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MICROWAVE NOISE CHARACTERIZATION OF GaAs MESFETs BY ON-WAFER MEASUREMENT OF THE OUTPUT NOISE CURRENT

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Abstract

A simplified noise equivalent circuit is presented for GaAs MESFETs in the common-source configuration, consisting of five linear circuit elements: the gate-to-source capacitance C_{gs}, the total input resistance R_T, the transconductance g_m, the output resistance R_o, and a noise current source of spectral density S_{io} at the output port. All of these elements have been determined by on-wafer measurements. The minimum noise figure F_{min} calculated from this model, as well as the bias and frequency dependence of F_{min}, agree with the measured microwave noise figure of the device. Thus the determination of the F_{min} can be done rapidly, conveniently, without the need for tuning, and at the wafer stage of device fabrication solely by on-wafer measurements.

Objectives

The GaAs MESFET along with the HEMT is the principal low-noise active device in the microwave and millimeter wave frequency range. Its potential for wide-spread use in low noise applications motivates the search for a method of determining and predicting F_{min} rapidly and in an efficient manner. The presently available methods for determining F_{min} are adequate for laboratory work, but inconvenient in a production setting. The calculation of F_{min} based on either theoretical [1] or empirical [2] models requires a knowledge of a number of parameters which are inconvenient to measure. As a result, the F_{min} is usually determined by actual measurement at the desired frequency of operation f_o [3]. Even with an automatic noise figure meter, this testing is a time consuming trial-and-error process since it requires manual tuning of the generator admittance Y_g presented to the device, so as to find the optimum value of Y_g for which the noise figure F is a minimum. The ability to test on-wafer and predict F_{min} of the device at f_o can result in substantial savings.

This paper presents a solution to the problem of predicting $F_{min}(f_o)$ on the basis of lower frequency measurements which can be carried out on an automated wafer probe station, and which do not involve a direct measurement of F at all. The method presented is based on a simplified noise equivalent circuit model, containing only four lumped circuit elements and one noise current source.

Noise Equivalent Circuit

Since our goal is only to predict the F_{min} which is invariant with respect to lossless transformations at the input and output ports, the inclusion of most parasitics is unnecessary. The proposed model therefore includes only four essential device parameters: C_{gs}, R_T, g_m, R_o, and a controlled current source at the output port. These four elements constitute the noiseless equivalent circuit of the MESFET and are shown in the dotted box in Fig. 1(a). These elements are linear, dc bias dependent, and independent of frequency.

Since experimental measurements yield the noise figure of a complete circuit, a model of the circuit in which the MESFET is embedded is also needed for the calculation of a noise figure. This circuit is modeled by a single circuit admittance Y_c interposed between the generator and the active device, and is also shown in Fig. 1(a).

The noise equivalent circuit of an amplifier is shown in Fig. 1(b) in which the thermal noise generated in G_g and G_c is represented by noise current sources i_g and i_c respectively, whose power spectral densities are obtained from the noise temperatures of the two conductances using Nyquist's theorem. The noise temperature of G_g and G_c is taken to be the reference temperature T_{ref}(= 290°K). The noise in the active device is modeled by the two noise current sources connected in shunt with the input and the output ports of the noiseless linear (small-signal) circuit model as shown in Fig. 1(b); these two noise sources i_{in} and i_o can be directly identified with gate and drain noise currents respectively. The input noise source, i_{in} can be subdivided into two parts: one uncorrelated and the other completely correlated with the output

