noise spectral density is frequency-normalized, in units of A^2). The extracted frequency exponent value is in this case 1.13.

In this case, the GaAs FET displays significantly higher noise, with sharp peaks around 20 Hz and broad peaks between 90 Hz and 200 Hz. The data is frequency normalized (multiplied by f^{Bf}). In contrast, Figure 4 shows a case of Si bipolar device, where the overall Flicker noise is lower than the GaAs device and the 1/f behavior is close to ideal.

Subsequently in the extraction procedure, we calculate the logarithm of the frequency normalized noise spectral density and average this data over frequencies below 100 Hz (defined as ***1 Hz*** S_{ib}) without taking into consideration the false 1/f noise peaks, in a manner similar to that described for the previous step. This is repeated for each bias point. The result is ultimately a fit over the logarithm of the output DC current ,in the case of FETs and passive devices, or of the base current, in the case of HBTs. A linear fit of $\log(S_{ib}*f^{B})$ versus $\log(I_b)$ provides an estimation of both noise parameters K_f and A_f as shown in Eq. 2.

$$\log_{10}\left(S_{iB}\cdot f^{B_f}\right)=\log_{10}\left(K_f\right)+A_f\cdot\log_{10}\left(I_{Bi}\right) \qquad \text{Eq. 2}$$

An example of fitted data, using the procedure described above, is shown in Figure 5. The plot represents data collected from approximately same size devices (25 um^2) in two technologies, GaAs HBTs and Si bipolar transistors. The two GaAs HBTs have different epitaxial structures. The variation between the 1/f characteristics of these devices is better understood plotting the Flicker noise parameters extracted from these linear fits as in Figure 6.

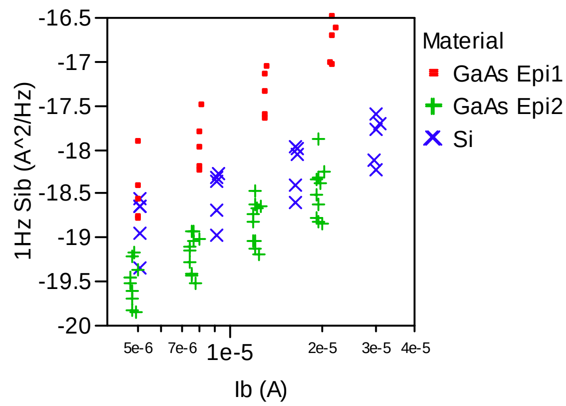

Figure 5. Comparison of fitted 1 Hz noise data versus base current for various device selections.

PERFORMANCE CONSIDERATIONS

Compared to conventional 1/f measurement methods, our implementation offers a fully automated solution which requires no operator intervention and is thus faster. The measurement time is approximately 10 minutes for a FET device and 18 minutes for an HBT. Through wafer prober automation, which is part of our solution, 1/f noise test mapping of an entire test wafer can be completed in a few hours. The longer measurement time of the HBT is due to constraints imposed by the low-pass filter. The filter, in this case, has a high low-frequency impedance (300 kOhm), requiring a significantly longer time for device bias stabilization.

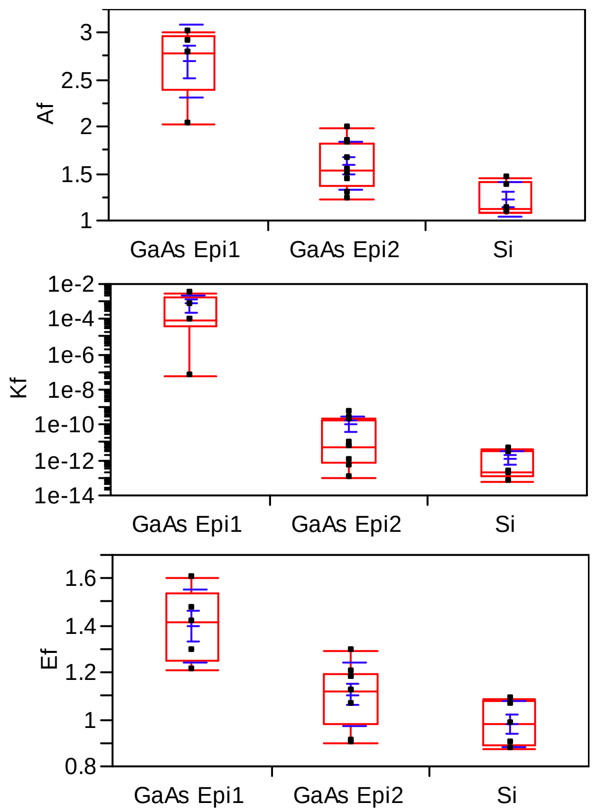

Figure 6. Comparison of extracted Flicker noise parameters for various device selections.

Because tantalum capacitors are used in the filter, there is a significant amount of capacitor leakage current, which leads to the requirement of a minimum 1 uA base current, a significant constraint for HBT testing. This is not an issue for FETs since the filter for FETs has a low (50 Ohm) impedance and the device is biased by applying gate voltage instead of current. There is an additional constraint for the output terminal, since the highest collector/drain current is 5 mA because of the current output capabilities of the Stanford SR570 LNA.

Additional consideration has been given to the timing of the three microwave switches. The high resistance of the low-pass filter for HBTs can result in a high voltage (above 40V) applied to the input of the filter. This potential may destroy the device if applied directly if no discharge time is allowed.

CONCLUSIONS

In this work we demonstrated a Flicker noise parameter extraction technique that is suitable for testing many device types, including active devices such as HBTs and FETs or passives such as resistors. Our fully automated test routine has improved robustness and convergence compared to conventional methods. The measurement setup allows us to collect a high volume of data very rapidly, making 1/f measurements applicable to routine characterization. This proves to be extremely beneficial in studies related to new device design or process development.

In addition, our test technique takes advantage of test equipment usually part of a regular device characterization laboratory, simplifying 1/f measurements and reducing cost compared to specialized flicker noise measurement systems.

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ACRONYMS

HBT: Heterojunction Bipolar Transistor
FET: Field Effect Transistor
LNA: Low Noise Amplifier
DUT: Device Under Test