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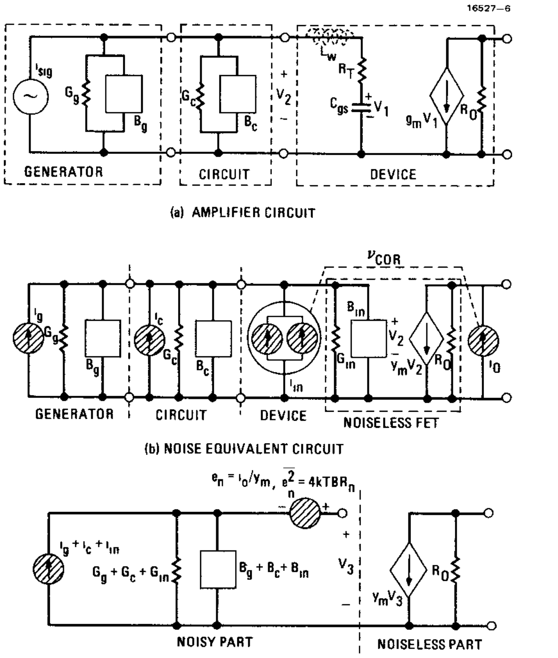

(a) AMPLIFIER CIRCUIT

(b) NOISE EQUIVALENT CIRCUIT

(c) SIMPLIFIED NOISE EQUIVALENT CIRCUIT FOR ANALYSIS

Fig. 1 Equivalent circuit models for noise analysis.

noise source i_o. Since the voltage controlling the current source in Fig. 1(b) is V_2 instead of V_1, the transconductance g_m is replaced by a transadmittance $y_m = (V_1/V_2)g_m$.

Calculation of Noise Figure

The noise equivalent circuit of Fig. 1(b) can be configured as in Fig. 1(c) in which the mutually uncorrelated noise sources i_g, i_c, and i_{in} are combined, as are the admittances $G_g + jB_g$, $G_c + jB_c$, and $G_{in} + jB_{in}$. In addition, the noise current source i_o at the output port is replaced by an equivalent noise voltage source e_n on the input side which is fully correlated with i_o, and which is added to the controlling voltage V_2. The source e_n is related to i_o by a correlation admittance equal to y_m; i.e., their correlation coefficient is $y_m/|y_m|$, and their spectral densities are related by $S_{io}(\omega) = |y_m|^2 S_{en}(\omega)$.

Three new parameters are now defined so as to express the results more compactly:

(1) An "equivalent noise resistance" $R_m(\omega)$ is defined as that resistance which at T_{ref} will produce an open-circuit noise voltage having the same spectral density as $S_{en}(\omega)$.

(2) An "uncorrelated noise conductance" G_{un} is defined as the conductance which at T_{ref} will produce a short-circuit thermal noise current having the same spectrum as the spectrum of the uncorrelated part of i_{in}.

(3) A correlation admittance Y_{cor} is defined as the transfer function relating the noise voltage e_n to that part of the noise current i_{in} which is fully correlated with i_o.

The noise figure of the amplifier circuit is given by:

$$F(Y_g) = 1 + \frac{G_c + G_{un}}{G_g} + \frac{R_m}{G_g}\left(|Y_g + Y_c + Y_{in} + Y_{cor}|^2\right). \quad (1)$$

and attains a minimum value

$$F_{min} = 1 + 2R_m\left(G_c + G_{in} + G_{cor}\right) \quad (2)$$

$$+ 2\sqrt{R_m\left(G_c + G_{un}\right) + R_m^2\left(G_c + G_{in} + G_{cor}\right)^2}$$

when the generator admittance has the optimum value of

$$Y_{g,op} = \left[\left(G_c + G_{in} + G_{cor}\right)^2 + \frac{G_c + G_{un}}{R_m}\right]^{1/2} \quad (3)$$

$$-j\left[B_c + B_{in} + B_{cor}\right] .$$

The fourth noise parameter R_n can be found by writing the noise figure in Eqn. (1) in terms of $Y_{g,op}$ and F_{min}, in the form [4]

$$F(Y_g) = F_{min} + \frac{R_n}{G_g}\left[\left(G_g - G_{g,op}\right)^2 + \left(B_g - B_{g,op}\right)^2\right] \quad (4)$$

where R_n (in units of ohms) is a measure of the sensitivity of F_{min} to Y_g, and its value is R_m.

Thus all four noise parameters $G_{g,op}$, $B_{g,op}$, F_{min}, and R_n of the MESFET amplifier can be determined.

Two assumptions are introduced to eliminate the variables G_{cor} and G_{un}, which are difficult to determine by direct measurement.

(1) If $f_o \ll f_t$ (device cutoff frequency), then y_m is real, so that the correlation coefficient between i_{in} and e_n is purely imaginary, and $G_{cor} = 0$. Then F_{min} in (2) is not influenced by the correlation between i_{in} and i_o, even if the two sources are highly correlated.

(2) If the shot noise is negligible, the uncorrelated part of i_{in} is dominated by the thermal noise in the input conductance G_{in}, so that, by definition, $G_{un} = G_{in}$.

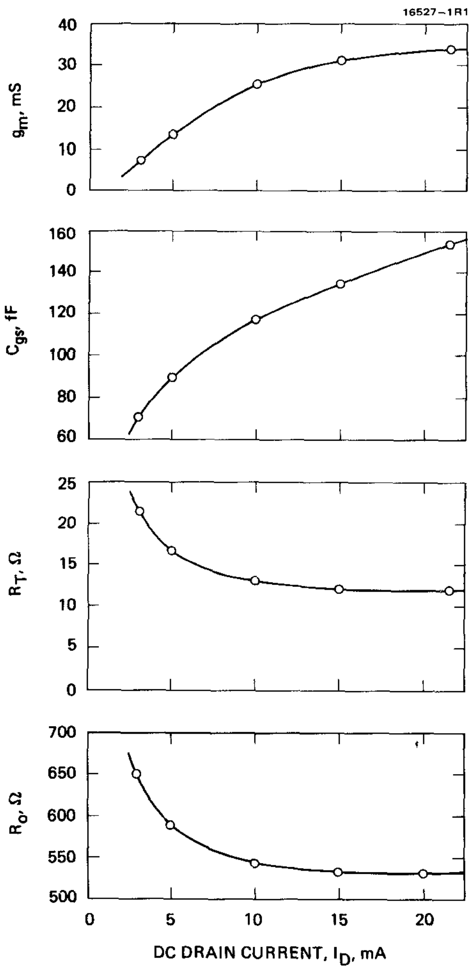

Fig. 2 Measured MESFET equivalent circuit parameters. (V_{DS} = 3))

With the above two assumptions, the minimum noise figure in (2) reduces to

$$F_{min} = 1 + 2R_n(G_c+G_{in}) + 2\sqrt{R_n(G_c+G_{in}) + R_n^2\,(G_c + G_{in})^2}\ . \tag{5}$$

On-Wafer Measurements

All experimental data reported in this paper were obtained on 0.25 μm T-gate GaAs MESFETs having a Ti/Pt/Au Schottky-barrier gate on a VPE grown active layer. The S-parameters of this device were measured over the frequency range 45 MHz to 18 GHz, and then a computer program [5] was used to determine the values of the equivalent circuit parameters. This procedure was repeated at each dc bias condition of interest to find the bias dependence of each element. The input resistance R_T is the sum of the gate, source, and channel resistances. The four parameters are plotted as a function of dc drain current I_D, and for a fixed drain-to-source voltage V_{DS} = 3 V, in Fig. 2.

The power spectral density S_{io} of the short-circuit noise current i_o at the output port can be measured directly with a narrow-band low-noise receiver. The measurement frequency f_L should be above those frequencies where the effects of low frequency noise sources, such as 1/f and generation-recombination noise, are negligible, thus assuring that S_{io} is flat between f_L and f_o. The noise spectral density S_{io} is calculated from the measured noise power, and a knowledge of the input impedance and the effective noise bandwidth of the receiver. Over the frequency range of 30 MHz to 1.2 GHz, and for V_{DS} in the range 1 V to 4 V, S_{io} was constant, and was dependent only on I_D, as shown in Fig. 3.

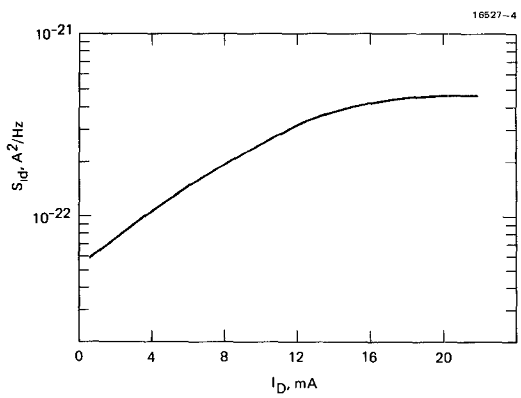

Fig. 3 Measured spectral density of the short-circuit noise current at the output port. (V_{DS} = 3V and V_{GS} = 0V)

Predicted and Measured Noise Performance

The noise figure of the MESFET amplifier has been expressed in (5) in terms of the three quantities R_n, G_{in}, and G_c. The noise resistance R_n and the input conductance G_{in} follow from the definition:

$$R_n = \frac{S_{io}/4k\,T_{ref}}{g_m^2\left(1 + \omega^2\,C_{gs}^{\,2}\,R_T^2\right)} \tag{6}$$

and

$$G_{in} = \frac{\omega^2 C_{gs}^{\,2} R_T}{1 + \omega^2\,C_{gs}^{\,2} R_T^2}\ . \tag{7}$$

The value of G_c is estimated by measuring the insertion loss of the circuit in which the MESFET is embedded, and further verified by a measurement of the F_{min} of this circuit at a low frequency (1.5 GHz), where G_{in} is small compared to G_c.

Given the three parameters R_n, G_{in}, and G_c, F_{min} can be calculated at any desired frequency and dc bias from (5). Calculated values of F_{min} are plotted in Figs. 4(a) and (b), as a function of I_D and f_o respectively. There was no variation with V_{DS} over the normal voltage range. F_{min} was measured in an RF noise figure test set, and the results of these measurements are also included in Figs. 4(a) and (b). The good agreement over a range of dc bias and frequency verifies the utility of the noise model.

Summary and Significance of Results

This paper has established a procedure whereby the minimum noise figure of a MESFET can be predicted at microwave frequencies solely from on-wafer measurements. The advantages of this method, compared with the actual microwave measurement of F_{min}, include the following:

(1) No individual tuning of devices is required for identifying the minimum of the noise figure.
(2) Measurements can be performed at the wafer stage of device fabrication,. prior to device dicing, mounting, bonding, etc.
(3) Measurement is possible on production batches, using automated test equipment.
(4) Since the procedure measures the five critical parameters which determine F_{min}, the technique is useful for diagnostics.

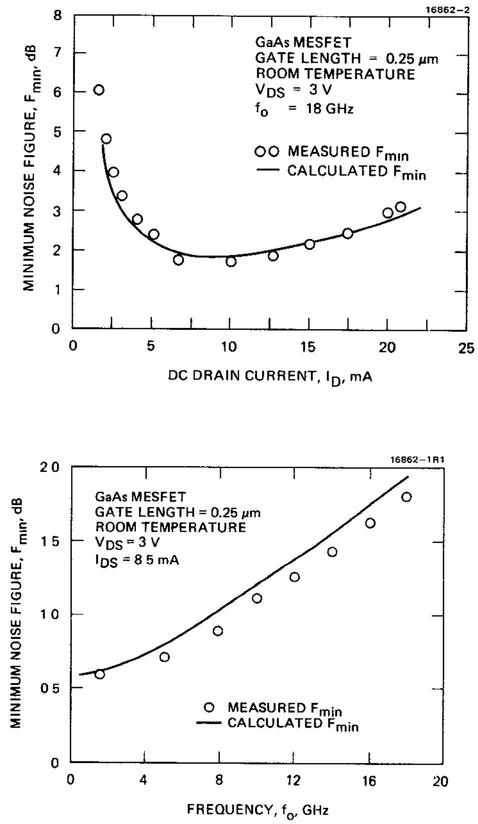

Fig. 4 Comparison of measured and predicted F_{min}.

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